# Welding Inspection Handbook

American Welding Society

# Welding Inspection Handbook

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Prepared by
AWS Committee on Methods of Inspection

Under the Direction of
AWS Technical Activities Committee

Approved by
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American Welding Society
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THE WELDING INSPECTION HANDBOOK is a collective effort of many volunteer technical specialists to provide information to assist welding inspectors and supervisors in the technology and application of visual and nondestructive examination.

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# Foreword

The inspection of welds and welded assemblies requires knowledge of many factors of welding quality control. This includes dimensional inspection, nondestructive examination methods, welding processes, welding metallurgy, destructive testing, and the qualification of welding procedures and personnel. It also includes the examination and test requirements of codes, criteria, and specifications; the acceptance standards to be employed; and an understanding of drawings, and welding and nondestructive examination symbols. Knowledge about discontinuities that may be associated with different welding processes, and the ability to evaluate the difference between discontinuities and rejectable defects, is also an important element of welding inspection.

This third edition of the *Welding Inspection Handbook* has been prepared by the AWS Committee on Methods of Inspection. The objective is to provide a reliable source of useful reference information. This is particularly relevant for the technically trained individual who may not be directly involved with inspection but whose position requires knowledge about welding inspection. This book also is intended for the inspector who needs a general refresher in the basic requirements of weld inspection.

Additional books on the subjects covered in each chapter may be found in good technical libraries. The many specifications and codes that have been used as examples may also be consulted for more detailed information.

This book is an instructive reference. Codes or specifications applicable to any particular weldment always take precedence over the generalized material contained herein. The text of this book has, of necessity, been written in general terms and cannot include all the conditions applicable to a specific instance. Thus, examples given are general and are used only for the purpose of illustration.

Every effort has been made to present this material in convenient form so that the book can be used as a training text for inspectors, engineers, and welders. Although the information generally relates to the arc welding processes, most of it applies to any weldment—fabricated by any joining process—for which the inspection methods described herein may be required.

For the inspection of brazed assemblies, refer to *The Brazing Handbook* published by the American Welding Society. For the inspection of resistance welded assemblies, refer to AWS/SAE D8.7, *Recommended Practices for Automotive Weld Quality—Resistance Spot Welding*, also published by the American Welding Society.

Information on nondestructive examination methods is available in AWS B1.10, *Guide for Nondestructive Examination of Welds*, and in AWS B1.11, *Guide for the Visual Examination of Welds.*

Comments and inquiries concerning this publication are welcome. They should be sent to the Managing Director, Technical Services Division, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

# Contents

# List of Tables

# List of Figures

| Figure | | Page |
|---|---|---|

**Figure** **Page**

# Chapter 1
# Scope and Application

## 1.1 Scope

The scope of this handbook includes testing and examination methods that apply to a majority of metallic and nonmetallic weldments used in construction. The extent of inspections should be clearly defined in contract documents or on drawings that refer to a particular weldment (unless otherwise defined in applicable codes or specifications). Furthermore, acceptance criteria should be clearly understood and agreed upon by both the supplier and the purchaser before any production welding begins. Acceptance criteria for weld discontinuities are specifically excluded from this handbook.

## 1.2 Application

The information in this handbook pertains to the general duties and responsibilities of welding inspectors and is intended to enhance their performance. This book provides specific information about methods of weldment inspection; however, much of the information will also generally apply to the examination of nonwelded components, such as base metal inspection prior to fabrication. For the inspection process to be effective, the welding inspector should be knowledgeable about each examination method required.

It is the responsibility of those charged with the administration and supervision of inspection to make certain that the principles and methods to be used are properly understood and applied uniformly. This responsibility may include the qualification and certification of inspectors where such certification is required by codes, specifications, job contracts, civil law, or company policies.

The following documents address the qualification of welding inspection and nondestructive examination personnel:[1]

(1) ASNT Recommended Practice SNT-TC-1a

(2) AWS QC1, *Specification for Qualification and Certification of Welding Inspectors*

Even when a particular qualification for certification program is not mandatory, every welding inspector should be aware of the ethical criteria for welding inspectors contained in documents such as AWS QC1.

1. See Chapter 17 for addresses of standards-writing organizations.

# Chapter 2
# Symbols

## 2.1 Communication

Communication can determine whether a job will be a success or a failure. In industry, drawings convey the designer's concepts to those performing the work. Intricate details can be much more accurately and efficiently described through graphic presentation than through the written word.

In the case of welded construction, a great deal of information may be required in order for the welder to successfully provide a weld adequate for the designer's intended purpose. Using written notes is one method for conveying the necessary design concepts. However, written descriptions can become quite complex and time consuming for intricate details. A simpler and more efficient method uses welding symbols.

The American Welding Society has developed a system of standard welding symbols now used and accepted worldwide. Figure 2.1 depicts the various types of weld and welding symbols and explains the purposes and locations of the basic elements. A detailed description of the system can be found in AWS A2.4, *Standard Symbols for Welding, Brazing, and Nondestructive Examination.* Figure 2.2 shows the advantages offered when welding symbols replace the written explanation. Figures 2.3 and 2.4 show other welding symbols and how they are used to specify the welding requirements. The adjacent details illustrate the significance of each symbol.

Just as the welding symbol is important to the welder, equally important is the welding inspector's knowledge of its meaning. Without this knowledge, the inspector would be unable to assure that the welder has complied with the requirements set forth by the designer. Typical information depicted by welding symbols that is of interest to a welding inspector includes type of weld, size of weld, weld location, joint configuration, finished condition of face and root of the weld, as well as any special instructions.

Knowledge of the information provided by the welding symbol is essential to the inspector when a weld is to be visually examined (VT). Once the inspector understands what the engineer requires, a thorough and highly effective visual examination can result. Many situations warrant a more extensive check than can be provided by visual examination alone. In such cases, other forms of nondestructive examination (NDE) are often employed.

The inspector can gain a great deal of insight from the welding symbol as to the applicability of a particular test when nondestructive examination is involved. In ultrasonic testing (UT), for example, useful information provided by the welding symbol might include the joint configuration and location. From this information, the NDE operator can determine whether the test can be physically conducted as well as what transducer angle would most readily reveal any discontinuities.

The welding symbol can also provide valuable information concerning how the test can be applied when radiographic examination (RT) is to be used. Information such as joint configuration, weld location, type of weld, and size of weld can help the radiographer to determine the types of discontinuities which may be present and the best method for their detection. Such details allow the inspector to plan his test so that the best technique and procedure will be used.

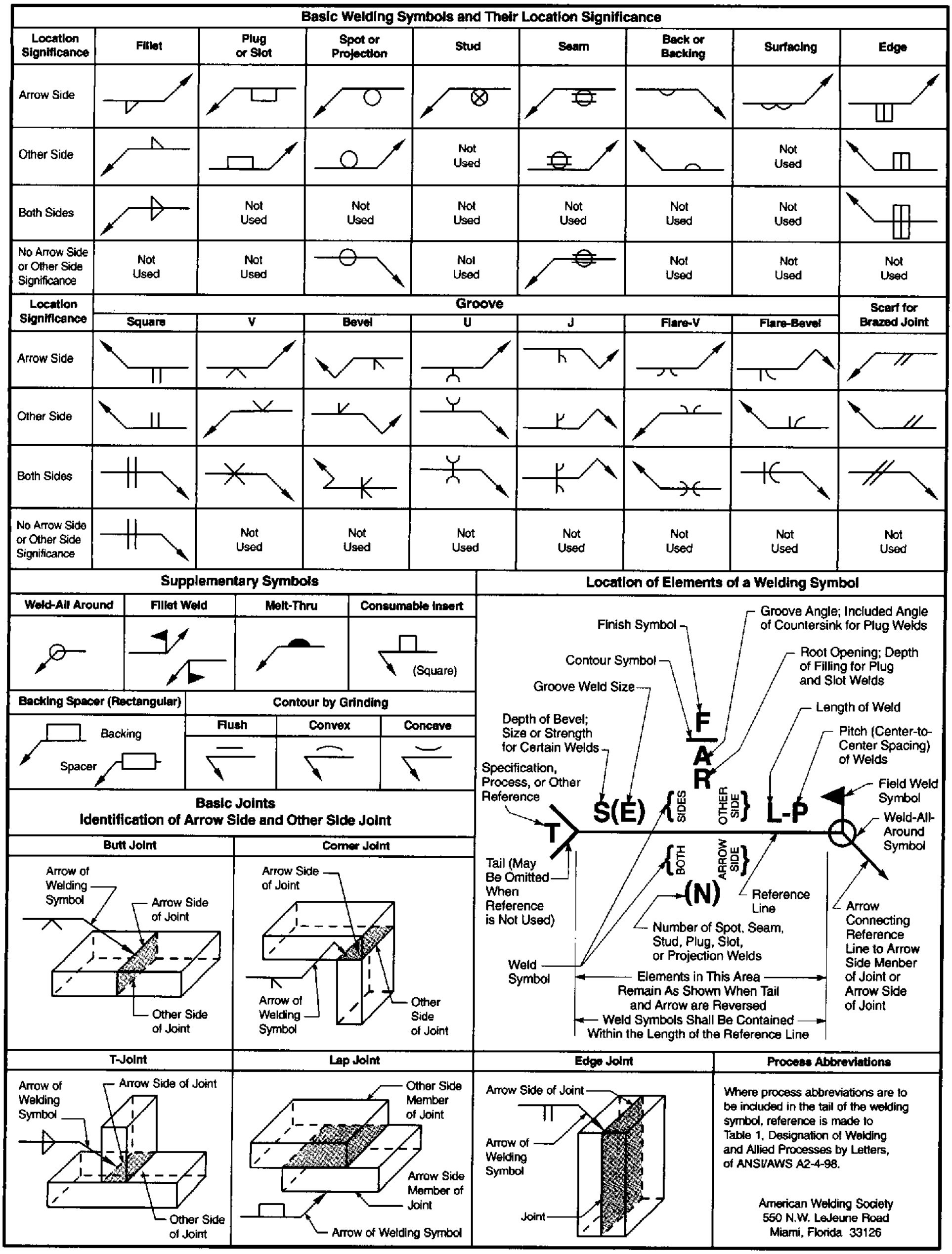



**Figure 2.1—AWS Standard Welding Symbols**

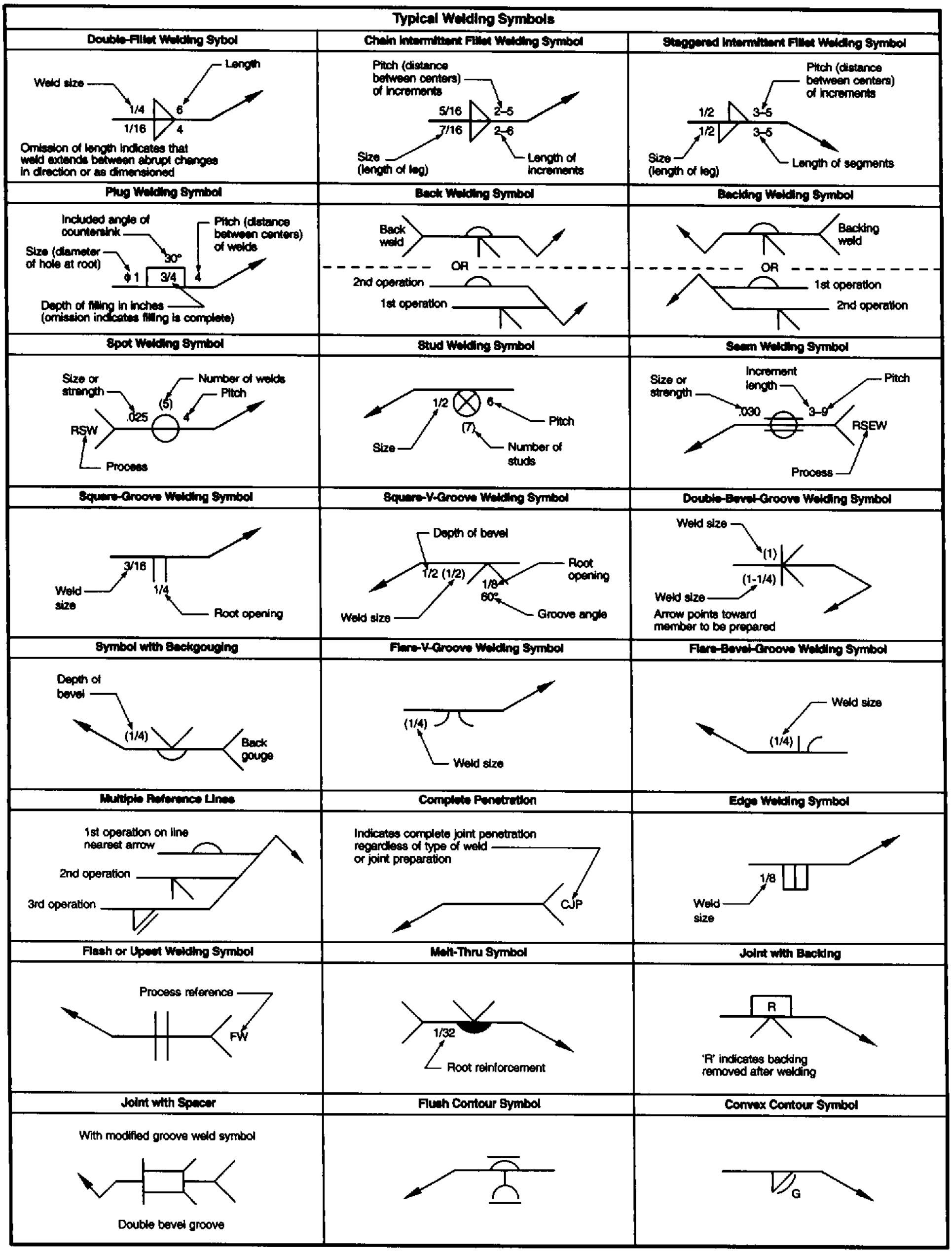



**Figure 2.1 (Continued)—AWS Standard Welding Symbols**

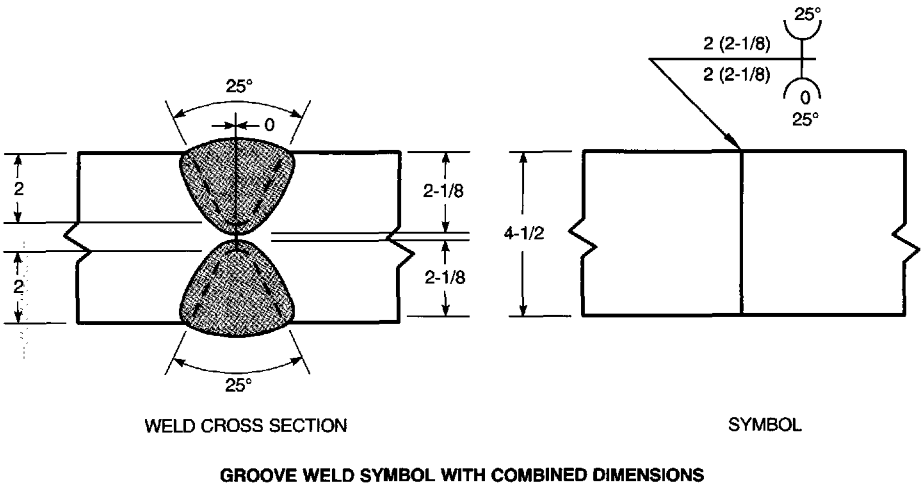



**Figure 2.2—Comparison of Welding Symbol and Written Explanation**

## 2.2 Nondestructive Examination Symbols

With the increased use of nondestructive examination by construction industries, it becomes convenient for the engineer to include testing requirements on the fabrication drawings. Noting testing requirements on the drawings helps to avoid many after-the-fact inconsistencies associated with the extent or type of testing. As with welding symbols, a system has been established to communicate nondestructive examination information using symbols similar to those used for welding. A complete description of this system is included in AWS A2.4.

The construction of nondestructive examination symbols uses the same basic elements found in welding symbols along with similar governing rules. Therefore, arrow-side and other-side designations retain their same location significance. Figure 2.5 shows the basic elements of the examination symbol and their standard locations with respect to one another.

Figure 2.6 illustrates the shorthand notations used with nondestructive examination symbols.

## 2.3 Master Chart of Welding, Allied Processes, and Thermal Cutting

Inspection personnel must be familiar with the welding and allied processes within the scope of their work. A welding or allied process is basic to the operation to be performed, and may be subdivided into more specific processes.

In the hierarchy of welding, the welding process stands first. Each welding process definition is complete so that it will stand alone. Processes are defined for prescribed elements of operation. This method of organization is the basis for the Master Chart shown in Figure 2.7.

The chart is a display of a hierarchy of welding and allied processes; the highest generic levels (least specific) are in the center, and the more specific are in boxes on the perimeter. The chart is intended to be comprehensive and includes not only widely used production processes, but also some that are of limited use because they have been replaced by other processes, have only recently been introduced, or have limited applications.

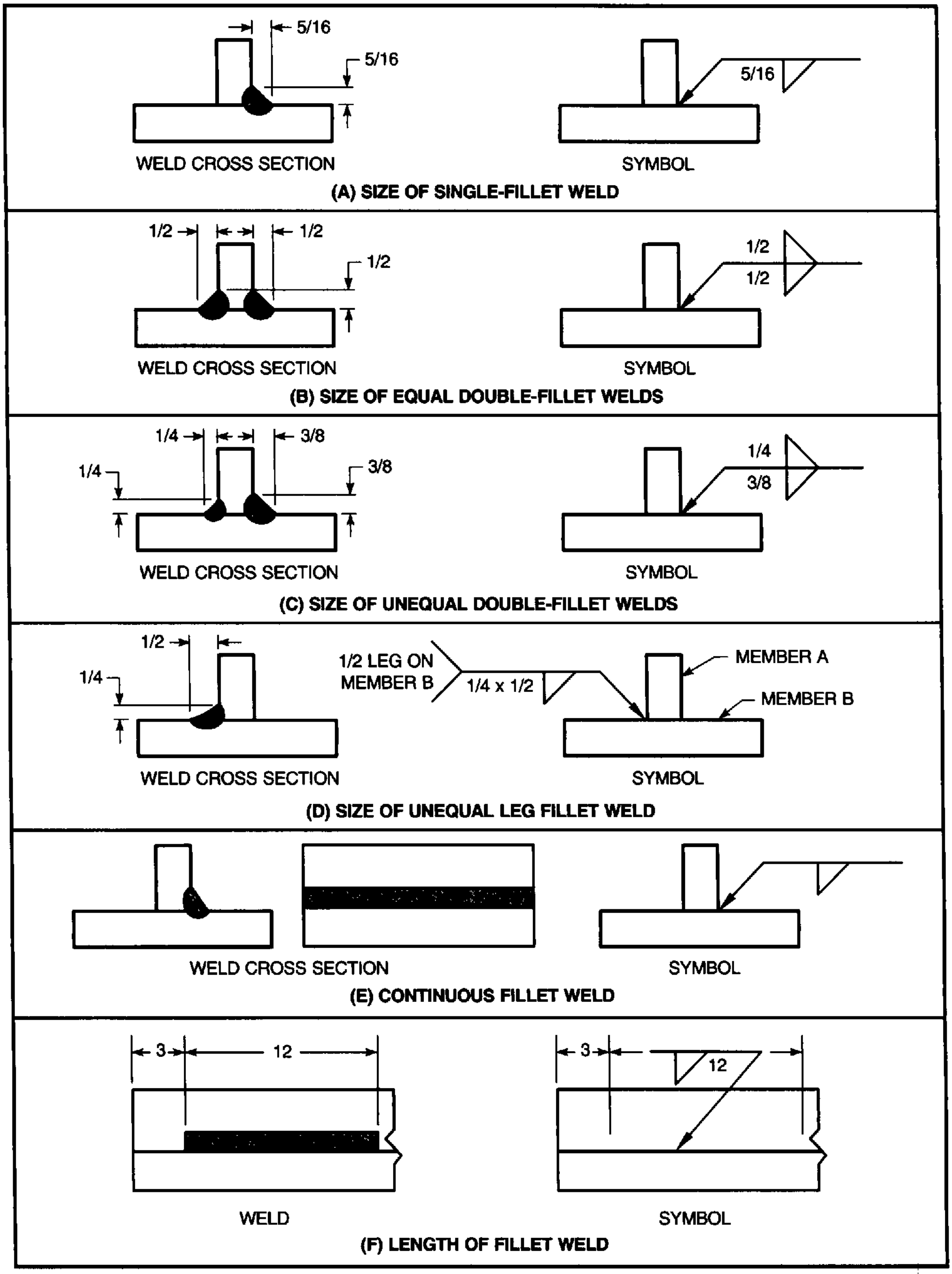



**Figure 2.3—Examples of Typical Fillet Welds Showing the Corresponding Symbols and Dimensions**

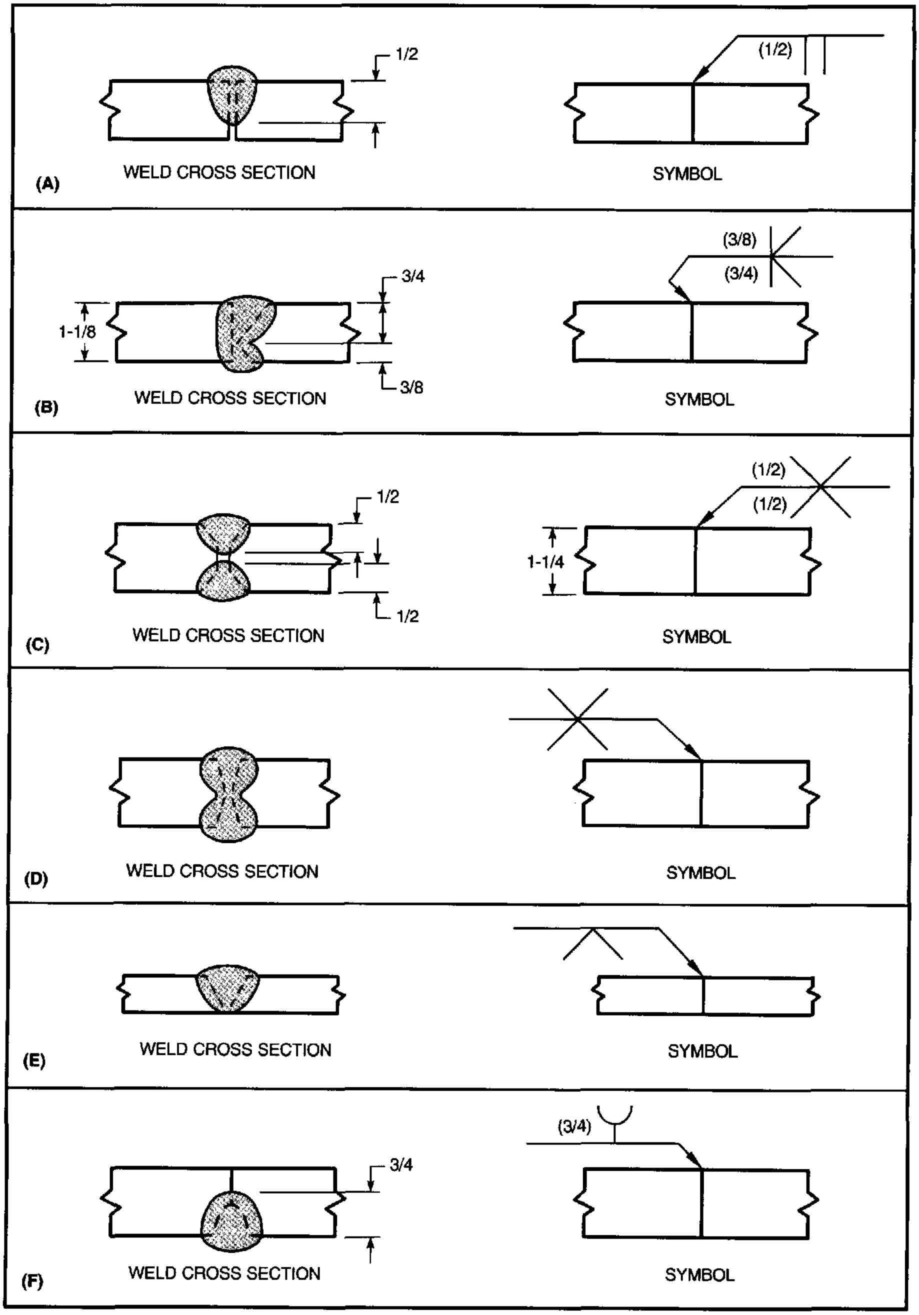



**Figure 2.4—Examples of Typical Groove Welds Showing the Corresponding Symbols and Dimensions**

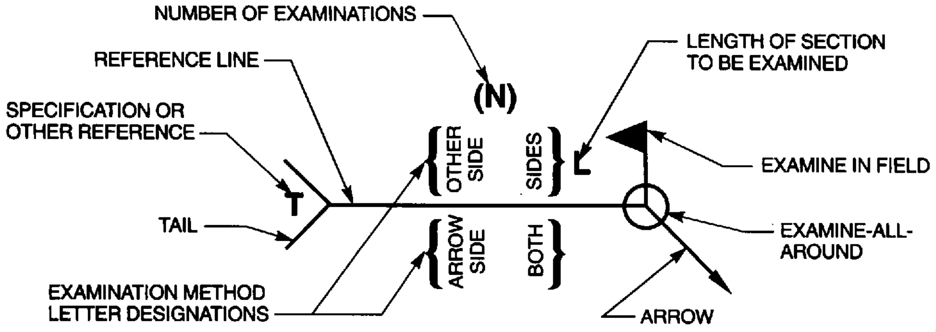



**Figure 2.5—Standard Location of Elements for NDE Symbols**

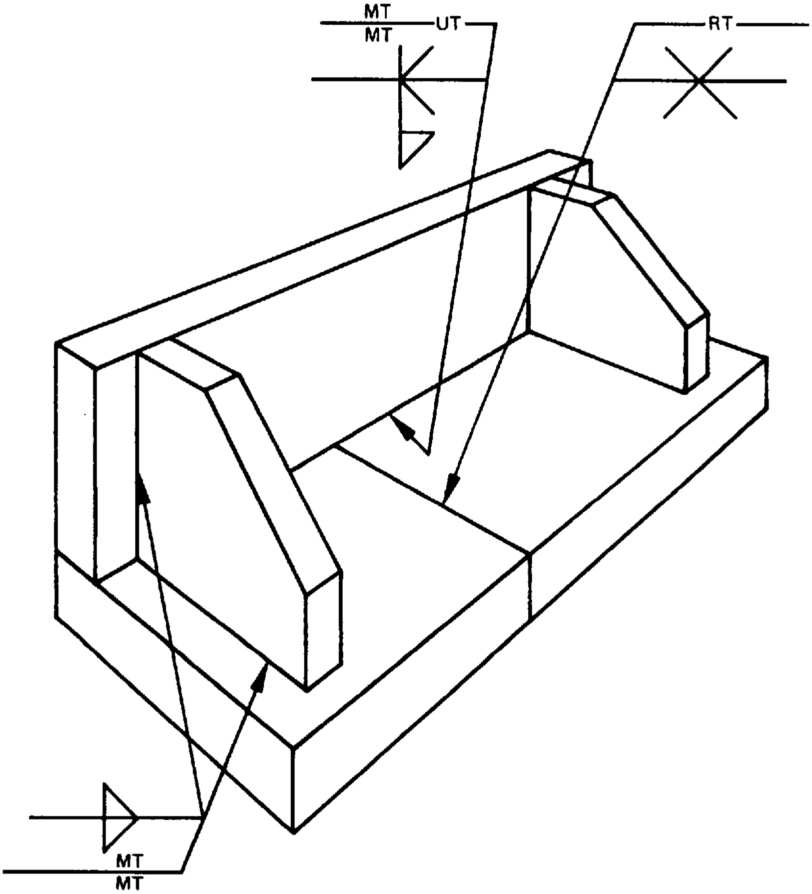



**Figure 2.6—Examples of Typical Nondestructive Examination Symbols**

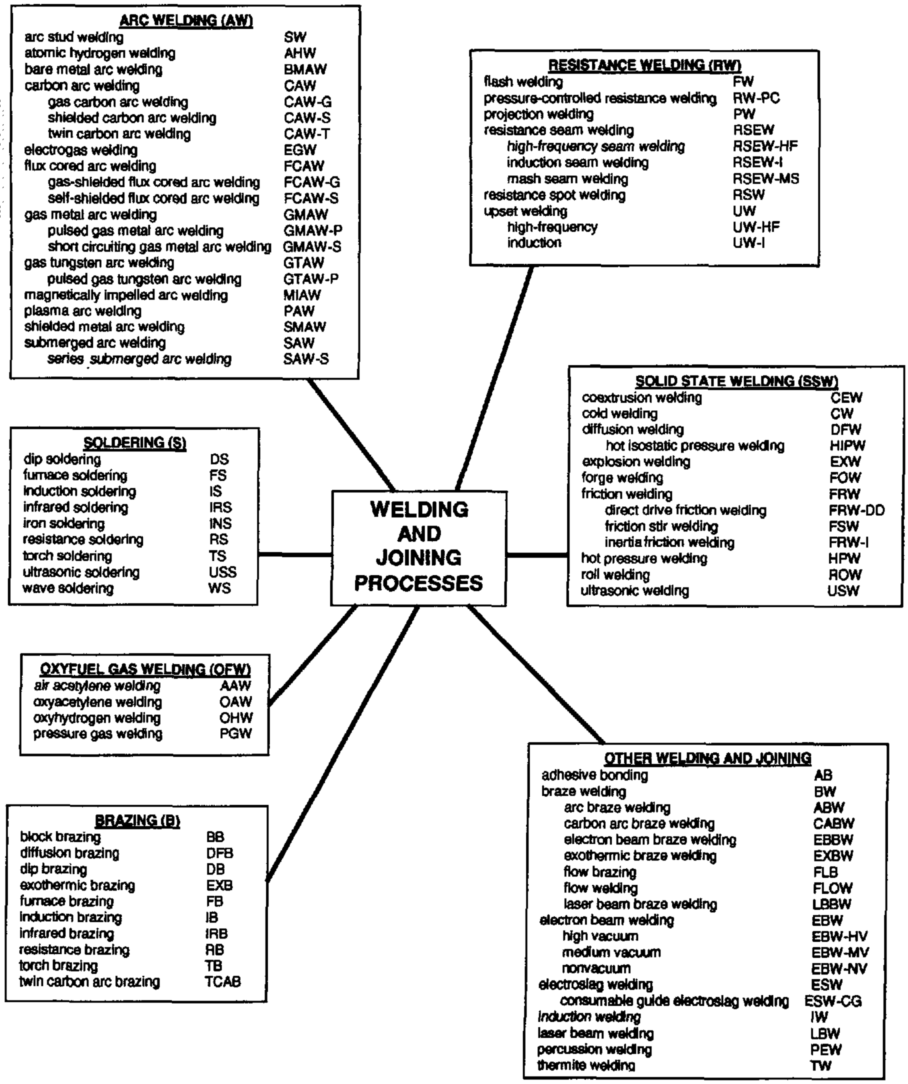



**Figure 2.7—Master Chart of Welding, Allied Processes, and Thermal Cutting**

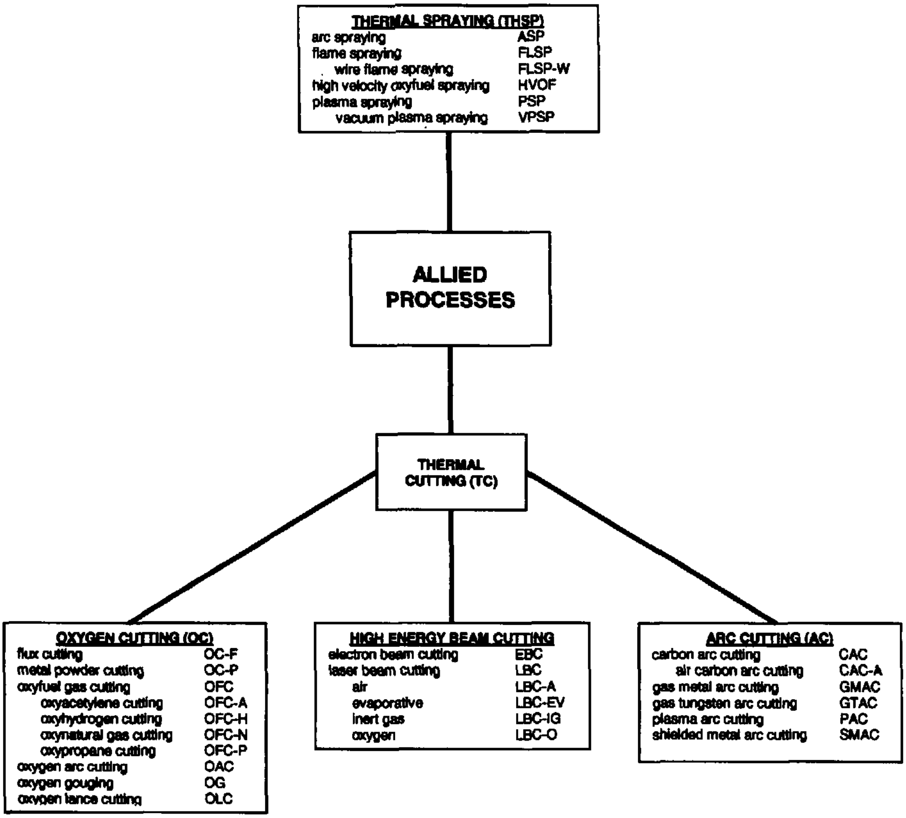



**Figure 2.7 (Continued)—Master Chart of Welding, Allied Processes, and Thermal Cutting**

# Chapter 3
# Requirements for the Welding Inspector

It is appropriate here to consider attributes desirable for an individual employed as a welding inspector. The nature of the job emphasizes an individual's physical, technical, and ethical qualities. Any weaknesses in these areas can reduce the effectiveness of the individual's performance.

## 3.1 Inspector Classifications

There are many types of welding inspectors, depending upon technical requirements for the particular fabrication process or processes. These include destructive testing specialists, nondestructive examination specialists, code inspectors, military inspectors, and owner's representative inspectors. All of these may consider themselves welding inspectors simply because they *do* inspect welds.

The fact that welding inspectors work in many different industries performing so many quality-related tasks makes it difficult to clearly and concisely describe what a welding inspector is and how that job function is specifically performed.

One fundamental complication is that an individual may perform many functions or only a single function. For example, it is common to perform numerous aspects of welding quality control (e.g., welding procedure qualification, welder qualification, in-process and final visual examination, destructive testing, and final nondestructive examination). However, it is also common for an individual involved in welding inspection to perform only one of those tasks (e.g., a nondestructive examination specialist).

Another important difference relates to the inspector's employer. The inspector may be directly employed by the manufacturer, the customer, the customer's representative, or an independent agency. While this should not affect the technical application of the individual's inspection skills, it may to some degree influence the logistics of that activity.

In this handbook, however, only a single inclusive category of "inspector" is used—one that includes as many different categories basic to the responsibility of the individual inspector as the particular job may require. Each specific job then would depend upon the relevant requirements, duties, and responsibilities of each inspector.

With this generic approach, descriptions given here are not intended to specifically define the job function of a welding inspector. Information herein should be viewed simply as a general overview of the numerous activities that could be considered part of the welding inspector's job. There will be descriptions of operations and activities which are beyond the scope of certain welding inspectors. In other cases, welding inspectors may be performing other functions that are not specifically addressed in this book. Information provided here should be applied only when in agreement with an inspector's specific job description.

The following are important factors that a company should take into consideration when selecting a person for the job of welding inspector.

## 3.2 Attributes of the Welding Inspector

The job of welding inspector carries a tremendous amount of responsibility. Selection of the right person for that position should be based on consideration of the following four critical attributes:

(1) Physical
(2) Technical
(3) Ethical
(4) Personal

### 3.2.1 Physical

**3.2.1.1 Physical Condition.** To perform duties in the most effective manner, the welding inspector should be in good physical condition. Since the primary job involves visual inspection, it is obvious that the welding inspector should have good vision, whether natural or corrected. For instance, if color or contrast is important to the inspection process being employed (liquid penetrant, magnetic particle, or color coded parts) then an individual should be tested for the ability to detect those colors. The AWS Certified Welding Inspector (CWI) program requires a minimum 20/40 visual acuity and the ability to perceive certain colors, as determined through actual testing.

Another aspect of physical conditioning involves the size of some welded structures. Since welds could be located anywhere on a very large structure, the inspector must be capable of going to the weld at any location in order to make an evaluation. The inspector must comply with safety regulations when performing these duties.

The ability of the welding inspector to get to the work may be reduced if the inspection is not performed immediately after welding. For example, such aids for the welder as ladders and scaffolding may be removed, making access impossible or dangerous. Within safety guidelines, the welding inspector should not be prevented from performing proper inspection because of a physical condition.

**3.2.1.2 Technical Ability.** While there may be no specific level of education and training required for welding inspectors, the job may involve interpretation of results. Therefore, an individual must have at least some level of technical knowledge to perform well as an inspector. In order to perform welding inspection, the individual will continually be asked to make judgments based on visual observations of physical characteristics of welds and weldments and their comparison with drawings or standards.

If an individual is unable to understand some written requirement, it will be difficult to make a judgment as to a weld's acceptability in accordance with that standard. There is more to an evaluation than just reading the specifications. Once read, the inspector must interpret its meaning. Even then, some requirement of a code or specification may appear very clear and straightforward when initially read; however, comparison of this written requirement with an existing physical condition may still prove to be extremely difficult.

Technical ability is also necessary in order for the welding inspector to effectively express ideas or inspection findings. In addition, once an inspection has been performed, the inspector must be capable of describing the methods used and subsequent results with sufficient accuracy to adequately communicate to others familiar with the work being performed.

### 3.2.2 Technical

**3.2.2.1 Interpretation of Drawings and Specifications.** Another quality which the welding inspector should develop is an ability to understand and apply the various documents describing weld requirements. These include, in part: drawings, codes, and specifications. These documents provide most of the information regarding what, when, where, and how the inspection is to be performed. In fact, these documents literally constitute the rules under which the welding inspector must perform. They also state the requirements by which the welding inspector will judge the weld quality. Obviously, such documents must be reviewed prior to the start of any work, because the welding inspector should be aware of the job requirements before any production. Many times this review will reveal required "hold points" for inspections, welding procedure and welder qualification requirements, and special processing steps or design deficiencies such as weld inaccessibility during fabrication.

Although the welding inspector should be thorough in reviewing documents, it is not necessary that requirements be memorized. These are *reference* documents and should be readily available at any time in the fabrication process. Generally, the inspector is the individual most familiar with all of these documents. The inspector may be called upon by others for information and interpretation regarding the welding requirements.

**3.2.2.2 Inspection Experience.** Having actual on-the-job inspection experience is very important. Text books and classroom studies simply do not provide all of the things needed to inspect effectively. Experience will aid the welding inspector in becoming more efficient. In time, better ways of thinking and working will develop.

On-the-job experience will also help the inspector develop the proper attitude and point of view regarding job assignment. After working with various codes and specifications, the inspector's effectiveness will improve because of an improved understanding of welding requirements. To emphasize the need for inspection experience, it is commonplace to see a novice inspector paired with an experienced one so that proper techniques can be passed along. Most inspector certification programs require some minimum level of actual inspection experience.

**3.2.2.3 Knowledge of Welding.** Another desirable quality for a welding inspector is a basic knowledge of welding and related processes. Because of their background, welders are sometimes chosen as welding inspector trainees. Such a person is certainly better prepared as an inspector to understand many problems that the welder may encounter. This knowledge helps the inspector in gaining respect and cooperation from the welders. Further, this understanding helps the welding inspector predict what weld discontinuities may be encountered in a specific situation. The welding inspector can then monitor critical welding variables in order to help prevent these welding problems. When the inspector is experienced in welding processes and understands their advantages and limitations, possible problems can be more easily identified and prevented.

**3.2.2.4 Knowledge of Examination Methods.** Knowledge of various destructive and nondestructive examination methods should be helpful to the welding inspector. Although the inspector may not perform these tests, from time to time it may be necessary to review test results. As with welding processes, the welding inspector is aided by a basic understanding of testing methods. It is important that the inspector be aware of alternate methods which could be applied to enhance visual inspection.

**3.2.3 Ethical.** In order to safeguard public health and to maintain integrity and high standards of skills, practice, and conduct in the occupation of welding inspection, the inspector must render decisions promptly while remaining impartial and tolerant of the opinions of others. The following recommendations for a welding inspector's behavior are patterned after the ethical requirements specified in AWS QC1, *Standard for Qualification and Certification of Welding Inspectors.*

**3.2.3.1 Integrity.** The welding inspector must act with complete integrity (honesty) in professional matters and be forthright and candid with respect to matters pertaining to welding inspector qualification requirements.

**3.2.3.2 Responsibility to the Public.** The welding inspector is obligated to preserve the health and well-being of the public by performing the duties required of weld inspection in a conscientious and impartial manner to the full extent of the inspector's moral and civic responsibilities and qualifications. Accordingly, the welding inspector shall:

(1) Undertake and perform assignments only when qualified by training, experience and capability,

(2) Present credentials upon request,

(3) Neither falsely represent current status nor seek to misrepresent certification level or modification of certification documents or false verbal or written testimony of current level or status,

(4) Be completely objective, thorough, and factual in any written report, statement or testimony of the work and include all relevant or pertinent testimony in such communiques or testimonials,

(5) Sign only for work that the inspector has inspected, or for work over which the inspector has personal knowledge through direct supervision, and

(6) Neither associate with nor knowingly participate in a fraudulent or dishonest venture.

**3.2.3.3 Public Statements.** The welding inspector will issue no statements, criticisms, or arguments on weld inspection matters connected with public policy which are inspired or paid for by an interested party, or parties, without first identifying the party, the speaker, and disclosing any possible pecuniary interest.

The welding inspector will not publicly express any opinion on a weld inspection subject unless it is founded upon adequate knowledge of the facts in issue, upon a background of technical competence pertinent to the subject, and upon honest conviction of the accuracy and propriety of the statement.

**3.2.3.4 Conflict of Interest.** The welding inspector shall avoid conflict of interest with the employer or client and will disclose any business association, or circumstances that might be so considered.

The welding inspector shall not accept compensation, financial or otherwise, from more than one party for services on the same project, or for services pertaining to the same project, unless the circumstances are fully disclosed and agreed to by all interested parties or their authorized agents.

The welding inspector shall not solicit or accept gratuities, directly or indirectly, from any party, or parties, dealing with the client or employer in connection with the CWI's and Certified Associate Welding Inspector's (CAWI's) work.

The welding inspector shall, while serving in the capacity of an elected, retained, or employed public official, neither inspect, review, nor approve work in the capacity of CWI or CAWI on projects also subject to the inspector's administrative jurisdiction as a public official, unless this practice is expressly dictated by a job description, specification, or both, and all affected parties to the action are in agreement.

**3.2.3.5 Solicitation of Employment.** The welding inspector shall neither pay, solicit, or offer, directly or indirectly, any bribe or commission for professional employment with the exception of the usual commission required from licensed employment agencies.

The welding inspector shall neither falsify, exaggerate, nor indulge in the misinterpretation of personal academic and professional qualifications, past assignments, accomplishments, and responsibilities, or those of the inspector's associates. Misrepresentation of current certification status at the time of, or subsequent to, submission of requested employment information, or in the solicitation of business contracts wherein current certification is either required or inherently beneficial (advertisements for training courses, consulting services, etc.) shall be a violation of this section.

The welding inspector is cautioned against functioning as an independent in fields out of his or her capability, without first investigating for possible industry or public requirements and additional education/experience requirements (e.g., industrial labs, in the concrete and soil testing field, etc.)

### 3.2.4 Personal

**3.2.4.1 Professional Attitude.** The first, and perhaps the most important personal quality, is a professional attitude. This is a real key to the success of the welding inspector, because it will determine the degree of respect and cooperation the inspector will receive from others during the performance of inspection duties. Included in this category is the ability of the welding inspector to make decisions based on facts so that they are fair, impartial and consistent. If an inspector's decisions show partiality or inconsistency, they will undermine the inspector's reliability.

In keeping with this professional attitude, the welding inspector's decision should be consistent with job requirements so that decisions are neither too critical nor too lenient. For example, it is a mistake to have preconceived ideas as to a component's acceptability. The inspector should review the facts and make decisions based solely on those facts.

This need for professionalism also extends into a person's dress and manner, and language used when dealing with others. If these characteristics become offensive to others, they may well, by themselves, reduce an inspector's effectiveness.

The inspector should develop a positive attitude. The goal is to assure that the welding has been done properly, rather than to try and find something wrong. Every attempt should be made to be cooperative and helpful. When decisions are being formulated, the welding inspector should genuinely consider all opinions and recommendations. Only after carefully listening to input from other involved parties, and combining that information with all the facts and requirements, can the welding inspector make a truly sound judgment.

Memberships in professional and technical organizations offer individual inspectors up-to-date information on revised standards and new industrial practices and requirements affecting their work.

The AWS CWI Program for Qualification and Certification of welding inspectors does not require AWS membership, but AWS membership does show the employer the intent and desire of the individual to improve and maintain welding technology.

**3.2.4.2 Learning Potential.** Individuals are often hired as welding inspectors primarily because of their learning potential. The inspector can perform the job more effectively after being trained extensively in a variety of subjects. In fact, because the job of welding inspector involves so many different aspects, it is virtually impossible to gain all of the necessary information through experience alone. Personal and professional experience must be supplemented by additional training.

**3.2.4.3 Completing and Maintaining Inspection Records.** A final attribute, which is not to be taken lightly, is the welding inspector's ability to complete and maintain inspection records. The welding inspector must be capable of accurately communicating all aspects of the inspection, including the results.

The records should be legible and understandable to anyone familiar with the work; therefore, neatness is important. The welding inspector should also consider these records as protection should questions later arise. Reports should contain sufficient information regarding how the inspection was performed so that similar results can be obtained later by someone else.

Once records have been developed, the welding inspector should be capable of maintaining all necessary information in an orderly fashion to facilitate easy retrieval. Accordingly, there are a few "rules of etiquette" relating to inspection records. First, records should be completed in ink; if incorrect entries are noted, they can be lined out and corrected. This corrective action should then be initialed and dated for explanation. Next, the report should accurately and completely state the job name and inspection location in addition to specific test information. The use of sketches and pictures may also help to convey information regarding the inspection results. Finally, the completed report should then be signed and dated by the inspector who actually performed the work.

## 3.3 Certification of Qualification

Education, training, and experience are crucial to the qualification of a welding inspector. A potential welding inspector should be aware that the increasing variety of welding processes, materials, codes, and other standards applied to today's product technologies makes the job more complicated and difficult. This simply means that welding inspectors have an increasingly important job and that this job must be done in a more uniform manner throughout the United States.

Since 1976, the American Welding Society has been actively involved in the examination, qualification, and certification of welding inspection personnel. The guidelines for the Certified Welding Inspector program have been established by the AWS Qualification Committee and Certification Committees and approved by the AWS Board of Directors. The administration of this program is the responsibility of the AWS Certification Department.

In order to qualify as a Certified Welding Inspector (CWI) or a Certified Associate Welding Inspector (CAWI), an individual must show evidence of specified minimum levels of experience, educational training, and vision requirements which have been established by the AWS Qualification Committee. After these preliminary requirements have been met, the individual is required to successfully pass a three-part examination. Upon passing of all three parts of the examination, AWS will certify, register, and document the qualification and issue an identification card. A stamp bearing the individual's name and certification number may be purchased for use in identifying parts or inspection reports approved by the Certified Welding Inspector. Recertification is required every three years.

For information regarding the CWI program, contact the AWS Certification Department. Other publications from Chapter 17, Codes and Other Standards, should be used as references and guides.

# Chapter 4
# Welding Inspection Operations

The last chapter outlined desirable characteristics and responsibilities of a welding inspector. This chapter concentrates on the most essential operations involved in the welding inspection process.

Welding inspectors can have a diversified range of responsibilities, depending upon the specification or code to which they are working, and the particular manufacturing or fabrication industry in which they are employed. Welding inspection operations will, for the most part, follow the general sequence of the fabrication process. The following outline is a list of activities encountered in welding inspection:

(1) Review of drawings, specifications, and manufacturing instructions

(2) Review of the manufacturer's approved quality assurance/ quality control program

(3) Verification of welding procedures and personnel qualifications

(4) Verification of approved procedure for qualifying welding and inspection personnel

(5) Selection and examination of production test samples

(6) Evaluation of test results

(7) Preparation of test reports and maintenance of records

(8) Observance and monitoring of recommended safety guidelines.

## 4.1 Review of Drawings, Specifications, and Manufacturing Instructions

Welding inspectors should have a working knowledge of the product being manufactured, especially those components or subassemblies which they will inspect. Detailed knowledge of drawing requirements, specification requirements, and any manufacturing instructions is essential. It also is helpful to have a knowledge of the material to be used in the weldment because certain metals may require special treatment for satisfactory welding. Welding and related procedures should contain information that incorporates all of the specified variables for performing the operation. Manufacturing instructions detail the use of particular procedures for various phases of fabrication.

The welding inspector should be alert to any changes made in these documents to assure compliance with all other procedures and fabrication requirements. Deviations from drawings, specifications, and manufacturing instructions should be referred to the appropriate technical function for resolution. In some instances, deviations from drawings or specifications should be referred to a regulatory agency for approval.

It is not always possible to write a specification that contains all the detailed information needed to provide an answer for all questions that might arise. Those parts of the specification that are unclear should be referred to the appropriate technical personnel for interpretation.

## 4.2 Review of the Manufacturer's Approved Quality Assurance/ Quality Control Program

The welding inspector should be aware of the manufacturer's quality program. A quality program provides the administrative steps needed to inspect and control the quality of the completed product. Chapter 6, "Quality Assurance," describes the elements of good program.

Quality assurance includes all planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily to design requirements or intended service. Quality control, which may be included in quality assurance, includes those actions related to the physical characteristics of a material, structure, component, or system. These actions provide a means to control the quality of the material, component, or system to predetermined requirements.

A quality program may include control over a manufacturer's procedures. This may include final approval and control of procedure revisions, or procedures and job order applicability. Other functions might include the administration of the manufacturer's instrument calibration program. A quality assurance program will document compliance to requirements of the applicable code or standard. The inspector should have general familiarity with program requirements to assure that compliance with the program is achieved.

The welding inspector should be familiar with rules, procedures, and methods for handling and reporting discrepancy findings to the manufacturer.

## 4.3 Verification of Welding Procedure and Personnel Qualifications

Prior to the start of fabrication, the inspector should verify that the fabricator has prepared written welding procedure specifications that meet the applicable specification, standard, or code. The welding procedure should be capable of producing weldments with adequate strength, ductility, and toughness to satisfy the applicable specification or code. Chapter 10, "Qualification of Welding Procedures," describes the elements of a welding procedure specification and explains the reasons for its use.

Prior to the start of production welding, the inspector should review the qualifications of welders and welding operators that will work on the project. It may be desirable, depending upon the contract, to review the fabricator's procedures for qualification of welders and welding operators. Some contracts may require this, and also require that the procedure be approved. The welding inspector should be sure that (1) only approved welding procedures are used on the applicable contract, and (2) welders and welding operators are qualified. The contract should specify the requirements as to how this may be accomplished.

Additionally, the welding inspector should be alert to changes of variables in any welding procedure. Changes or deviations in the procedural requirements should be brought to the attention of the proper personnel. Revisions should be qualified by tests where required and distributed to welders and welding operators performing the work. New performance qualifications may be required if the revised procedures exceed the welder or welding operator's limitations of variables defined in the applicable specification or code.

The chapters on "Qualification of Welding Procedures" and "Qualification of Welders and Welding Operators" contain sample qualification requirements and examples where welders may not be working within the limits of their qualifications.

The objective of a welding procedure qualification test is to determine the mechanical properties of the welded joint. The objective of performance qualification is to determine the ability of an individual to deposit sound weld metal with a previously qualified welding procedure.

As with welder and welding operator qualifications, inspection personnel should also be qualified prior to the start of the inspection of production welds. The fabricator should ensure that only qualified personnel are allowed to perform inspection operations. It may be desirable or a requirement, depending upon the contract, to have a procedure detailing qualification methods. Some contracts may require the procedure to be approved.

## 4.4 Verification of Approved Procedures for Qualifying Welding and Inspection Personnel

Although welding and inspection personnel are qualified in accordance with approved procedures, verification is nonetheless necessary to provide added assurance that procedures are applied properly and competently. To a large extent, the quality of welding and the quality of inspection depend upon the application of the correct inspection procedures. The welding inspector should verify that procedures specifically approved or agreed upon for the job are being used. The welding inspector may find it advantageous to prepare a checklist for each inspection procedure to use as a guide for performing the required duties. Various recognized inspection methods and tests are described in Chapters 13, "Destructive Testing of Welds," 14, "Proof Tests," and 15, "Nondestructive Examination Methods."

In general, inspection processes should be performed in sequence with the manufacturing operations, as established by the fabricator. There are good reasons for doing this, some of which are the following:

(1) Interference between inspection and production is kept to a minimum.

(2) Inspection operations required at a particular stage of fabrication can be completed (such as when performance of the next manufacturing step would make inspection of the preceding step impossible).

(3) In-process inspection permits early detection and correction of deficiencies, improving economics and efficiency.

The following sequence of welding and inspection operations is offered as a general overall guide. It should be understood that the actual operations and the order in which they are accomplished will depend upon the type of weldment, the method of manufacture, and the requirements of the governing contract. The inspector may want to establish witness or hold points to verify one or more of the items shown in Table 4.1.

## 4.5 Selection and Examination of Production Test Samples

In many types of welded assemblies, certain inspections of the finished product may be performed on samples selected by the welding inspector from the production line. These samples may be selected at random, or in accordance with established criteria. In either case, the selection and the witnessing of the testing of these samples are among the important duties of the welding inspector. In some cases, selection of samples is left to the judgment and discretion of the welding inspector, rather than prescribed by specification or code. In such cases, the number of samples should not be more than is needed to reasonably determine conformance to the required standards. It is common practice for most contracts to mandate a specific sampling plan and, further, to require additional sampling be performed for each unsatisfactory sample until workmanship standards are confirmed.

Certain tests or treatments may be prescribed for the samples selected by the welding inspector. These may include radiography, hydrostatic tests, trepanning, metallurgical examination, mechanical testing to destruction, or other detailed examinations. The welding inspector should determine that such work, as prescribed, is properly carried out. Various sampling, testing, and inspecting methods are described in this handbook.

## 4.6 Evaluation of Test Results

It would be impractical for the welding inspector to perform or witness all tests made in connection with some weldments. Where the job requires, however, the welding inspec-

**Table 4.1**
**Sequence of Welding and Inspection Operations**

| Prior to Welding | During Welding | After Welding |
|---|---|---|
| • Material Identification<br>— Chemical analysis<br>— Mechanical properties<br>• Base Metal Conditions<br>— Freedom from internal and surface discontinuities<br>— Flatness, straightness, dimensional accuracy<br>• Joint Condition<br>— Edge Shape<br>— Dimensional accuracy<br>— Cleanliness<br>— Root opening<br>— Alignment<br>— Backing<br>— Tack welds<br>• Special Assembly/Fabrication Practice<br>— Adequacy and accuracy of jigging, bracing, or fixturing<br>— Application and accuracy of pre-stressing or precambering | • Preheat and interpass temperatures<br>— Controls<br>— Measurement methods<br>• Filler Metal<br>— Identification<br>— Control<br>— Handling<br>• Root Pass<br>— Contour<br>— Soundness<br>• Root preparation prior to welding second side<br>• Cleaning between passes<br>• Appearance or passes (sometimes in comparison with workmanship standard)<br>• In-process NDE as required or specified<br>• Conformance to approved welding procedure | • Postheat treatment requirements<br>• Acceptance inspection<br>• Method of cleaning for inspection<br>• Nondestructive examination<br>— Visual examination<br>— Surface contour and finish of welds<br>— Conformity of welds with drawings<br>— Magnetic particle<br>— Liquid penetrant examination<br>— Radiographic examination<br>— Ultrasonic examination<br>— Proof testing<br>— Other suitable methods<br>• Destructive testing<br>— Chemical<br>— Mechanical<br>— Metallographic<br>• Marking for acceptance or rejection<br>• Repairs<br>• Inspection after repair |

tor should witness or observe sufficient test processes to assure that the tests are being performed in the proper manner and that the results are accurate. Evaluation and final disposition of test results will usually require the welding inspector to carefully consider the attributes of the entire process.

From time to time, the welding inspector will review test or inspection results that do not meet the required standards for acceptance in every detail. The final disposition or decision will require careful judgment by appropriate technical personnel as to whether the product meets the intent of the specification requirements. In such cases, the results of the test should be carefully evaluated. In some instances, such as inadvertent inspection of work not intended to be or not required to be inspected, or when the work has borderline acceptability, an engineering judgement by appropriate technical personnel should be made as to the acceptability of the product. Engineering judgements should be performed only where the specification or contract allows and only when sufficient information is available from which to exercise sound judgment.

## 4.7 Preparation of Test Reports and Maintenance of Records

Any work performed under a specification or code that requires inspection or tests will also require records. However, whether required or not, the welding inspector should keep adequate records. Records provide documentation for the welding inspector should questions arise at some later time.

It is also the welding inspector's duty to check his/her records for completeness and accuracy in accordance with specified requirements and to make certain that they are available when needed.

Any records that require the fabricator's signature should be prepared by the fabricator rather than by the welding inspector.

Records should contain as much detail as necessary. It is desirable that the welding inspector comment on the general character of the work, how well it stayed within prescribed tolerances, difficulties that were encountered, and whether any defects were noted. All repairs should be explained. Copies of these records should go to all persons entitled to receive them, and the welding inspector should keep a copy on file.

## 4.8 Observance and Monitoring of Recommended Safety Guidelines

Another of the welding inspector's duties is to recognize a safety hazard that could result in injury to welding and inspection personnel. For more information, refer to Chapter 5, "Inspection Safety Considerations" or ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*. Well versed welding inspectors should be able to recognize problems such as poor ventilation, which could cause dizziness and cause injury to the welder.

When welding is being performed it is a good idea to assure that all aspects of welding safety procedures are being followed. This is true not only for proper welding quality, but to make the shop a safe place to work. These practices do not only show up in good weld quality, but result in money saved in the prevention of down time due to accidents.

# Chapter 5
# Inspection Safety Considerations

## 5.1 Scope

Safety is an important consideration in all aspects of nondestructive examination (NDE) methods. This chapter covers hazards that may be encountered with nondestructive inspection equipment and processes. The inspector should read and understand the manufacturers' instructions and the material safety data sheets (MSDSs) on safety and recommended practices for the inspection process, materials, and equipment, to minimize personal injury and property damage, and assure proper disposal of wastes.

The NDE methods used that are applicable to the inspection of weldments listed below will be discussed in this chapter:

(1) Visual Testing (VT)
(2) Liquid Penetrant Testing (PT)
(3) Magnetic Particle Testing (MT)
(4) Radiographic Testing (RT)
(5) Electromagnetic Testing (ET)
(6) Ultrasonic Testing (UT), and Acoustic Emission Testing (AET)

## 5.2 Visual Testing (VT)

Lighting of the weld joint should be sufficient for good visibility. In addition to ambient light, auxiliary lighting may be needed. The inspector should be aware that improper lighting may cause eye problems. If the area to be inspected is not readily visible, the inspector may use mirrors, borescopes, flashlights, or other aids.

## 5.3 Liquid Penetrant Testing (PT)

Liquid penetrant inspection material consists of fluorescent and visible penetrants, emulsifiers, solvent base removers, and developer. These materials typically contain trichloroethylene, trichloroethane, methyl chloroform, perchloroethylene, acetone, or a volatile petroleum distillate. These materials may be toxic or flammable, or both. The following safety and health inspection precautions are recommended per the material safety data sheets by the manufacturer and should be observed:

(1) Keep flammable materials away from heat, arcs, and flames. Do not smoke in work areas. Do not puncture, incinerate, or store pressurized containers above 120°F (48°C). Aerosol cans may rupture at temperatures above 130°F (54°C) and spray out flammable liquids.

(2) Use chemicals in well-ventilated areas only. Avoid breathing vapors or spray mists. Inhalation of vapors may cause dizziness and nausea. When affected by fumes, move the victim to fresh air.

(3) If a solvent or other chemical is ingested, do not induce vomiting. In all cases, immediately call a physician.

(4) Wear appropriate eye protection at all times. If a chemical or foreign particle enters an eye, flush the eye promptly with water.

(5) Avoid repeated or prolonged skin contact with solvents and other test substances. After contact, wash the exposed areas promptly, and apply a soothing lotion.

(6) Verify all chemical containers in the work area are clearly labeled with the contents. Never use a chemical from an unlabeled container.

(7) Do not combine products from different manufacturers in the same container.

## 5.4 Magnetic Particle Testing (MT)

Operators should be aware of any potential hazards and know how to prevent them. The following precautions are recommended per the Material Safety Data Sheets by the manufacturer and should be observed.

Magnetic powders should be kept dry and protected from moisture at all times. Oil-based suspensions may be flammable and should be handled with care where ignition is possible. Be aware that water-based suspensions may contribute to a shock hazard when used near electrical equipment.

## 5.5 Radiographic Testing (RT)

Federal, state, and local governments issue licenses for the operation of industrial radiographic equipment. The federal licensing program is concerned mainly with those companies that use radioactive isotopes as sources. To become licensed under federal programs, a facility or operator should show that it meets standard protection of both operating personnel and the general public from excessive levels of radiation.

The amount of radiation that is allowed to escape from the area over which the licensee has direct and exclusive control is limited to an amount that is safe for continuous exposure. In most cases, a maximum exposure of 2 millirems per hour (2 mrem/h), 100 mrem in seven consecutive days, or 500 mrem in a 12-month period is considered to be safe.

**5.5.1 Radiation Monitoring.** A radiation safety program should ensure that both the facility and all personnel subject to radiation exposure are monitored. Facility monitoring generally is accomplished by periodically taking readings of radiation leakage during operation of each source under various conditions. Calibrated instruments should be used to measure radiation dose rates at various points within the restricted area and at various points around the perimeter of the restricted area.

To guard against inadvertent leakage of radiation from a shielded work area, interlocks disconnect power to an X-ray tube when an access door is opened, or prevents any door from being opened if the unit is turned on. Alarms are connected to a separate power source which activate audible or visible signals, or both, whenever the radiation level exceeds a preset value.

All personnel within the restricted area should be monitored to assure that no one absorbs excessive amounts of radiation. Devices such as pocket dosimeters and film badges are the usual means of monitoring. Often both devices are worn. Pocket dosimeters may be direct reading or remote reading.

**5.5.2 Access Control.** Permanent facilities are usually separated from unrestricted areas by shielded walls. Sometimes, particularly with on-site radiographic inspection, access barriers may be only ropes and sawhorses, or both. In such instances, the entire perimeter around the work area should be under continual surveillance by radiographic personnel. Signs that carry a symbol designated by the U.S. Government should be posted around any high-radiation area. This helps to inform casual bystanders of the potential hazard, but should never be assumed to prevent unauthorized entry into the danger zone. In fact, no interlock, no radiation alarm, and no other safety devices should be considered a substitute for constant vigilance on the part of radiographic personnel.

## 5.6 Electromagnetic Testing (ET)

Electromagnetic testing, commonly called eddy current testing, uses alternating current sources, therefore, normal electrical precautions should be observed—see Electrical Hazards section 5.8. Eddy current testing does not present unique safety hazards to personnel.

## 5.7 Ultrasonic Testing (UT) and Acoustic Emission Testing (AET)

With high-power ultrasonic and acoustic emission equipment, high voltages are present in the frequency converter and the coaxial cables connecting these components. The equipment should not be operated with the panel doors open or housing covers removed. Door interlocks are usually installed to prevent introduction of power to the equipment when the high voltage circuitry is exposed. The cables are fully shielded and present no hazard when properly connected and maintained. All operators should beware of electrical hazards. See Electrical Hazards section 5.8.

## 5.8 Electrical Hazard

Electrical shock can kill. However, it can be avoided. Do not touch live electrical parts. Read and understand the manufacturing instructions and recommended safe practices. Faulty installations, improper grounding, and incorrect operation and maintenance of electrical equipment are all sources of danger.

Make sure all electrical connections are tight, clean, and dry. Poor connections can overheat and even melt. Further, they can produce dangerous arcs and sparks. Do not allow water, grease, or dirt to accumulate on plugs, sockets, or electrical units. Moisture can conduct electricity. To prevent shock, keep the work area, equipment, and clothing dry at all times. Wear dry gloves, rubber soled shoes, or stand on a dry board or insulated platform.

Keep cables and connectors in good condition. Improper or worn electrical connections may set up conditions that could cause electrical shock or short circuits. Do not use worn, damaged, or bare cables. Do not touch live electrical parts.

In case of electrical shock, turn off the power. If the rescuer must resort to pulling the victim from the live contact, use nonconducting material. If the victim is not breathing, qualified personnel should administer cardiopulmonary resuscitation (CPR) as soon as contact with the electrical source is broken. Call a physician and continue CPR until breathing has been restored, or until a physician has arrived. Cover electrical or thermal burns with a clean, dry, and cold (iced) compress to prevent contamination. Call a physician.

## 5.9 General Safety Information

(1) Wear proper eye and hand protection. Use face shields, safety glasses, and goggles as appropriate. Should a foreign particle enter an eye, promptly flush the eye with water to minimize irritation.

(2) Be aware of electrical hazards—see section 5.8.

(3) Be alert for sharp objects, pinch points, and moving objects. Avoid wearing clothing or jewelry that could be snagged by moving machinery. Items of particular concern are rings, necklaces, bracelets, long hair, and loose clothing.

## 5.10 References

1. *Welding Handbook*, Volume 1. American Welding Society, Miami, Fla.

2. Manufacturer's Instructions and Material Safety Data Sheets (MSDSs).

3. *Training for Nondestructive Testing*. ASNT and ASM International, Metals Park, Ohio.

# Chapter 6
# Quality Assurance

Quality assurance (QA) includes all planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily to design requirements or intended service. This includes periodic audits of the QA system's operation and related controls to assure that they are being implemented and functioning as expected.

Quality control (QC) is the implementation part of quality assurance through examination of physical characteristics and comparison with predetermined requirements from applicable codes, specifications, other standards, and drawings. A quality control program may stand alone or be part of a larger QA plan. In either case, quality control specifications, procedures, and acceptance criteria should be written for all required inspection operations. If a quality program is to be implemented, the following attributes may be a consideration.

## 6.1 Quality Assurance Program

It is the responsibility of the manufacturer to provide for the development and implementation of a QA program. The program should describe the company's commitment to provide products and services in accordance with established requirements. The following representative areas to be included in a quality assurance program that describes the elements of a QA system are subsequently supported by detailed QC implementation procedures.

**6.1.1 Organization Requirements.** Administration of the quality assurance program is vested in a responsible element of the organization. The QA/QC function's authority and responsibility should be clearly defined, independent of production, and have direct access to upper management. The organization should be staffed with technically qualified personnel to make decisions with regard to:

(1) Identification of quality problems,

(2) Determining compliance with specifications and procedures,

(3) Providing solution(s) through functional channels,

(4) Determining implementation of solutions, and

(5) Controlling further actions until an acceptable quality has been attained.

**6.1.2 Purchasing.** The quality assurance department should determine quality assurance and inspection requirements for the project, the magnitude of the inspection work for each class of material and equipment, and the extent of the work to be performed by the department prior to purchasing.

The quality assurance and inspection requirements for procured items should be included in the purchase requisition and include the following, as applicable:

(1) Descriptive title of item or service desired

(2) List of drawings and technical specifications, including revision level

(3) Codes, other standards, and regulatory requirements

(4) Inspection acceptance criteria

(5) Special process requirements

(6) Customer contract requirements

(7) Documentation and record requirements

(8) Source inspection and audit requirements

Purchasing should maintain an approved list of acceptable vendors that comply with the specified QA and QC program for the project. This list should be maintained to ensure vendors are selected that have an acceptable QA/QC program. In the event a quality assurance program is not being used, the quality control program should encompass the qualifications of the vendors.

**6.1.3 Document Control.** Control of documents relating to engineering, procurement, policies, procedures, and instructions should be maintained. Procedures should be implemented to provide appropriate review of changes prior to revision and issuance of these documents. Document control measures should include the following:

(1) Identification of individuals responsible for preparation, revision, review, approval, and distribution of documents

(2) Use of correct documents identified and verified

(3) Procedures for controlling receipt, reproduction, distribution, storage, and retrieval of contract documents.

**6.1.4 Process Control.** Manufacturing processes should be controlled and implemented using established procedures for standard commercial processes and special manufacturing processes. Special processes such as welding, heat treating, nondestructive examination, testing, and inspection should be controlled and accomplished by qualified personnel. Special process procedures should define process methods, personnel training and qualification criteria, required certification and records, as well as requirements from applicable codes, other standards, and specifications.

Welding procedures should be reviewed prior to use to ensure that the procedures meet the specification requirements. Audits or surveillance should be performed during production to ascertain that the correct procedures are being implemented. Welder performance records should be audited periodically to determine that welders are properly qualified to procedures being used for fabrication. If required by specifications, permanent identification or records of welders' performance qualifications should be maintained. It should be noted that a decision to inspect only after completion of welding is not the best way to ensure quality.

**6.1.5 Inspection.** The quality control personnel who perform inspections during the various stages of fabrication should be qualified in accordance with a formal certification program. It is the responsibility of those charged with the administration and supervision of inspection to assure that inspectors are qualified and certified. Quality control personnel should perform nondestructive examination and destructive testing in accordance with established procedures.

Certification of inspection personnel may be required by contract, codes, specifications, or civil laws. In this regard, it may be beneficial to consider certification of welding inspectors by the American Welding Society under the Certified Welding Inspector (CWI) and Certified Associate Welding Inspector (CAWI) programs. The American Society for Nondestructive Testing (ASNT) and AWS provide certification guidelines for NDE personnel. Other programs may be used for certification of inspection personnel.

Inspection activities may be performed by quality control personnel in accordance with written procedures and instructions to assure that the product meets applicable requirements. The welding inspector determines the accuracy, completeness, and acceptability of materials and workmanship. Inspection activities also include verification that:

(1) Measuring and test equipment used for inspections are calibrated.

(2) Process hold points are observed.

(3) Surveillance of manufacturing activities is accomplished.

(4) Material receiving inspection is performed.

A sampling program may be used to verify acceptability of a group of items. The sample procedure should be based on standard practices and provide sample size and selection process. For example, MIL-STD-105 provides sample sizes and acceptable quality levels.

**6.1.6 Identification and Control of Material.** The QA/QC procedures should specify the requirements and control of items. Identification and control may be maintained by heat number, part number, serial number, or purchase order number. The identification should be placed on the item. Identification marking should be clear and applied so as not to affect the function or identity of the item during processing.

**6.1.7 Nonconforming Materials or Items.** The QA/QC program should establish detailed written procedures that describe the controls used for the identification, documentation, segregation, and disposition of nonconforming items, material deficiencies, and procedural requirements. Individuals having the responsibility and authority for the disposition of nonconforming items or deficiencies should be identified in the procedures. Items that do not meet requirements should be so identified to prevent inadvertent use.

**6.1.8 Records.** Records should document the quality of items and should meet the requirements of the applicable codes, other standards, specifications, and contracts. Records may include results of inspections, audits, material analyses, and process and test activities. Quality procedures should describe the necessary controls for the identification, preparation, legibility, maintenance, and retrieval of these records, and how they are to be protected against damage, deterioration, or loss. Unless otherwise specified by the engineering design, the retention of records should be based on the requirements of the applicable standard for the project.

**6.1.9 Audits.** Audits are useful to verify compliance with a quality assurance program and contract requirements and determine the effectiveness of the program. A system should be established by QA/QC procedures for internal and external audits. The audit procedures should include the requirements for training and qualifying auditors, the planning and scheduling of audits, preparation of audit reports, and resolution of audit findings and implementation of corrective actions.

# Chapter 7
# Ferrous Welding Metallurgy

This is an introduction to metallurgical concepts that influence welding processes and welding quality control. Special emphasis is placed upon the terms often used during inspection activities.

This chapter is intended to provide introductory material. Simplified definitions and explanations will at times be employed.

## 7.1 Carbon Steel

The two general types of steel are plain carbon steels, and alloy steels.

Plain carbon steel contains iron with controlled amounts of carbon.

Among plain carbon steels are: low-carbon types which contain less than 0.30% carbon (C); medium-carbon steels contain approximately 0.30–0.55% C; and high-carbon steels contain up to 1.7% C.

Alloy steel may be defined as a steel whose distinctive properties are due to the presence of one or more elements other than carbon.

The following are some elements which are alloyed with carbon steels:

(1) *Chromium.* Increases resistance to corrosion; improves hardness and toughness, improves the response to heat treatment.

(2) *Manganese.* Increases strength and responsiveness to heat treatment.

(3) *Molybdenum.* Increases toughness and improves strength at higher temperatures.

(4) *Nickel.* Increases strength, ductility and toughness.

(5) *Vanadium.* Retards grain growth and improves toughness.

Plain carbon steels contain iron plus small quantities of other elements. The five most common elements mixed with iron and their quantitative limits in a representative grade, AISI/SAE 1020 steel, are the following:

| | |
|---|---|
| (1) Carbon (C) | 0.18–0.23% |
| (2) Manganese (Mn) | 0.30–0.60% |
| (3) Silicon (Si) | 0.30% max |
| (4) Phosphorus (P) | 0.040% max |
| (5) Sulfur (S) | 0.050% max |

These are commonly called *ferritic* or *ferrite-pearlite steels.* The terms *ferrite* and *pearlite* refer to the microstructural aspects of the slowly cooled steel, but, as will be shown, other microstructures can form if the steel is rapidly cooled from high temperatures.

Slowly cooled plain-carbon steels have a uniform microstructure with low tensile strength and high ductility. These properties can be changed by heat treating, mechanical working, addition of alloying elements, or combinations thereof. The effect of heating and cooling is of particular interest to welding, since part of the metal is heated to the melting point in most welding processes.

When plain-carbon steel is heated during welding or heat treating, the first important change, a predominately mechanical one, starts at about 950°F (500°C). The change lowers the yield strength of the steel. Some of the residual stresses caused by cold working or weld shrinkage are relieved, and the material is softened.

A major metallurgical change occurs when ferritic steel is heated above its lower transformation temperature, often referred to as the *$A_1$ temperature*. The temperature that should be reached to complete the transformation, which is referred to as *upper transformation temperature*, depends upon the specific chemical composition of the steel. For plain-carbon steel (e.g., AISI 1020), the transformation temperature is at about 1560°F (850°C). Figure 7.1 shows the changes that occur at various temperatures during heating and cooling.

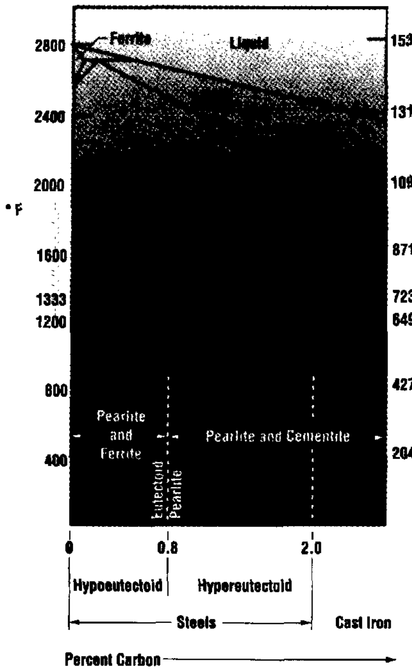



**Figure 7.1—Iron-Carbon Phase Diagram**

It is important to note that metallurgical changes occur every time a weld bead is deposited. Changes in the metallurgical properties also occur in the base metal adjacent to the bead that did not melt during the welding process. This area is called the heat-affected zone (HAZ). The width of the HAZ is primarily determined by the amount of heat applied, and the metal's chemistry and thickness. Aluminum welds, for example, exhibit larger HAZs than welds in steel because aluminum conducts heat faster than steel, i.e., has a higher thermal conductivity.

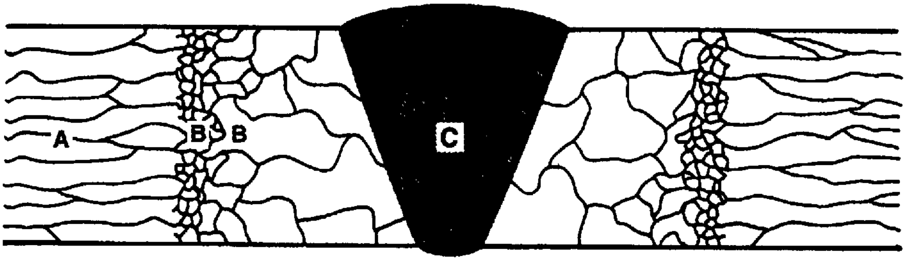
As a weld cools, two major events occur:

(1) Residual stresses and distortions develop. These stresses are caused by a combination of expansion and shrinkage during the cooling and solidification of the metal. Shrinking and expansion may be due to thermal contraction and expansion, and they may be complicated by metallurgical transformations to other phases which have different densities. The resulting mechanical effects are discussed in Chapter 9.

(2) The mechanical properties of the weld metal and the HAZ are changed. These changes depend markedly on the rate at which the cooling takes place through the metal's transformation range. If slow cooling can be achieved, the transformation cycle upon cooling will be the reverse of the transformation cycle upon heating. Although grain size may be changed, as shown in Figure 7.2, the HAZ will contain a combination of either ferrite and pearlite, or pearlite and cementite, depending on the chemical composition of the steel. Because these products were not quenched to produce hard martensite, the strength will be similar to the original soft base metal.

Cooling rates can be affected by total heat input, and preheat temperature, and the metal's size, thickness, and thermal conductivity. Since the mass melted during welding is usually quite small compared to the adjacent base metal, rapid cooling rates do occur. This can be observed by noting that the weld bead cools from the molten state to about 1200°F (650°C) in just a few seconds. When very-low-carbon steels (e.g., modern lower-strength steels with less than 0.10% C) are cooled rapidly, the steel remains soft and ductile. For this reason, many types of welding electrodes are designed with relatively low carbon content. However, conventional plain carbon steels containing between 0.18–0.35% C are commonly used for piping, pressure vessels, and structures. The rapid cooling rate associated with welding tends to produce harder and less-ductile metallurgical structures called martensite or bainite. Both martensite and bainite have a needle-like or acicular appearance, as shown for martensite in Figure 7.3.

While a certain amount of martensite and bainite is normally unavoidable, their amount and their effect can be minimized by proper base metal and electrode selection, welding technique, and proper preheating and inter-




A – Cold worked area (elongated grains)
B – Recrystalized area or equiaxed grains with coarsest grains adjacent to weld
C – Weld area (cast structure or columnar grains)

**Figure 7.2—Crystal Structure of Cold Rolled Steel in Weld Area**

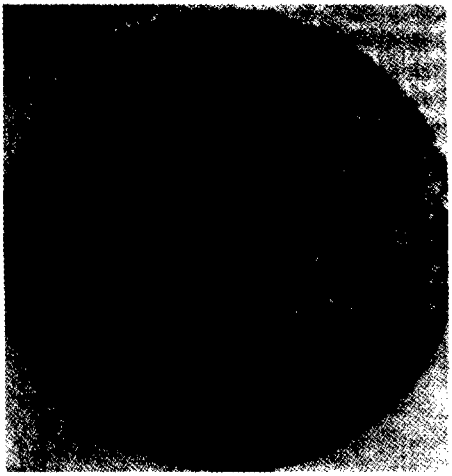


**Figure 7.3—Martensite Showing Needle-Like or Acicular Structure (500X Before Reduction)**

pass temperatures. The need for such actions becomes more important as material thickness or carbon content, or both, increase. Thicker base metal removes heat in less time from the weld area and thus increases the rate of cooling. A unit called *carbon equivalent* *(CE)* is often employed to predict the combined effect of carbon and manganese upon the tendency to form martensite. For mild-carbon steel, the carbon equivalent is most commonly expressed as:

$$CE = \%C + \%\frac{Mn}{4} \text{ or } CE = \%C + \%\frac{Mn}{6} \quad \text{(Eq. 7-1)}$$

The higher the CE and the thicker the material, the greater the need for preheating.

As the CE, or the thickness, or both increase, even the use of preheating and carefully planned welding techniques may fail to limit the amount of residual stresses and unwanted martensite formations. This may introduce the need for postweld heat treatment (PWHT). In most cases, this is accomplished by heating the weldment between 950°F (500°C) and the lower transformation temperature of 1333°F (723°C). Within that temperature range, the yield point of the material drops considerably. This causes locked in or residual stresses to be lowered; at the higher temperatures within that range, some of the martensite will be softened. Metallurgists refer to the second effect of this operation, which softens the steel, as *tempering*. This explains why the PWHT operation is often called "stress relieving" by the welder and "tempering" by the metallurgist.

## 7.2 Low-Alloy Steels

Alloy steels contain carbon and other intentionally added elements, such as nickel, chromium, copper, molybdenum, and vanadium. Other elements may also be added for special applications that do not involve welding.

Weldable alloy steels are designed to permit higher strength with adequate ductility, low-temperature notch toughness, improved corrosion resistance, or other specific properties.

The welding engineer should select electrodes capable of matching the mechanical properties and the chemical composition of these alloy steels in order to achieve a uniform structure.

Although the addition of such elements as chromium, nickel, molybdenum, copper, and vanadium can significantly change the properties of the steel, the basic metallurgical concepts are similar to those that apply to plain-carbon steel. Softening will start between 1000°F (540°C) and 1250°F (680°C), depending upon the specific composition. The lower transformation temperature of a given alloy steel may be above or below that of a carbon steel. In general, nickel alloying lowers the lower transformation temperature, while chromium and molybdenum alloying raises the lower transformation temperature. Numerous reference books, such as the *Atlas of Isothermal Transformation Diagrams*, published by ASM International, contain information about alloy steels to allow reasonable estimation of the transformation of many steels. Since this temperature varies some for each low-alloy steel classification, optimum PWHT temperatures should be established and documented for each. For several alloy steels, it is not uncommon to stress relieve the welded component at much higher temperatures.

During welding, part of the alloy steel will pass through the lower and the upper transformation temperatures. In this respect, there is little difference between plain carbon and low-alloy steel. Also, all other things being equal, the weld cooling rate for low-alloy steels is the same as the rate for plain-carbon steels. However, the alloy material is more susceptible to hardening, to embrittling, and subsequently to cracking, since martensite can form at slower cooling rates. The ability of the alloy steel to form martensite can again be expressed as a carbon equivalent (CE) for which there are many similar formulas that include many elements in addition to carbon and manganese. The following formula is commonly used to show the effects of adding various elements to alloy steels, taken from *Welding Handbook*, Volume 4, 8th Edition:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15} \quad \text{(Eq. 7-2)}$$

With a high CE, even a relatively slow cooling of the weldment will produce large quantities of martensite and bainite. Preheating, while essential for nearly all alloy-steel welds, often fails to retard the cooling rate sufficiently; however, it can prevent cracking during fabrication. Thus, PWHT is mandatory for many alloy steels to restore sufficient ductility prior to exposing the assemblies to service conditions.

## 7.3 Delayed Cracking

**7.3.1 Causes of Delayed Cracking.** Delayed cracking is undoubtedly the most widespread type of heat-affected zone defect. The cracks may form up to 48 hours after completion of the weld. The delayed cracking process depends on the diffusion of soluble hydrogen into the stressed sites. Common sites for these cracks are in the toe or root of the weld, and at local details, which result in sharp stress concentrations. A typical example is shown in Figure 7.4.

Buried underbead cracks may also be observed, but these are less common. The cracks are generally quite shallow, but can

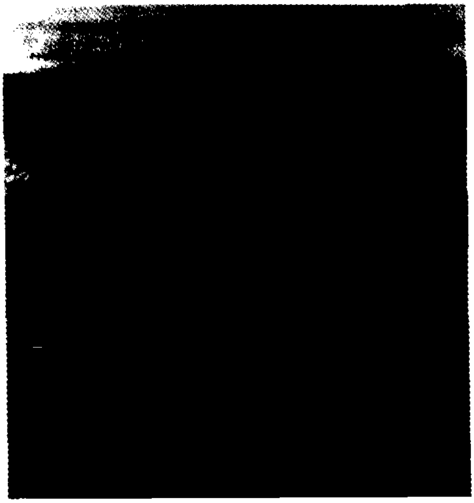


**Figure 7.4—Example of Delayed Cracking in HAZ**

sometimes penetrate several millimeters into the base metal. They are usually, but not exclusively, confined to the HAZ.

The formation of delayed cracks in the HAZ requires the presence of four independent conditions. If any one of these conditions is missing, a delayed crack cannot form. The four conditions are: 1) the presence of hydrogen; 2) a susceptible microstructure; 3) the presence of stress; and 4) low temperature. Each of these four conditions is described in detail below.

**7.3.2 Presence of Hydrogen.** All arc welding processes introduce hydrogen into the weld metal to various degrees. The hydrogen can originate from moisture in electrode coatings, shielding gases, and the flux. Moisture may also originate from oxides on the metal, from hydrocarbons, lubricants, or other contaminants on the plate or welding wire, and even from the moisture in the room air.

The welding arc's intense heat is sufficient to break down most compounds into their constituent elements. Molten steel has a substantial capacity for dissolving hydrogen. Immediately after solidification, the diffusion rate of hydrogen in steel is high. Thus, there is considerable potential for hydrogen to diffuse into the HAZ during the welding operation.

While the steel is above the Ac temperature, it has a relatively high solubility for hydrogen. However, upon cooling, it transforms to a phase that has a much lower solubility for hydrogen. As cooling continues, the solubility decreases, as does the diffusion rate. The situation can arise where a supersaturation of hydrogen exists that cannot diffuse away. Under such conditions, the hydrogen can be a potent embrittling agent in the steel.

**7.3.3 Susceptible Microstructure.** A wide variety of microstructure can exist in the HAZ of carbon-manganese and low-alloy steels, depending on the composition of the steel and the welding procedure. In general, only hard microstructures are susceptible to hydrogen cracking. Such microstructures are promoted by high hardenability in the steel and by fast cooling rates (which also restrict the time available for hydrogen diffusion), and are generally martensitic or bainitic in nature. Fast cooling rates are promoted by low-arc energy levels, low preheat/interpass temperatures and thick sections. The critical hardness level to cause cracking is a function of hydrogen content of the weld, and to a lesser extent of restraint, but would typically be 350HV for high hydrogen levels and 450HV for low hydrogen levels. There is a lot of evidence to suggest that the critical hardness level is lower in lower carbon equivalent steels.

**7.3.4 Presence of Stress.** No crack of any description can form in the absence of stress. For hydrogen cracking, this would arise from stresses imposed by the contraction on cooling. It should be recognized that the residual stresses due to welding in a carbon-manganese steel can be of yield point magnitude. The presence of notches or sharp profile changes causes stress concentrations which can help initiate cracks.

**7.3.5 Low Temperature.** The embrittling effect of hydrogen on steel is very dependent on temperature since the minimum notch tensile strength occurs at temperatures of only slightly above ambient. At higher temperatures, the cracking is less likely to form since hydrogen can more readily diffuse away, and the inherent toughness of the steel is also increased. At lower temperatures, the hydrogen is effectively immobilized by its low diffusion rate, although the toughness of the steel will also decrease.

The mechanism of hydrogen embrittlement is complex, and is far from being totally understood.

The term *delayed cracking* is sometimes used to describe hydrogen cracking. Often cracks are not detected until some time after the weld has been completed and cooled down. One school of thought suggests that it initiates very soon after ambient temperatures have been reached, but that the rate of growth is fairly slow, and a considerable time is required to allow the defect to grow to a detectable size. However, it is also not uncommon for an incubation period of cracking to occur, associated presumably with time required for hydrogen to diffuse to appropriate areas.

## 7.4 Prevention

Since delayed cracking requires four conditions to be present at the same time. Delayed cracking can be minimized or eliminated completely by removing or controlling any one of those conditions.

**7.4.1 Controlling the Presence of Hydrogen.** It is possible to severely limit the amount of hydrogen entering the weld metal by the use of suitably prepared consumables, use of low-hydrogen electrodes, and by scrupulous cleanliness. Flux shielded welding processes, including flux cored arc welding, can introduce hydrogen through moisture in the flux because it is generally impossible to remove all the inherent moisture. In fact, moisture removal from cellulosic coated electrodes (EXX10 type) is undesirable because these electrode types require a reducing atmosphere in the arc to work satisfactorily.

The manufacturer's instructions for the care and storage of welding consumables should be carefully followed.

Note that "low hydrogen" as applied to consumables does not mean hydrogen-free. Even low-hydrogen consumables can contribute the hydrogen needed to cause delayed cracking. The moisture content of fluxes and electrodes can be reduced by drying the electrodes or fluxes in ovens. The electrode manufacturer should be consulted regarding the proper oven temperature. Care should be taken to ensure that ovens are not overloaded, and that drying lasts sufficiently long to ensure that *all* the contents receive the minimum baking time at the correct temperature.

Recently, fluxes and coatings that are significantly less hygroscopic have been developed. However, the coatings on low-hydrogen electrodes will absorb moisture rapidly if not stored at proper temperatures or in airtight containers.

The hydrogen level can also be reduced by the use of gas shielded processes such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). Maximum diffusible hydrogen levels under specific test conditions for various types of welding electrodes and wires can be included on product purchase orders by invoking optional supplemental diffusible hydrogen designators which are included in AWS filler metal specifications.

Cleanliness of the weld joint, wire, and welding apparatus is also important. Paint, rust, grease, degreasing agents, and lubricants on welding wire are other potential sources of hydrogen.

Another prevention measure is to remove some of the hydrogen that inevitably enters the weld, such that the levels are reduced to acceptable values by the time the weld has cooled. This is achieved by increasing the duration of the weld thermal cycle, usually by applying a preheat. This reduces the cooling rate and therefore allows more time for the hydrogen to diffuse away from the weld zone.

Maintenance of the proper interpass temperature will prevent the weld from cooling into the range of maximum embrittlement, and will also aid hydrogen diffusion. However, the interpass temperature should be sufficiently low to permit the austenite decomposition reaction to go to completion, since austenitic weld metal has a comparatively high solubility for hydrogen. The use of higher arc energies is also beneficial since this also increases the duration of the thermal cycle. However, the use of high arc energies can result in a loss of toughness in both weld metal and heat-affected zone (HAZ). Hydrogen levels can also be reduced by post-weld heat treatment for several hours after welding, possibly at a higher level than was used for preheating during welding.

In severe cases where it is not possible to apply preheat, or dry electrodes satisfactorily, austenitic filler metal can be used. This technique is particularly valuable when undertaking difficult repairs on very hardenable steels. Austenitic stainless steel weld metal has a comparatively high solubility for hydrogen, coupled with a low diffusivity. The hydrogen therefore tends to remain in the austenitic weld metal, where it is relatively harmless. While providing a method for reducing the susceptibility for hydrogen cracking, the use of austenitic stainless steel for welding alloy steel should be considered carefully by the engineers to ensure that issues of corrosion, differences in thermal expansion, and other metallurgical factors are considered.

**7.4.2 Microstructural.** The risk of delayed cracking in the HAZ is reduced as the hardness decreases. The hardness level in carbon-manganese and low-alloy steels increases as the cooling rate through the transformation temperature ranges increases, since this leads to the formation of lower temperature transformation products such as martensite and lower bainite, which have lower inherent ductility. The formation of these hard constituents can be restricted by the following:

(1) Reducing the cooling rate by using a higher heat input.

(2) Using a suitably developed multipass procedure in which the hard HAZ constituents of one pass are heated by subsequent passes. This can result in retransformation to a softer microstructure, or tempering of the hard structures without subsequent transformation.

(3) Increasing the preheat/interpass temperature level to reduce the cooling rate through the transformation temperature range.

It should be noted that items (1) and (3) will also aid hydrogen diffusion, although they may conflict with other requirements, such as achieving good toughness.

**7.4.3 Restraint.** The restraint of a weld is often difficult to vary, although a certain degree of control can be exercised by altering the edge preparation, strongback design, etc. In production, the restraint imposed on two identical joints may vary considerably. For instance, a weld made early in a rigid structure will be lightly restrained, but identical closing welds that complete the structure may be highly restrained. Since restraint is difficult to predict or control in practice, it is advisable to ensure that conditions of high restraint are present in procedural trials by the use of suitable strongbacks, end beams to prevent angular rotation and lateral contraction, or both. Restraint is also increased by poor fit-up.

**7.4.4 Temperature.** Delayed cracking is most likely to occur at temperatures below 212°F (100°C). The use of high preheat and interpass temperatures will promote hydrogen diffusion, thus reducing the risk of cracking. In some instances, such as repair welds on thick sections in confined situations, it may be impractical to apply a stipulated preheat level and maintain an environment in which a welder can comfortably work. In such cases, the use of the maximum feasible preheat would be required. The temperature should then be increased to 400°–475°F (200°–250°C) after completion of welding—without allowing the weld to cool—thereby allowing additional time for the hydrogen to diffuse out of the metal.

## 7.5 Austenitic Stainless Steel

The most common austenitic stainless steels contain between 18 and 25 percent chromium and between 8 and 20 percent nickel as primary alloying elements. Product forms such as plates, castings, forgings, and filler metals are classified by a three-digit numbering system and can be easily recognized since the first digit is a 3, and the detailed chemical composition is indicated by the last two digits. These materials are often referred to as *austenitic chromium-nickel steels* or 300-series steels.

The 300-series steels have many chemical and metallurgical characteristics that clearly distinguish them from ferritic steels such as plain carbon or low-alloy steels. Specifically, the 300-series steels are more corrosion resistant in most environments and nonmagnetic or only slightly magnetic, have higher tensile and creep strength at elevated temperatures, and cannot be hardened by heat treatment.

Austenitic stainless steels do not undergo the normal phase changes associated with ferritic steels. While plain-carbon steel is austenitic and nonmagnetic at elevated temperatures, it will transform into ferrite, pearlite, martensite, and other phases as it is cooled through the transformation range.

However, when austenitic stainless steel is cooled, all or nearly all of the material is retained as austenite at room temperature. Without phase changes, no hardening will occur. Thus, hard areas are not found in the heat-affected zone (HAZ) of 300-series stainless steels. This reduces the need for preheating and postweld heat treating.

This chapter will not discuss the different grades of stainless steels and the optimum application of each. However, when these materials are welded, two forms of metallurgical degradation can occur: sensitization and microfissuring.

The corrosion resistance of the 300-series stainless steels depends upon the addition of various alloying elements, of which chromium is of primary importance. If the alloy is heated to the sensitization temperature range of 800–1600°F (425–870°C), some of the chromium can combine with any carbon that is available and form a chromium-rich precipitate. Whenever this occurs, as it can in certain zones during welding, less chromium is available to resist corrosion. This is especially serious if the corrodent is an acid (for example, see Figure 7.5).

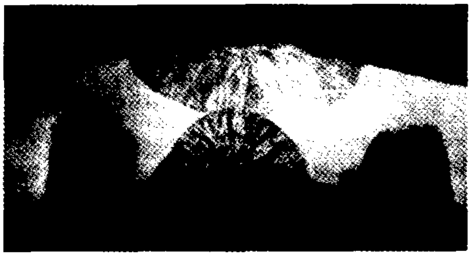


**Figure 7.5—Corrosion Attack of Sensitized Stainless Steel in Acid Environment**

This sensitization can be overcome by any one of the following actions:

(1) Heat the steel after welding to about 1900°F (1050°C) to dissolve the carbides, and cool rapidly through the sensitization range. This is called *solution annealing*. It is practiced in steel and pipe mills, but it is not easily adapted to shop assemblies and field erection.

(2) Use 300 series stainless steels in the filler metal and base metal with low carbon content. By limiting the percent carbon to a maximum of 0.03 or 0.04, these L grades (e.g., 308L, 316L, etc.) limit the amount of carbides that can form and thus limit the amount of chromium that may be depleted. Extra-low-carbon stainless steel filler metal are also available.

(3) Use stabilized stainless steel materials. Elements like columbium and titanium will combine preferentially with carbon and reduce the carbon available to form chromium carbide. This will retain the chromium dispersed for corrosion protection even when

reaching the sensitization range during welding or other operations.

Microfissuring is another problem associated with austenitic stainless steels. It was noted earlier that 300-series steels are predominantly austenitic. Pure austenite has excellent mechanical and corrosion-resistant properties. However, its ability to absorb impurities without cracking during solidification and cooling from elevated temperatures is limited. Low-melting point impurities may be forced to the grain boundaries. Excessive amounts weaken these grain boundaries, creating the possibility of microscopic grain-boundary flaws called *micro-fissures* (shown on Figure 7.6). This condition is of greater concern when the solidification is under the high restraint associated with welding.

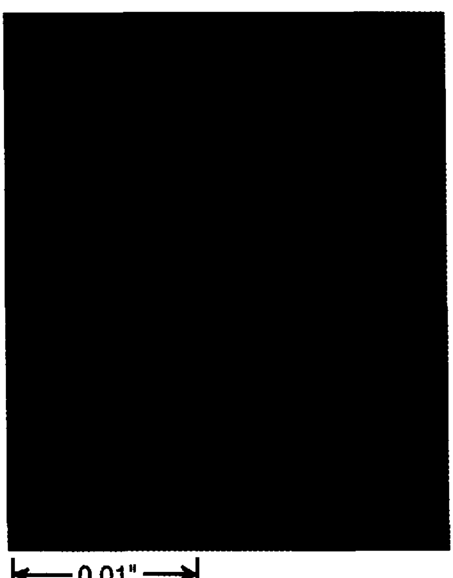



**Figure 7.6—Microfissure in Austenitic Stainless Steel (100X)**

One method of reducing microfissuring is to disperse these impurities among disconnected grain boundaries that surround islands of a second phase, delta ferrite. This is accomplished by modifying the chemical composition of the weld metal. Ferrite can absorb many impurities, and will definitely reduce microfissuring tendencies.

However, too much delta ferrite can cause a second problem by transforming to sigma phase when the metal is heated to temperatures associated with welding and heat treating. Small amounts of sigma phase can embrittle large areas of stainless steel.

Minimum and maximum limitations on ferrite are desirable to prevent microfissuring and sigma phase formation. Many nominally austenitic stainless steel electrode compositions can be formulated to produce deposits within a specific Ferrite Number (FN) range, such as 4 to 10 FN or 5 to 15 FN. The Ferrite Number can be measured as a scheduled inspection operation by using a magnetic gauge calibrated to AWS A4.2, *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Austenitic-Ferritic Stainless Steel Weld Metal.*[2] In addition, it is possible to estimate the FN from the chemical analysis of the weld deposit using various "constitution diagrams." Estimation by diagram should not be substituted for actual measurement.

## 7.6 Lamellar Tearing

Lamellar tearing occurs in rolled-steel plate where welding imposes high through-thickness stress on the plate. The tear, or crack, usually occurs just outside the weld heat-affected zone (HAZ). It has a characteristic stepped appearance. Figure 7.7 shows a typical lamellar tear.

The tear forms in two stages. First, through-thickness stress perpendicular to the rolling direction separates rolled-out inclusions from the steel at their interface. Then, fractures perpendicular to the rolling

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2. Available from American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

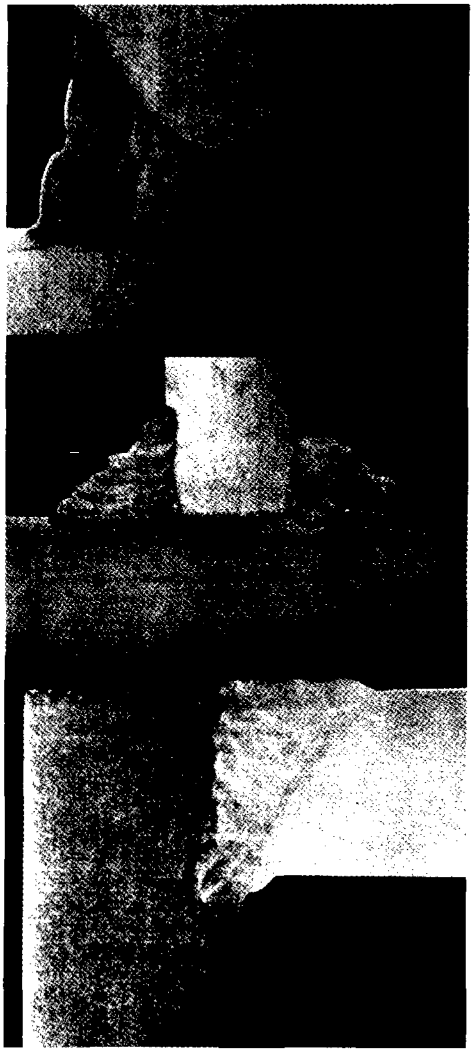


**Figure 7.7—Closeup of Lamellar Tear Under a Fillet Weld Showing Typical Stepped Appearance (Magnification 8X)**

direction connect the inclusions to relieve through-thickness stresses, resulting in the characteristic stepped appearance.

**7.6.1 Causes.** Lamellar tearing results from a combination of through-thickness stress on the plate resulting from welding and from use of susceptible base material. Level of through-thickness stress depends on joint design and on joint restraint.

**7.6.2 Joint Design.** Corner joints impose the highest level of through-thickness stress. Such joints are found in set-through nozzles, welded girders, and ring stiffeners in cylindrical structures, for example.

**7.6.3 Joint Restraint.** Degree of joint restraint is difficult to quantify. However, analysis of joint design can give a qualitative indication of the amount of restraint to be expected. A T-joint in a welded I-beam or girder, for example, would produce moderate through-thickness restraint on the flange. A weld of identical dimension that was acting as a stiffener or a closing weld in a rigid structure would be highly restrained.

**7.6.4 Material.** Susceptibility of a steel to lamellar tearing depends on its inclusion content and on the shape and distribution of the inclusions (All steels contain some inclusions, by-products of the steel-refining process). Presence of a large number of widely spread plate-like inclusions leads to poor through-thickness ductility and to high susceptibility to lamellar tearing. Lamellar tearing rarely occurs in castings because inclusions in castings are not rolled flat but retain their spherical form.

A steel grade shows no correlation with susceptibility to lamellar tearing. Neither does steel composition. However, in carbon-manganese steel, measures of short-transverse reduction in area (STRA) can relate to sulfur content and hence to inclusion content for specific thickness ranges.

Thin plate, able to flex in response to stress, shows little susceptibility to lamellar tearing. Tears have been seen, however, in plate 5/16 in. (8 mm) thick. The fact that material is thin is not a guarantee that lamellar tearing will not occur.

**7.6.5 Avoidance.** Most measures to avoid lamellar tearing come at an increase in cost. However, experience indicates that added preventive costs are substantially less than cost of remedial action, including repair, late-delivery penalties, or subsequent litigation.

Preventive action relies on the use of non-susceptible material and avoidance of designs that impose through-thickness stress. The following are some approaches to minimize lamellar tearing:

(1) Change the location and design of the welded joint to minimize through-thickness strains.

(2) Use a lower strength weld metal.

(3) Reduce available hydrogen.

(4) Use preheat and interpass temperatures of at least 200°F (90°C).

**7.6.6 Material Selection.** Specification of suitable steels at the design stage will in most cases avoid lamellar tearing. Where lamellar tearing is a possibility, the designer should specify steel of guaranteed through-thickness ductility.

**7.6.7 Design to Avoid Through-Thickness Stress.** Attention to joint design in fillets, T-, and corner welds can significantly reduce risk of tearing. Where possible, design to avoid stress in the through-thickness direction. Use suitably bevelled edge preparations on corner joints.

Designers should avoid use of excessively thick material, which increases stiffness (and cost), complex node structures, unnecessary stiffeners, and other attachments. In lightly loaded structures, cruciform joints may be staggered to reduce risk of lamellar tearing, though this is generally considered poor design practice.

**7.6.8 Welding Procedures.** In general, modifications to welding procedures will not prevent lamellar tearing. The welding process has little effect. High-heat-input processes, like submerged arc welding, reduce the risk by producing large HAZ with graduated hardness and strain gradients and low peak hardness. Electroslag and electrogas welding, sometimes cited as low-risk processes, are not normally suited to joint designs considered here. High-heat-input processes deposit soft weld metal, which can absorb some strain that would otherwise go to the base plate. For similar reasons, selection of a low-strength consumable is advised. Some manufacturers supply low-hydrogen electrodes specifically formulated for avoidance of lamellar tearing.

The use of consumables that deposit weld metal of unnecessarily high strength should be avoided.

Where tearing is a risk and where base-material cannot be changed (e.g., in existing weldments). One or more layers of ductile material should be deposited onto the lamellar-tearing-susceptible substrate. Weld passes are then made on top of the buttering. The softer layers absorb contraction stresses, helping to prevent lamellar tears.

Evidence suggests that HAZ hydrogen cracking can trigger lamellar tearing. If this is so, preheat and high-heat input would aid in its avoidance in steels.

**7.6.9 Fabricating Techniques.** Joint design is important in avoiding lamellar tearing: a tight fit raises the restraint stress on plate; a large gap raises the volume of weld metal required. A gap of 0.04 to 0.12 in. (1–3 mm) is reasonable; this range is within requirements of most welding codes. In some cases, soft steel wires can hold a root gap.

If the member being stressed through the thickness is buttered with a layer of weld metal prior to welding the main joint, the propensity for delaminating is reduced.

Peening, which introduces compressive stresses below the weld, has been suggested as a preventive measure. However, peening may provide limited benefits and may degrade toughness and lead to cracking in the weld metal.

## 7.7 Other Metallurgical Considerations

The soundness of a weld during fabrication and during its service life is influenced by many metallurgical considerations. While most are beyond the scope of this book and the activities of an inspector, a few concepts have been highlighted below.

Many elements are added to steel or other base metals to produce certain desirable properties. However, certain elements may severely deteriorate the base and weld metal properties by penetrating into the molten weld metal. These include the following elements that may be in contact with a metal during welding related operations:

(1) Copper (in the form of contact tips and magnetic particle examination prods)

(2) Lead (in the form of caulking or lining)

(3) Sulfur (in the form of molecular sulfur that has been deposited while the equipment was in service)

(4) Zinc when welding austenitic stainless steel and carbon steels (in the form of galvanized components or cathodic protection equipment)

# Chapter 8
# Preheating and Postweld Heat Treating

Preheating and postweld heat treating may be necessary in order to produce sound welded assemblies for certain base metals and welded joints. These preheat and postweld heat-treat requirements should be specified in the applicable welding procedure specification(s) and should be followed during production welding.

## 8.1 Preheating

Preheating is the heating of the weld joint to attain and maintain the specified preheat temperature prior to welding. In addition to establishing a preheat temperature, an interpass temperature limitation may need to be considered for many materials.

When preheating is specified, the entire weld joint area should be heated through the metal thickness to the desired minimum temperature. To obtain a uniform temperature through the metal thickness, it is desirable to locate the heating source(s) on one surface of the metal and to measure the metal temperature on the opposite surface. However, when heating and temperature measurement should be done from the same surface, the inspector should be certain that more than just the surface has been heated; the heat should have soaked through the entire material thickness.

In a multipass weld, the temperature of the weld area prior to depositing the next weld pass is called the *interpass temperature.* When specified, the interpass temperature should be checked prior to the next pass. The applicable code may specify the location at which interpass temperature is to be measured. Welding may not continue if the measured temperature is not within the temperature range specified in applicable welding procedures. Within the instructions of the WPS, accelerated cooling is sometimes authorized for certain alloys (e.g., austenitic stainless steel and high-nickel alloys). However, it should be noted that for other alloys, accelerated cooling may be detrimental, and its use should be investigated carefully.

Depending on the metallurgical or mechanical properties of the weldment, or both, preheat and interpass temperature may be specified as follows:

(1) Minimum temperature only (e.g., mild carbon steel without special requirements)

(2) Maximum temperature only (e.g., aluminum and nickel alloys)

(3) Minimum and maximum temperatures (e.g., low-alloy steels with impact requirements)

In situations where a preheat temperature has been specified but neither range nor interpass temperatures have been defined, it is normal to consider the preheat temperature as a minimum preheat and interpass temperature.

While furnace preheating is sometimes employed (as for cast iron), local heating sources are selected for most preheating operations. Local heating sources include resistance elements, induction coils, and oxyfuel torches. The selection of a heat source is usually based on the shape of the component, the number of welds involved, the geographic location of the work, the availability of equipment, and the cost of the operation.

The welding inspector should monitor the heating process with thermocouples, pyrometers, or temperature-indicating materials such as crayons, paints, and pellets that melt or change color at predetermined temperatures. Such indicators should be removed prior to depositing the next bead to avoid contaminating the weld. When thermocouples and surface pyrometers are employed, they should be calibrated according to the manufacturer's instructions.

A drying operation is desirable for most metals and is designed to remove surface condensate and other forms of moisture that otherwise would cause porosity or weld cracking. Such a drying operation requires only that the surface be heated to evaporate the surface moisture prior to starting a welding operation.

## 8.2 Postweld Heat Treating (PWHT)

As the name implies, PWHT is any heat treatment occurring after the welding operation. In a stress relieving treatment, the residual stresses created by the localized heating and cooling associated with welding are reduced by plastic and creep deformation. All welds can be expected to retain localized residual stresses equal to the room temperature yield strength of the material. When the equipment designer or the applicable code considers the retention of such stresses unacceptable, the situation can be corrected by heating the weldment to a temperature at which the yield strength is considerably reduced. At such elevated temperatures, the residual stresses will dissipate or equalize with time to a level equal to the yield strength of the material at that temperature. Thus, the effectiveness or the completeness of the stress relieving operation is increased as the holding temperature or holding time, or both, are increased. To prevent the reestablishment of high residual stresses, slow and uniform cooling is needed from the PWHT temperature.

The effectiveness of stress relieving depends primarily on the holding temperature selected for the PWHT operation. Some codes permit a lowering of the stress relief temperature with a concurrent increase in time. Other factors that may contribute to the success of PWHT operations include the following:

(1) Holding time should be of sufficient length, since stress relieving does not occur instantaneously. For carbon steels, holding times of one hour per inch of thickness within a minimum of one hour has proven effective when no other instructions are available.

(2) The heating area is of special concern during localized PWHT. Since "spot" PWHT causes high localized stresses, the heating of a wide area or a circumferential band is desirable and usually mandated by the applicable code.

(3) The rate of heating should be uniform over and through the thickness to be treated. Some codes and other standards restrict the maximum heating rate for this purpose.

(4) Cooling rates and the uniformity of the cooling operation should be specified in detail and executed with care. Some codes restrict the maximum cooling rate. To achieve specific properties in some metals, accelerated cooling is desirable. However, for most components, slow cooling maximizes tempering and minimizes residual stresses. Some PWHT operations have failed to meet their objective due to the occurrence of improper cooling rates.

Applicable codes and specifications, job requirements and qualification test results govern the specific PWHT cycle. The adequacy of a PWHT operation on carbon and low-alloy steels can often be measured by hardness testing. Such a testing is mandated by a few specifications (e.g., ASME B31.3, *Chemical Plant and Petroleum Piping*).

In addition to full furnace PWHT operations, local PWHT equipment is frequently employed. The same processes used for preheating, mentioned earlier in this chapter, may be successfully employed for this purpose. However, the use of oxyfuel torch heating is generally undesirable for PWHT operations since uniform temperature distribution is difficult to achieve. A detailed discussion of each process, including the relative advantages and disadvantages of each, is presented in AWS D10.10, *Recommended Practices for the Local Heating of Welds in Piping and Tubing*.

**8.2.1 Heat Treating Inspection.** Many programs implemented by the manufacturer to control the quality of the product utilize inspection during various points of the fabrication sequence. Those inspection points related to weldment heat treating may include the following:

(1) Verification of preheat, interpass, and postweld heat treat temperatures

(2) Verification of surface cleanliness prior to preheating, welding, and postweld heat treating

(3) Calibration of temperature indicating and measuring devices and monitoring of their correct placement

(4) Monitoring the postweld heat treating operation to assure that the procedure requirements have been met

(5) Verification of the dimensional accuracy of the weldment after the final heat treatment

(6) Verification of weld quality after final heat treatment

**8.2.2 Precautions.** In all heating operations, care is needed to assure that the heat sources and the temperature-indicating tools do not adversely affect the weldment.

Weld surfaces should be thoroughly cleaned prior to heat treating if they have been exposed to materials that may be detrimental to the metal during heat treating. Items of special concern include:

(1) Copper, lead, and mercury (this applies to most metals)

(2) Chlorides and zinc (this applies especially when using stainless steels)

(3) Sulfur in small quantities (this applies especially when using nickel alloys)

(4) Sulfur in large quantities (this applies to most metals)

(5) Metal cutting fluids used for cooling that contain halogens

(6) Painted metal should have the paint removed prior to heating operations

(7) Paint or other surface coatings

The aforementioned contaminants can deteriorate the properties of the weld and adjacent area or accelerate the corrosion process. The most severe deterioration will occur when an accidental arc strike or a scheduled welding operation melts the contaminant. Such molten materials can attack and destroy the grain boundaries, resulting in cracks in the weld or the base metal.

# Chapter 9
# Weld and Weld Related Discontinuities

A weld discontinuity is an interruption of the typical structure of a weldment, such as an inhomogeneity in the mechanical, metallurgical, or physical characteristics of the material or weldment. A discontinuity is, by definition, not necessarily a defect.

## 9.1 General

A weld that does not meet any or all of the specific requirements of a particular specification or code is considered a defective weld. A defective weld is impossible to assess without reference to some particular standard or requirement related to the intended use of the weld.

For practical reasons, the terminology used in this chapter will be addressed without regard to any particular code or standard for determination of acceptability or rejectability. This chapter will address itself to three general classifications of discontinuities:

(1) Procedure/Process
(2) Metallurgical
(3) Base Metal

These classes of discontinuities may be further subdivided as follows:

(1) *Procedure/Process*
- (a) Geometric
  - — Misalignment
  - — Distortion
  - — Final Dimension
  - — Weld Size
  - — Overlap
  - — Weld Profile
  - — Convexity
  - — Concavity
  - — Weld Reinforcement
- (b) Weld/Structural
  - — Incomplete Fusion
  - — Incomplete Joint Penetration
  - — Undercut
  - — Underfill
  - — Inclusions
    - – Slag
    - – Tungsten
  - — Cracks
    - – Hot/Cold
    - – Weld/Base Metal
    - – Longitudinal/Transverse
    - – Root
    - – Toe
    - – Crater
    - – Throat
    - – Underbead
  - — Delayed Cracking
  - — Porosity
    - – Scattered
    - – Cluster
    - – Aligned
    - – Piping
  - — Surface Irregularities
    - – Weld Ripples
    - – Spatter
    - – Arc Strikes

(2) *Metallurgical*
- (a) Mechanical
  - — Strength
  - — Ductility
  - — Hardness
- (b) Chemical
  - — Chemistry
  - — Corrosion Resistance

(3) *Base Metal*
- — Laminations
- — Delaminations
- — Lamellar Tears
- — Seams and Laps

The text describes some of the preceding welding discontinuities, limiting its scope to (1) defining the discontinuity, (2) explaining the plausible cause of the discontinuity, and (3) outlining methods for possible corrective actions. The text is based on the most commonly used welding processes; however, the information will be useful for welds made by many other welding processes, applied to (1) metals known to permit satisfactory production welds, (2) joint designs that can produce satisfactory weldments, and (3) filler metals that are capable of producing sound deposits.

## 9.2 Procedure/Process

**9.2.1 Geometric.** In order for a production weldment to be satisfactory, its final dimensions, as well as individual weld sizes and lengths, shall be as specified on the applicable drawing. Dimensional data with tolerances may be found on drawings and in specifications and codes. Assemblies not meeting the requirements should be corrected before final acceptance. Discontinuities of this nature are described in the paragraphs that follow.

**9.2.1.1 Misalignment.** The term misalignment is often used to denote the amount of offset or mismatch across a butt joint between members of equal thickness. Many codes and specifications limit the amount of allowable offset because misalignment can result in stress risers at the toe and the root. Excessive misalignment can be a result of improper fit, fixturing, tack welding, or a combination of these factors.

**9.2.1.2 Distortion.** The welding operation commonly involves the application of heat to produce fusion of the base metal. Stresses of high magnitude will result from thermal expansion and contraction and weld metal solidification, and will remain in the weldment after the structure has cooled. Such stresses tend to cause distortion when the welding sequence is not properly controlled (see Figures 9.1 and 9.2). Rigid fixtures and

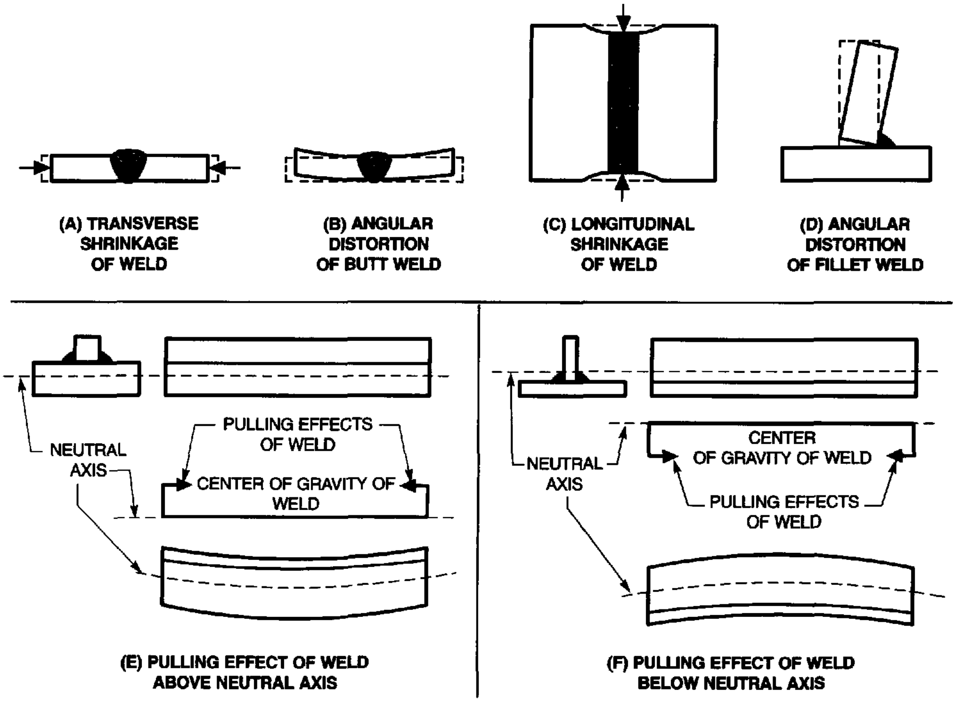



**Figure 9.1—Typical Distortion of Welded Joints**

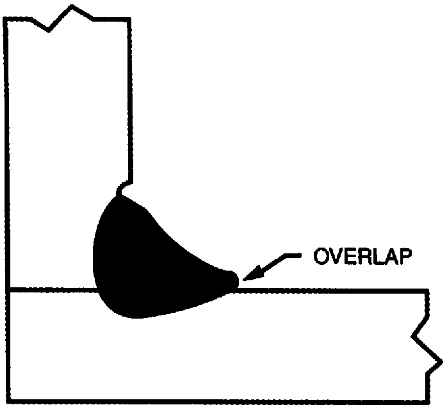



**Figure 9.2—Overlap**

careful selection of welding sequence, welding processes, and joint design can minimize this condition. Peening, if permitted by specification and performed under controlled conditions, has also been used to some extent to help reduce distortion. Sequencing of welds may balance stresses and reduce or avoid distortion. Correction of distortion in a completed weldment requires one or more of the following procedures:

(1) A mechanical straightening operation, with or without the application of heat

(2) The removal of the weld or welds causing the distortion and subsequent rewelding

(3) The addition of heat from a welding process (with or without a filler metal addition) in specific areas

(4) A postweld heat treatment

(5) Flame straightening

The corrective measures selected usually depend upon the applicable specification or the terms of an agreement between the fabricator and the customer.

**9.2.1.3 Final Dimensions.** Weldments are fabricated to meet certain dimensions, whether specified on detailed drawings or hand-written sketches. The fabricator should be aware of the amount of shrinkage to be expected at each weld joint. This will affect the final overall dimensions of the product. The effect of welding sequence on distortion and the use of postweld heat treatment to provide dimensional stability of the weldment in service should also be recognized by the fabricator.

Weldments that require rigid control of final dimensions usually should be finished by machining or grinding after welding or after postweld heat treatment to stay within limits. Tolerances for as-welded components obviously will depend upon the thickness of the material, the alloy being welded, and the overall size of the product. Thus, tolerances in final dimensions might be specified in ranges from plus-or-minus a few thousandths of an inch to as much as plus-or-minus a quarter of an inch or more.

The inspector should discuss weldment dimensions and tolerances with the fabricator or the designer, or both, so that the inspector may closely watch those dimensions that are critical. Discussion prior to fabrication is most important.

**9.2.1.4 Overlap.** Overlap is the condition in which weld metal protrudes beyond the weld interface at the toe of a weld as illustrated in Figure 9.2. The condition tends to produce notches which can be detrimental to weldment performance.

Overlap is usually caused by the use of either incorrect welding technique or by improper welding parameter settings. Overlap can occur at the toe of either a fillet or groove weld, as well as at the weld root of a groove weld.

**9.2.1.5 Weld Size.** The size of a normal equal-leg fillet weld is expressed as the leg length of the largest isosceles right triangle that can be inscribed within the fillet weld cross section (shown in Figure 9.3). The size of a groove weld is the depth of the joint penetration. Welds that are not of the correct size, either too big or too small, may be detected visually. This examination is often aided by

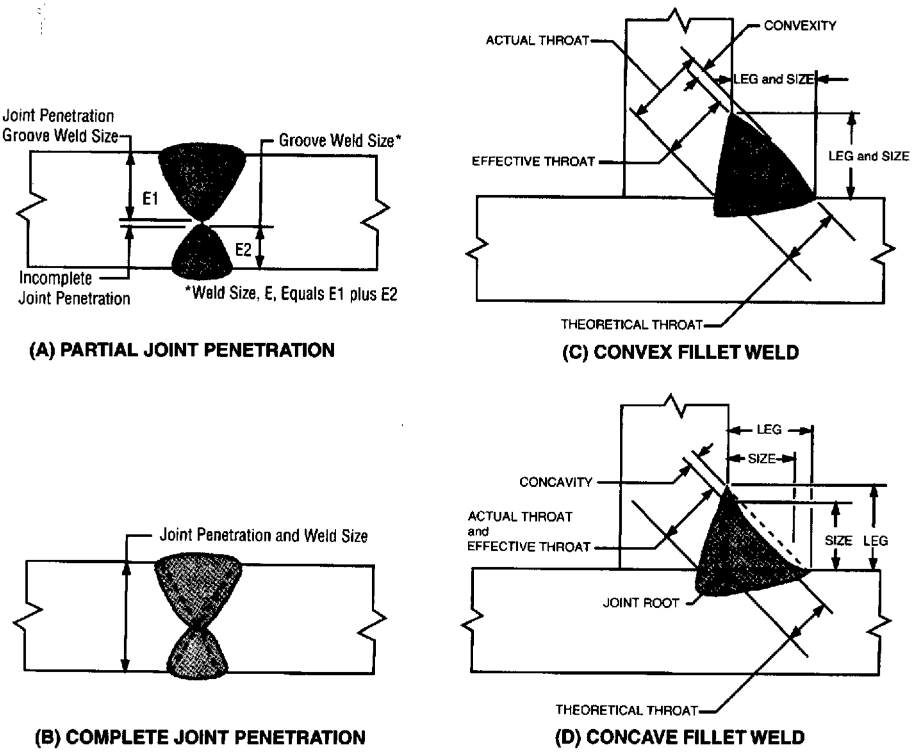


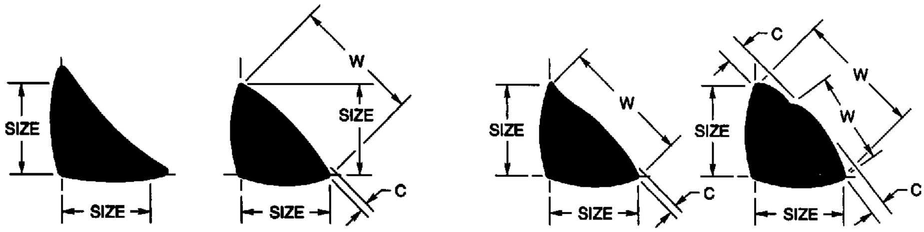

**Figure 9.3—Weld Sizes**

the use of a weld gauge or by comparison with approved workmanship samples.

**9.2.1.6 Weld Profile.** The profile of a finished weld may affect the service performance of the joint. The surface profile of an internal pass or layer of a multipass weld may contribute to the formation of incomplete fusion or slag inclusions when the next layer is deposited. Figure 9.4 illustrates various types of weld profiles in fillet and groove welds.

**9.2.1.7 Convexity.** Convexity is the maximum distance from the face of a convex fillet weld to a line joining the weld toes. At the junction of the weld layer and the base metal, it forms a mechanical notch, similar to that produced by an overlap discontinuity, but not nearly as severe. It may effectively stiffen the weld section. Also, as convexity increases in height, the stiffening effect may increase and the notch effect could intensify. The angle formed by the intersection of the reinforcement and the base material is critical. Angles less than 90° result in geometric notches being formed which will increase the concentration of stresses. As such, the amount of convexity or weld reinforcement (in terms or maximum allowable height) or the re-entrant angle is normally limited by the applicable weld specification.

The notch effected by excessive convexity can also be detrimental when located in an

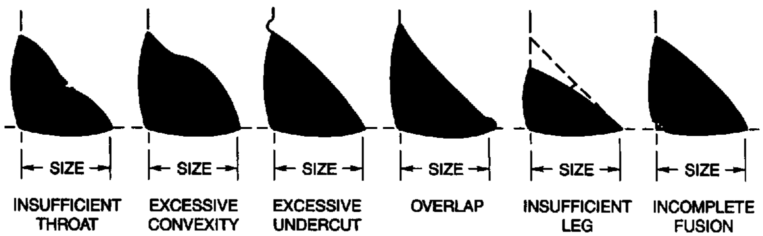



**(A) DESIRABLE FILLET WELD PROFILES**

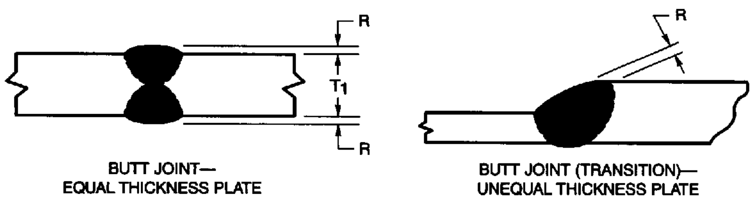
**(B) ACCEPTABLE FILLET WELD PROFILES**

NOTE: CONVEXITY, C, OF A WELD OR INDIVIDUAL SURFACE BEAD WITH DIMENSION W SHALL NOT EXCEED THE VALUE OF THE FOLLOWING TABLE:

| WIDTH OF WELD FACE OR INDIVIDUAL SURFACE BEAD, W | MAX CONVEXITY, C |
|---|---|
| W ≤ 5/16 in. (8 mm) | 1/16 in. (2 mm) |
| W > 5/16 in. (8 mm) TO W < 1 in. (25 mm) | 1/8 in. (3 mm) |
| W ≥ 1 in. (25 mm) | 3/16 in. (5 mm) |

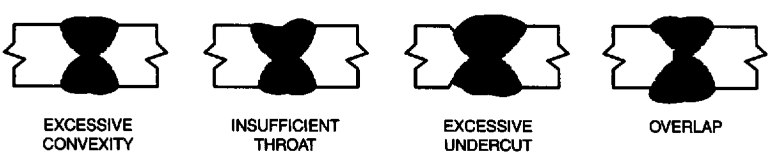



**(C) UNACCEPTABLE FILLET WELD PROFILES**




NOTE: REINFORCEMENT R SHALL NOT EXCEED 1/8 in. (3 mm). SEE 5.24.4.

**(D) ACCEPTABLE GROOVE WELD PROFILE IN BUTT JOINT**




**(E) UNACCEPTABLE GROOVE WELD PROFILES IN BUTT JOINTS**

**Figure 9.4—Acceptable and Unacceptable Weld Profiles per AWS D1.1**

intermediate pass of a multipass weld. It may be the cause for incomplete fusion or slag inclusions. Corrective action, by grinding or gouging should be performed prior to depositing the next weld layer.

**9.2.1.8 Concavity.** Concavity is the maximum distance from the face of a concave fillet weld perpendicular to a line joining the weld toes. A concave profile fillet weld size cannot correctly be measured by its leg size. If measured by its leg size and accepted as the design size, the weld throat will be less than that required by the design. Thus, the weld strength will be less than that intended by the design specification. Concave fillet welds should be inspected by using a fillet weld gauge capable of measuring the throat dimension.

The condition of concavity tends to occur primarily in the flat welding position or when welding pipe in the 5G and 6G positions. It is caused by employing excessive welding current or arc length in arc welding, or in downhill position welding.

**9.2.1.9 Weld Reinforcement.** This condition is weld metal in excess of the quantity required to fill a weld groove. Weld reinforcements may be located at either the weld face or root surface, and may therefore be more specifically referred to as either face reinforcement or root reinforcement, respectively. Excessive weld reinforcement is also undesirable. The problems associated with excessive reinforcement have been described in 9.2.1.7. This condition may result from improper welding technique or insufficient welding current.

**9.2.2 Weld/Structural Discontinuities.** During welding, a number of types of discontinuities may be developed within the weld. These include porosity, cracks, incomplete joint penetration, slag inclusions, etc. These types of discontinuities are described as weldment and structural-related discontinuities. The term is not used in the sense that there is a change in metallographic structure at these points, but rather that there is an interruption or a discontinuity in the soundness of the weld or its adjacent base material. Discontinuities of this nature are described in the paragraphs that follow.

**9.2.2.1 Incomplete Fusion.** This is a discontinuity in which fusion did not occur between the weld metal and the fusion faces or adjoining weld beads (see Figure 9.5). In other words, deposited weld metal did not fuse with the base metal or the weld metal did not fuse with previously deposited weld metal. Incomplete fusion may be caused by failure to raise the temperature of the base metal or previously deposited weld metal to the melting point. Incorrect welding techniques, improper preparation of the materials for welding, or incorrect joint designs promote incomplete fusion in welds. The welding conditions that principally contribute to incomplete fusion are insufficient welding current and lack of access to all faces of the weld joint that should be fused during welding. Insufficient preweld cleaning may contribute to incomplete fusion, even if the welding conditions and technique are adequate.

**9.2.2.2 Incomplete Joint Penetration.** Incomplete joint penetration is a joint root condition in a groove weld in which weld metal does not extend through the joint thickness. Figure 9.6 illustrates incomplete joint penetration. It may be caused by the failure of the root face or root edge of a groove weld to reach fusion temperature for its entire depth. This would leave a void that was caused by bridging of the weld metal from one member to the other.

Although incomplete joint penetration may, in a few cases, be due to failure to dissolve surface oxides and impurities, reduced heat transfer at the joint is a more common source of this discontinuity. If the areas of base metal that first reach fusion temperatures are above the root, molten metal may bridge these areas and insulate the arc from the base metal at the root of the joint. In arc welding, the arc will establish itself between the electrode and the nearest part of the base metal to the electrode. All other areas of the base metal will receive

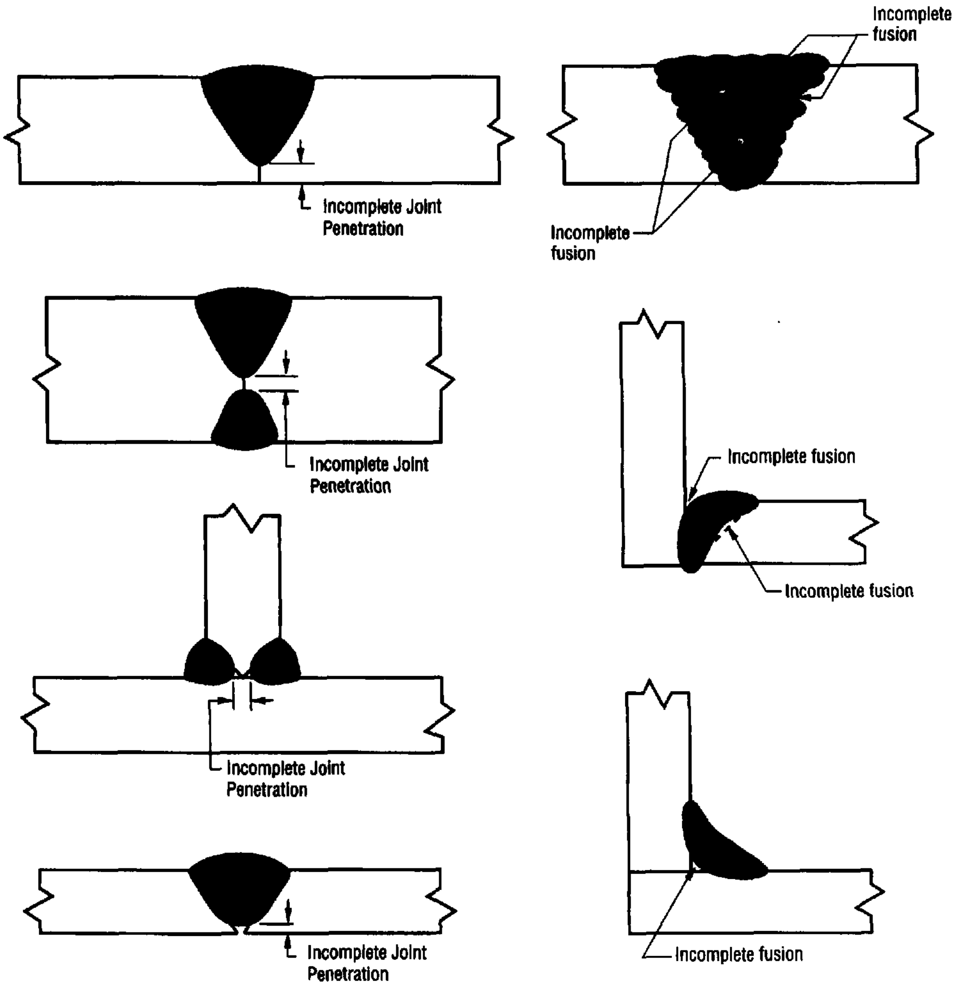



**Figure 9.5—Incomplete Joint Penetration and Incomplete Fusion**

heat principally by conduction. If the portion of the base metal closest to the electrode is a considerable distance from the root, conduction of heat may be insufficient to attain the fusion temperature at the root.

Incomplete joint penetration may be undesirable, particularly if the root of the weld is subject to either tension or bending stresses. The unfused area permits stress concentrations that could cause failure without appreciable deformation. Even though the service stresses in the structure may not involve tension or bending at this point, the shrinkage stresses and consequent distortion of the parts during welding will frequently cause a crack to initiate from the unfused area. Such cracks may progress, as successive beads are deposited, until they extend through or nearly through the entire thickness of the weld.

The most frequent cause of this type of discontinuity is the use of a groove design not suitable for the welding process or the conditions of actual construction. When a groove is welded from one side only, complete joint penetration is not likely to be obtained consistently under certain conditions. These conditions are: if the root face dimension is too great (even though the root opening is adequate), the root opening is too small, or the groove angle is too small. Any of these conditions will make it difficult to reproduce qualification test results under conditions of actual production. If, however, the design is known to be satisfactory, incomplete joint penetration may be caused by the use of electrodes that are too large, electrode types that have a tendency to bridge rather than to penetrate at an abnormally high rate of travel, or insufficient welding current.

**9.2.2.3 Undercut.** This term is used to describe either (1) the melting away of the sidewall of a welding groove at the edge of a layer or bead, thus forming a sharp recess in the sidewall in the area to which the next layer or bead should fuse, or (2) the reduction in base metal thickness at the junction of the weld reinforcement with the base metal surface (e.g., at the toe of the weld). See Figure 9.5.

Visible undercut is generally associated with either improper welding technique, such as excessive arc length, or welding current, or both. Undercut may also result where excessive travel speeds are used. Undercut discontinuities create a mechanical notch at the weld interface. If examined carefully, many welds have some degree of undercut. Often, the undercut may only be seen in metallographic examination where etched weld cross sections are evaluated under magnification. When undercut is controlled within the limits of the required specification and does not constitute a sharp or deep notch, it is not considered to be detrimental.

Undercut in the sidewalls of a multipass weld will not affect the completed weld if the condition is corrected before the next bead is deposited. Correction can be accomplished by grinding to allow access to the root of the undercut.

**9.2.2.4 Underfill.** This is associated with groove welds and is described as a depression on the weld face or root surface extending below the adjacent surface of base metal. *Underfill* is usually defined as a condition where the total thickness through a weld is less than the thickness of the adjacent base metal. It results from the failure of a welder or welding operator to completely fill the weld joint called for in the job specifications, as a result, the groove weld is undersize. It is rarely acceptable. Figure 9.6 illustrates the configurations of underfill.

**Figure 9.6—Underfill**

**9.2.2.5 Inclusions.** There are two basic types of inclusions related to welds, slag inclusions and tungsten inclusions.

(1) *Slag Inclusions.* During deposition of filler metal and subsequent solidification of weld metal, many chemical reactions occur between the weld metal and the electrode covering materials, forming slag compounds soluble only to a slight degree in the molten metal. Due to their lower specific gravity, slags rise to the surface of the molten metal unless they are restrained.

During welding with flux shielded processes, slag will be formed and forced below the surface of the molten metal by the stirring action of the arc. Slag may also flow ahead of the arc, allowing the metal to be deposited over it. Also, with some electrode types, slag in crevices of previously deposited weld metal will not remelt and will become trapped in that location. When slag is present in the molten metal from any cause, factors such as high viscosity of the weld metal, rapid solidification, or too low a temperature may prevent its release. Most slag inclusions can be prevented by proper preparation of the groove before each bead is deposited, using care to correct contours that are difficult to fully penetrate with the arc. The release of slag from the molten metal will be expedited by any factor that tends to make the metal less viscous or retard its solidification (such as high-heat input).

(2) *Tungsten Inclusions.* Tungsten inclusions are pieces of the electrode that have separated and become trapped in weld metal deposited with the gas tungsten arc welding process, and to a lesser degree, the plasma arc welding process. These inclusions may be trapped in a weld if the tungsten electrode is dipped into the molten weld metal, or if the welding current is too high and causes melting and transfer of tungsten droplets into the molten weld metal.

Tungsten inclusions appear as light areas on a radiograph because tungsten is more dense than the surrounding metal and absorbs larger amounts of x-rays or gamma radiation.

**9.2.2.6 Cracks.** Cracking of welded joints results from localized stresses that exceed the ultimate strength of the material. When cracks occur during or as a result of welding, little deformation is usually apparent. Figure 9.7 illustrates various types of cracks.

Cracks which occur during solidification are sometimes called *hot cracks. Cold cracks* are those that occur after the weld has cooled to ambient temperature, or once the weldment has been placed in service. Hot cracks will propagate along grain boundaries while cold cracks, sometimes associated with hydrogen embrittlement, will propagate both along grain boundaries and through grains.

It is known that materials having low ductility, when stressed in a single direction, may fail without appreciable deformation. However, when stresses on a material are multi-directional, failure can occur in a more brittle manner. Typically, shrinkage stresses from welding can result in the creation of these multi-directional stresses, especially in cases where welds having different orientations are connected. Because of such stresses, a joint [or any adjacent region such as the heat-affected zone (HAZ)] may be unable to withstand appreciable deformation without failure. In that case, additional stresses set up due to deposition of subsequent layers (or in the welding of adjacent joints) may force that part to deform and fail. An unfused area at the root of a weld may result in cracks without appreciable deformation if this area is subjected to tensile or bending stresses. When welding two members together, the root of the weld is subjected to tensile stress as successive layers are deposited, and, as already stated, a partially fused root will frequently permit a crack to start and progress through practically the entire thickness of the weld.

After a welded joint has cooled, cracking is more likely to occur if the metal is either excessively hard or brittle. A ductile material, by localized yielding, may withstand stress concentrations that might cause a hard or brittle material to fail.

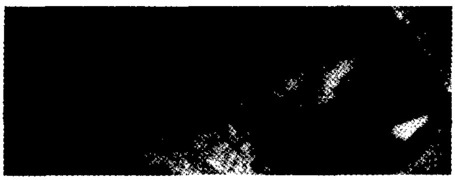
**9.2.2.7 Weld Metal Cracking.** The ability of the weld metal to remain intact under the stresses that are imposed during the welding operation depends upon the composition and structure of the weld metal. In multi-layer welds, cracking is most likely to occur in the first layer of the weld and, unless repaired, will often continue through other layers as they are deposited. When cracking of the weld metal is encountered, improvement may be obtained by one or more of the following modifications:

(1) Change the welding technique or welding parameters to improve the contour or composition of the deposit.

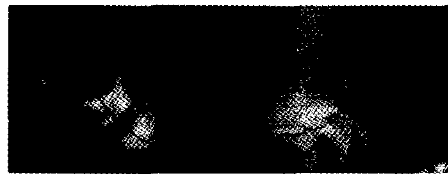
(2) Decrease the travel speed. This increases the thickness of the deposit and provides more weld metal to resist the stresses.

(A) Longitudinal Crack

(B) Transverse Cracks

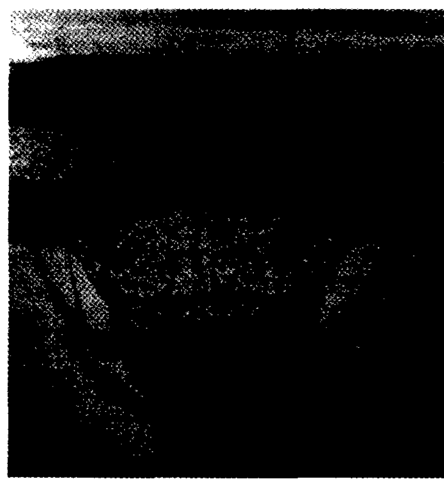


(C) Closeup of Crater Crack in Aluminum Weld



(D) Propagation of Crater Crack in Aluminum Weld

(E) Throat Crack in a Fillet Weld Root



(F) Toe Cracks

**Figure 9.7—Various Types of Cracks**

(3) Use preheat to reduce the cooling rate and to reduce thermal stresses.

(4) Use low-hydrogen electrodes.

(5) Sequence welds to balance shrinkage stresses.

(6) Avoid quenching and rapid cooling conditions.

(7) Maintain filler metals and other welding materials properly.

Three different types of cracks that can occur in weld metal are as follows:

(1) *Transverse Weld Cracks.* These cracks are perpendicular to the axis of the weld and, in some cases, extend beyond the weld into the base metal—see Figure 9.7(B). This type of crack is more common in joints that have a high degree of restraint in the weld axis direction. Use of low-ductility weld metal tends to promote transverse cracking.

(2) *Longitudinal Weld Cracks.* Longitudinal weld cracks are found mostly within the weld metal, and are usually confined to the center of the weld—see Figure 9.7(A). In fillet welds, longitudinal weld metal cracks are also referred to as throat cracks—see Figure 9.7(E). Such cracks may occur as the extension of crater cracks formed at the end of the weld. They may also be the extension, through successive layers, of a crack that started in the first layer. A crack formed in the first layer and not removed or completely remelted before the next layer is deposited tends to progress into the layer above, and thence each succeeding layer, until finally, it may appear at the surface. The final extension to the surface may occur during cooling after welding has been completed. Those joints exhibiting a high degree of restraint perpendicular to the weld axis are most prone to this type of weld metal cracking.

(3) *Crater Cracks.* Whenever the welding operation is interrupted, there is a tendency for a crack to form in the crater. These cracks are often star shaped and progress only to the edge of the crater—see Figure 9.7(C). However, these may be starting points for longitudinal weld cracks, particularly when they occur in the crater formed at the end of the weld—see Figure 9.7(D). This, however, is not always the case, and sometimes fine, star-shaped cracks are seen at various locations. Crater cracks are found most frequently in materials with high coefficients of thermal expansion, for example austenitic stainless steel. However, the occurrence of any such cracks can be minimized or even prevented by filling craters to a slightly convex shape prior to extinguishing the arc.

The above discussion on cracking is an attempt to give a rudimentary knowledge of what can cause cracking. However, such knowledge cannot always be applied, since many designs provide no other alternatives because of the thicknesses involved, design criteria, accessibility, etc.

**9.2.2.8 Base Metal Cracking.** This type of cracking occurs within the heat-affected zone of the metal being welded and is almost always associated with hardenable materials. High hardness and low ductility in the HAZ welded joints are metallurgical effects that result from the thermal cycle of welding and are among the principal factors that tend to cause cracking. While a complete metallurgical discussion is beyond the scope of this section, a rudimentary knowledge of the tendency of various groups of metals to harden or become brittle will be of value to the inspector.

In the case of low carbon, medium carbon, and low-alloy steels, hardness and the ability to deform without rupture depend upon the alloy group to which the steel belongs and also upon the rate of cooling from the elevated temperatures produced by the welding operation. The rate of cooling will obviously depend upon a number of physical factors such as the following:

(1) The temperatures produced by the welding

(2) The temperatures of the base metal

(3) The thickness and thermal conductivity of the base metal

(4) The heat input per unit time at a given section of the weld

(5) The ambient temperature

With a given cooling rate, the low-carbon steels will harden considerably less than the medium-carbon steels. Low-alloy steels exhibit a wider variation in their hardening characteristics; some of them may be similar to low-carbon steel, while others will react like medium-carbon steel.

High-alloy steels should be considered separately since this group includes the austenitic and ferritic stainless steels, as well as the martensitic steels. The latter behave similarly to the medium carbon and low-alloy groups, except that they harden to a greater degree with a given cooling rate. Neither the austenitic steels (of which the common 18% chromium-8% nickel stainless steel is an example) nor the ferritic stainless steels (of which the low carbon straight chromium steels containing 12% or more chromium are an example) harden upon quenching from elevated temperatures. However, in general, the ferritic stainless steels are rendered brittle (but not hard) by welding operations.

The metallurgical characteristics of the metals are of prime importance. Base metal cracking is associated with lack of ductility in the HAZ. Since ductility usually decreases with increasing hardness, cracking often occurs. This is not the complete answer, however, for it has been established that different heats of the same steel of equal hardenability vary appreciably in cracking tendency. Furthermore, recent information establishes beyond a doubt that in shielded metal arc welding the characteristics of the electrode as determined by its covering have considerable effect upon the tendency toward HAZ cracking.

Hardenable steels are usually more difficult to weld for two reasons:

(1) Variations in microstructure of the HAZ, which can occur with variations in the cooling rate, cause differences in mechanical properties.

(2) Due to the hardenability of the steel, a reduction in ductility occurs.

When base metal cracking is encountered with hardenable steels, the condition can be improved in the following ways.

(1) Use of preheat to control cooling rate

(2) Use of controlled heat input

(3) Use of the correct filler metal

While this subject has been treated in a general manner, each case usually involves conditions peculiar to the particular weldment in question. However, the four types of base metal cracking that can occur as a result of the welding operation are as follows:

(1) *Transverse Base Metal Cracks.* This type of cracking is oriented perpendicular to the axis of welding and usually associated with welds on steels of high hardenability. Such cracks usually cannot be detected until the weldment has cooled to room temperature.

(2) *Longitudinal Base Metal Cracks.* These cracks lie parallel to the weld and are in the base metal. They may be extensions of weld interface cracks. Longitudinal base metal cracks may be divided into three types: toe cracks, root cracks, and underbead cracks.

(a) *Toe Cracks.* Toe cracks are generally cold cracks that initiate approximately normal to the base material surface and then propagate from the toe of the weld where residual stresses are high, and the weld profile produces a stress concentration—see Figure 9.7(F). These cracks are generally the result of thermal shrinkage strains acting on a weld HAZ. Toe cracks sometimes occur when the base metal cannot accommodate the shrinkage strains that are imposed by welding.

(b) *Root Cracks.* Root cracks are longitudinal cracks which might progress into the base metal.

(c) *Underbead Cracks.* Underbead cracks are cold cracks that form in the HAZ. They are also called delayed cracks since they may not appear until several hours after the weldment has cooled to room temperature. They may be short and discontinuous, but may also extend to form a continuous crack. Underbead cracking can occur in steels when three elements are present:

— Hydrogen in solid solution

— A crack susceptible microstructure

— High residual stress

When present, these cracks are usually found at regular intervals under the weld metal and do not normally extend to the surface.

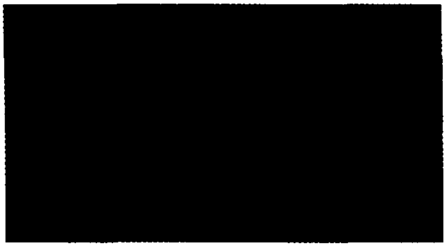
**9.2.2.9 Porosity.** Porosity, as shown in Figure 9.8, is the result of gas being entrapped in solidifying weld metal. The discontinuity is generally spherical, but may be elongated.

Porosity results when contaminants or moisture become included in the weld puddle. Sources of these impurities include: the base metal surface, the filler metal surface, welding fluxes, welding gases, and welding equipment (cooling systems, drive rolls, etc.) Porosity differs from inclusions in that porosity contains a gas rather than a solid substance and generally are spherical in shape.

The formation of porosity can be avoided by maintaining cleanliness for welding, by providing protection barriers in preventing

**(A) Uniformly Scattered Surface Porosity**

**(B) Aligned Surface Porosity with Connecting Crack**



**(C) Isolated Surface Porosity**

**(D) Elongated Surface Porosity**

**Figure 9.8—Porosity**

the loss of gas shielding, and by keeping the equipment maintained. During welding, excessive current and excessive arc length should be avoided. Either of these may result in excessive loss of deoxidizer elements as they transfer across the arc, leading to incomplete deoxidation within the molten weld pool and subsequently porosity.

Porosity may be subdivided into four types: scattered, cluster, linear, and piping.

(1) *Scattered Porosity.* Scattered porosity, as shown in Figure 9.8(A), is widely distributed in a single weld bead or in several beads of a multipass weld. Whenever scattered porosity is encountered, the cause is generally faulty welding technique or contaminated materials or both.

(2) *Cluster Porosity.* Cluster porosity is a localized grouping of pores occurring in clusters separated by considerable lengths of porosity-free weld metal. Cluster porosity may result from improper initiation or termination of the welding arc.

(3) *Aligned Porosity.* Aligned porosity is a localized array of porosity oriented in a line—see Figure 9.8(B). It often occurs along the weld interface, the weld root, or an interbead boundary and develops by contamination that causes gas to be liberated at these locations.

(4) *Piping Porosity.* Piping porosity has length greater than its width, and lies approximately perpendicular to the weld face. In fillet welds it extends from the root toward the weld face. When a few pores are seen in the weld face, careful excavation will often show that there are many subsurface pores that do not extend all the way to the weld face.

(5) *Elongated Porosity.* Elongated porosity has a length greater than its width, and lies approximately parallel to the weld axis. It is sometimes seen on the weld face where gases became trapped between the already solidified slag and the still-molten weld metal. This condition is sometimes called pock marks or worm tracks—see Figure 9.8(D). In pipeline welding of the root bead with cellulosic electrodes and excessive travel speed, the resulting porosity is called hollow bead.

**9.2.2.10 Surface Irregularities.** Perfectly acceptable welds will naturally exhibit some degree of surface roughness, however, improper technique or equipment adjustment can result in surface irregularities that exceed specification requirements. Unsatisfactory workmanship indicates that proper procedures are not being followed. Surface irregularities are not limited to, but generally grouped as weld ripples, spatter, and arc strikes.

(1) *Weld Ripples*. While depressions and variations in the weld surface are considered to be discontinuities, they may not affect the ability of the weld to perform its intended purpose. The applicable standard should describe the degree of surface irregularity permissible to prevent the presence of high-stress concentrations.

(2) *Spatter*. Spatter consists of metal particles expelled during fusion welding that do not form a part of the weld. Spatter particles that become attached to the base metal adjacent to the weld are the most detrimental to the product, but spatter propelled away from the weld and base metal is of concern because of its potential to inflict burns.

Normally, spatter is not considered to be a serious flaw unless its presence interferes with subsequent operations, especially nondestructive examinations or serviceability of the part.

(3) *Arc Strikes*. An arc strike is a discontinuity resulting from an arc consisting of any localized remelted metal, HAZ, or change in the surface profile of any metal object. Arc strikes result when the arc is initiated on the base metal surface away from the weld joint, either intentionally or accidentally. When this occurs, there is a localized area of the base metal surface which is melted and then rapidly cooled due to the massive heat sink created by the surrounding base metal. Arc strikes are not desirable and often are not acceptable, as they could lead to cracking and should be removed.

## 9.3 Metallurgical

**9.3.1 Mechanical Properties.** Metals not only offer many useful properties and characteristics in their mechanical behavior, but they can also develop a large number of combinations of those properties. The versatility of metals with respect to mechanical properties has encouraged the selection of the best combination of properties to facilitate fabrication and to ensure good service performance. Some applications require considerable thought about base and filler metal selection and treatment, particularly where fabricating properties differ from the required service properties.

Mechanical properties that should be checked against prescribed requirements include tensile strength, yield strength, ductility, hardness and impact strength. Also, chemical properties may be deficient because of incorrect weld metal composition or unsatisfactory corrosion resistance; where required, these can be checked against the welding procedure specification.

**9.3.2 Base Metal Properties.** It should be pointed out that not all discontinuities are due to improper welding conditions. Many such discontinuities may be attributed to the base metal. Base metal requirements are defined by applicable specifications or codes. Departure from these requirements should be considered cause for rejection.

**9.3.2.1 Tensile Strength.** When material has reached its highest tensile load it can sustain before rupturing, it is said to have reached its ultimate tensile strength, which is the value regularly listed for the strength of material.

Tensile strength values obtained for metals are influenced by many factors. Tensile strength is dependent upon chemistry, microstructure, grain size and other factors.

**9.3.2.2 Yield Strength.** The yield point of material is the load at which deformation increases without any additional increase of the applied load. Once the yield strength has been exceeded, the material exhibits permanent deformation, and will never return to its original size and shape. Certain metals, such as low-carbon steel, exhibit a yield point which is the stress just above the elastic limit. The elastic limit is the upper limit of stress where the material will return to its original dimensions when the load is released.

Engineers and designers are most often concerned with yield strength when selecting materials for construction. The allowable stresses defined by most codes are calculated as a percentage of the yield strength, depending upon the desired safety factor, the type of applied stress, and the operating temperature of the material.

**9.3.2.3 Chemistry.** The chemical composition of base metals and filler metals determines a material's relative weldability. A base metal's chemical composition also affect its hardness, ductility, tensile strength and corrosion resistance. Low carbon and medium carbon steels (up to 0.4%) are considered to have good weldability. The higher the carbon content, the more hardenable the material and hence the more difficult to weld. High-carbon (more than 0.4%) steels may require preheat, interpass temperature control, and strict attention to the welding procedure.

Elements such as excess sulfur might lead to cracking or a reduction in its corrosion resistance. For these reasons, chemical elements should be verified between the material test report and the material specification, which are established by several codes.

**9.3.2.4 Corrosion Resistance.** The corrosion properties of a metal determine its mode and rate of deterioration by chemical or electrochemical reaction with the surrounding environment. Metals and alloys differ greatly in their corrosion resistance. Corrosion resistance often is an important consideration in planning and fabricating a weldment for a particular service. Therefore, a designer should know something about the behavior of weld joints under corrosive conditions.

Many times, weld joints display corrosion properties that differ from the remainder of the weldment. These differences may be observed between the weld metal and the base metal, and sometimes between the HAZ and the unaffected base metal. Even the surface effects produced by welding, like heat tint formation or oxidation, fluxing action of slag, and moisture absorption by slag particles, can be important factors in the corrosion behavior of the weld metal. These considerations are particularly important in the design and fabrication of weldments of unpainted weathering steels, including the selection of filler metals.

Welds made between dissimilar metals or with a dissimilar filler metal may be subject to electrochemical corrosion.

## 9.4 Base Metal

It should be pointed out that not all discontinuities are due to improper welding conditions. Many such discontinuities may be attributed to the base metal. Base metal requirements are defined by applicable specifications or codes. Departure from these requirements should be considered cause for rejection.

Base metal properties that may not meet prescribed requirements include chemical composition, cleanliness, lamination/delamination, mechanical properties, seams and laps. The inspector should keep factors such as these in mind when trying to determine the reason for welding discontinuities that have no apparent cause (see Figure 9.9).

**9.4.1 Laminations.** Laminations may exist in any rolled product to some degree. Laminations normally occur near the center of the thickness of plate or pipe materials and tend to be parallel to the surface. They are usually caused by inclusions or blow holes in the original ingot. During rolling, these discontinuities become elongated and appear as flat, longitudinal stringers of nonmetallics.

**9.4.2 Delamination.** Delamination is the separation of lamination under stress. The stresses may be generated by welding or by externally applied loads. Both lamination or delamination, if extended to the edges of the material, may be detected by visual, magnetic particle, or liquid penetrant examination. If lamination or delamination is a concern, ultrasonic testing should be conducted utilizing the straight beam method to assure material integrity.

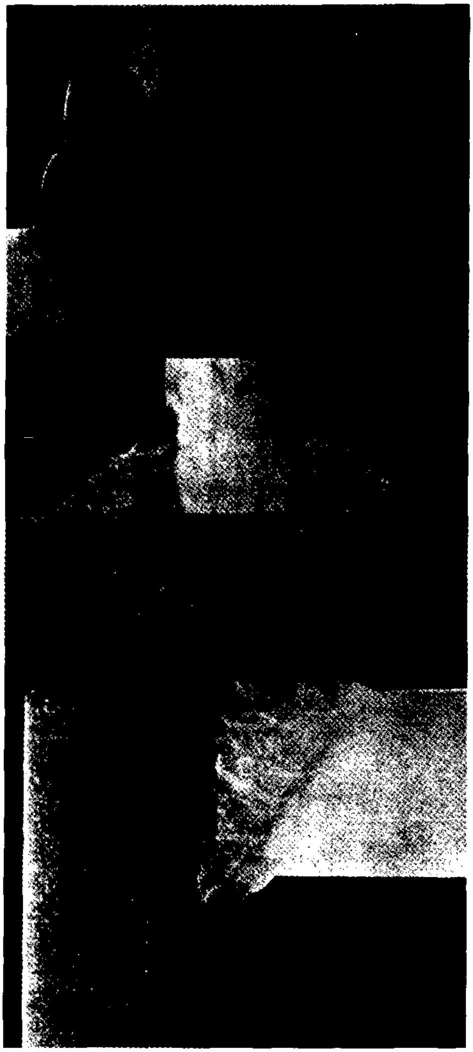


Figure 9.9—Lamellar Tearing

**9.4.3 Lamellar Tearing.** Some rolled structural materials are susceptible to a cracking defect known as *lamellar tearing*. This crack has a characteristic morphology, which is step-like in nature—see Figure 9.9. The most commonly accepted theory is that when restraint stresses and thermal strains imposed by welding exceed the strength of the material in the through-thickness direction, the stress concentration at nonmetallic inclusions (common to most structural materials) initiates cracks. The cracks initiate by decohesion of the inclusion-metal interface and propagate by ductile rupture to the next inclusion in that plane or by localized shear fracture to an inclusion which is in a slightly different plane.

**9.4.4 Seams and Laps.** Seams and laps are longitudinal base-metal discontinuities sometimes found in forged and rolled products. They differ from laminations in that they propagate to the rolled surface even though they may run in a lamellar direction (parallel to the rolled surfaces) for some portion of their length. When one of these discontinuities lies parallel to the principal stress, it is not generally considered to be a critical flaw. However, when seams and laps are perpendicular to the applied or residual stresses, they will often propagate as cracks. Seams and laps are surface-connected discontinuities. However, their presence may be masked by manufacturing processes that have subsequently modified the surface of the mill product. Welding over seams and laps can cause cracking and should be avoided.

# Chapter 10
# Qualification of Welding Procedure Specifications

There are numerous welding process variables that should be described in a welding procedure. It is always desirable and often essential that the variables associated with the welding be described in a welding procedure with sufficient detail to permit reproduction of the weld and to afford a clear understanding of the parameters for performing the production weld. These variables are stipulated in two different documents:

(1) *Welding Procedure Specifications (WPSs)*—Detailed methods and practices involved in the production of a weldment.[3]

(2) *Procedure Qualification Records (PQRs)*—A record of actual welding variables used to produce an acceptable test weldment and the results of the tests conducted on the weldment. This document qualifies the WPS.[7]

Generally, proposed welding procedures should be proven adequate by either procedure qualification tests or by sufficient prior use and service experience to assure dependability. The purpose of a welding procedure specification is, therefore, to define those details that are to be carried out in welding specific materials or parts. To fulfill this purpose effectively, a welding procedure specification should be as concise and clear as possible; it is a recipe for welding.

## 10.1 Description and Important Details

Industry today uses two common types of welding procedure specifications. One is a broad, general type that applies to all welding processes of a given kind on a specific material. The other is a narrower, more definitive type that spells out in detail the welding of a single size and type of joint in a specific material or part.

The narrower, more definitive type is most frequently used by manufacturers for their own control of repetitive in-plant welding operations or by purchasers desiring certain specific metallurgical, chemical, or mechanical properties. However, either type may be required by a customer or agency, depending upon the nature of the welding involved and the judgment of those in charge. In addition, the two types are sometimes combined in varying degrees, with addenda to show the exact details for specific joints attached to the general specification.

Arrangement and details of the welding procedure specifications as written should be in accordance with the contract or purchase requirements and good industry practice. The procedure should be sufficiently detailed to ensure welding that will satisfy the requirements of the applicable code, purchase specifications, or both.

Welding procedure specifications are sometimes required by the purchaser to govern fabrication of a given product in a fabricator's shop. Most often, however, the purchaser will simply specify the properties desired in the weldment in accordance with a code or specification, leaving the fabricator to use a welding procedure that will produce the specified results. In other cases, the purchaser will prescribe that the fabricator establish definite welding procedure specifications and test them to prove that the resulting welds will meet requirements specified by the purchaser.

3. WPS and PQR documents are available from American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

The fabricator is then required to use these procedures during production.

The following paragraphs list the details usually covered in welding procedure specifications.

**10.1.1 Scope.** The welding process(es), the material, and the governing specifications should be clearly stated.

**10.1.2 Base Metals and Applicable Specifications.** Base metals should be specified. This may be done either by giving the chemical composition and mechanical properties or by referring to the applicable material specifications. In addition, if the base metal requires special care before welding, this also should be indicated (i.e., normalized, annealed, quenched and tempered, solution treated, cold worked, etc.). The thickness of the base metal has an effect on the cooling rate from welding temperatures, and therefore, should be specified. Usually a range is specified (i.e., 1/4 in.–1 in.).

In some cases, these factors are very important. A welding procedure that will provide excellent results with one material might not provide the same results with another, or even with the same material that has been processed differently. Thus, the fabricator should identify material.

**10.1.3 Welding Processes.** The welding process(es) that is (are) to be used should be clearly defined. Most specifications consider the welding process an essential variable, and require requalification if the process is changed.

**10.1.4 Type, Classification, Composition, and Storage of Filler Metals.** Chemical composition, specification, or classification of the filler metal should always be specified. In addition, sizes of filler metal or electrodes that can be used when welding different thicknesses of material in the different positions should be designated. Filler metal marking is usually sufficient for identification. For some applications, additional details are specified. These may include manufacturer, type, heat, lot, or batch of welding consumables.

Certain types of filler metals and fluxes require special conditions during storage and handling. For example, low-hydrogen electrodes should be stored at elevated temperature to maintain the moisture content at a low level. The welding procedure can state these requirements.

**10.1.5 Type of Current and Current Range.** Whenever welding involves the use of electric current, the type of current to be used should be specified. Some electrodes work better on alternating current (ac) than direct current (dc). If dc is specified, the polarity should be specified, since most electrodes operate better on a certain polarity. In addition, the current ranges for the different sizes of electrodes for different positions and for welding various thicknesses of material should be specified.

**10.1.6 Arc Voltage and Travel Speed.** For all arc welding processes, it is common practice to list voltage ranges. Ranges for travel speed are sometimes mandatory for automatic welding processes and are desirable many times for semiautomatic processes. Also, when welding some steels where heat input is an important consideration, it becomes imperative that the permissible limits for travel speed be specified.

**10.1.7 Joint Designs and Tolerances.** Permissible joint design details should be indicated, as well as the designated sequence for welding. This may be done by means of cross-sectional sketches showing the thickness of material and details of the joint or by referring to standard drawings or specifications. Tolerances should be indicated for all dimensions. These tolerances are important, since, for example, increasing the root opening may create a condition wherein even the most expert welder may not be able to produce a satisfactory weld.

**10.1.8 Joint Preparation and Cleaning of Surfaces for Welding.** The methods that may be used to prepare joints, as well as the degree of surface cleaning and surface roughness required, should be designated in the procedure specification. This may include oxygen cutting, air carbon arc, or plasma cutting (with or without post-cleaning). It may also involve machining or grinding followed by vapor, ultrasonic, dip, or lint-free cloth cleaning with any of a variety of special cleaners. The cleaning methods and practices specified for the production work should be used when qualifying the welding procedure. This includes the use of weld spatter-resisting compounds on the surfaces.

**10.1.9 Tack Welding.** Whenever the tack welding practices could affect the end results, details concerning just what is to be done in connection with tack welds should be included in the welding procedure specification.

**10.1.10 Joint Welding Details.** All details that influence weld quality, in terms of the specification requirements, should be clearly outlined. Details often include the sizes of electrodes for the different portions of the joints and the different positions, the arrangement of weld passes for filling the joints, pass width or electrode weave limitations, current ranges, and whatever other details are important. These details help determine the soundness of the welds and influence the properties of the finished joint.

**10.1.11 Positions of Welding.** A procedure specification should always designate the position(s) in which the welding is to be (or may be) performed.

**10.1.12 Preheat and Interpass Temperatures.** Whenever preheat or interpass temperatures are significant factors in the production of sound welds, or influence the properties of weld joints, the temperature limits should be specified. With heat-treated alloy steels, the preheat and interpass temperatures should be kept within a well-defined specified range to avoid degradation of the base-metal heat-affected zone.

Preheat and interpass temperatures are generally determined by touching the workpiece close to the weld joint with temperature indicating materials or mechanical thermometers. These materials melt at a specified temperature or indicate the temperature by the color of the mark. Contact pyrometers or temperature-indicating paints are also used.

When chemical temperature indicating materials are used on austenitic stainless steels, nickel alloys, and other materials, care should be taken to ensure that these materials do not contain elements that are detrimental (such as sulfur, zinc, lead, mercury, and chlorine).

**10.1.13 Heat Input.** Heat input during welding is usually important (for example, when welding heat-treated steels and alloys or whenever impact property testing is specified). Whenever heat input is of concern, it should be prescribed with the details for control outlined in the procedure specification.

**10.1.14 Root Preparation Prior to Welding From Second Side.** When joints are to be welded from both sides, the methods that are to be used (or may be used) to prepare the second side should be stated in the procedure specification. Specifying any necessary preparation is of primary importance in producing sound weld joints. These may include chipping, grinding, air carbon arc or oxyfuel gouging, or whatever is needed to prepare the root.

**10.1.15 Peening.** Indiscriminate use of peening should not be allowed. However, it is sometimes used to avoid cracking or to reduce distortion of the weldment. If peening is to be used, the details of its application and tooling should be covered in the procedure specifications.

**10.1.16 Removal of Weld Sections for Repair.** When repairs to welds are required, local section(s) or the complete weld may have to be removed. The methods to be used for removing welds or sections of welds for such repair may be designated in the welding procedure specification or in a separate procedure. Quite often, the metal removal methods are the same as those used for preparing the second side of joints for welding.

**10.1.17 Repair Welding.** Repairs to welds may be performed using the same procedure specified for the original weld or may require a separate procedure.

**10.1.18 Post Weld Heat Treatment.** When materials or structures require heat treatment after welding to develop required mechanical properties, dimensional stability, or corrosion resistance, such treatment should be stated in the welding procedure specification and be applied to all procedure qualification test welds. This may include a full description of the heat treatment in the actual welding procedure or in a separate fabrication document, such as a shopheat-treating procedure or a shop drawing.

**10.1.19 Summary of Important Welding Procedure Details.** Not all of the preceding applies to every process or application. The various items are listed only for illustration. Due to the diversity of welding methods and application requirements, many of the items could be of major consequence in one application and of minor influence if applicable at all in another. In considering or reviewing welding procedure specifications, inspectors should weigh these points accordingly.

The factors which are consider critical in a welding procedure are called *variables*. Some essential variables could effect the mechanical properties of a weldment and would require requalification of the welding procedure. Changes to other variables would require that the welding procedure be rewritten to recognize the change, but would not require requalification. The applicable code or specification should be consulted to determine which variables are essential.

## 10.2 Prequalified and Standard Welding Procedure Specifications (WPSs)

**10.2.1 Prequalified WPSs.** The AWS D1.1, *Structural Welding Code—Steel*, employs the concept of prequalified weld joints. By following a number of well-defined variables, the user of this code does not have to qualify the procedure. Instead, the values of the specific variables used are recorded. Qualification is required only if any of these variables are changed beyond their specified limits. Records of such procedures are maintained using the form shown in Figure 10.1, and the factors to be considered in qualification are listed in Table 10.1.

**10.2.2 Standard WPSs.** AWS publishes Standard Welding Procedure Specifications (SWPSs). These specifications are prepared by the Welding Procedures Committee of the Welding Research Council, and are balloted through the AWS standards development program as American national standards. Standard WPSs may be used on work covered by AWS D1.1, *Structural Welding Code—Steel*, the National Board Inspection Code, ASME *Boiler and Pressure Vessel Code*, and on other general fabrication work.

## 10.3 Qualification of Welding Procedure Specifications

The mechanical and metallurgical properties of a welded joint may be altered by the welding procedure specifications selected for the job. It is the responsibility of each manufacturer or contractor to conduct the proper weld metal tests required by the applicable codes and contractual documents. It is the duty of the engineer or inspector to review and evaluate the results of such qualifications. These qualification activities should be completed prior to any production welding to assure that the selected combination of materials and methods to be used is capable of achieving the desired results. This is accomplished by any of the following three alternatives or a combination thereof:

**10.3.1 Employment of Prequalified Welding Procedures.** This concept is based on the reliability of certain proven procedures spelled out by the applicable code or specification. Any deviation outside specified limits voids

**WELDING PROCEDURE SPECIFICATION (WPS) Yes ☐**
**PREQUALIFIED ________ QUALIFIED BY TESTING ________**
**or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☐**

Identification # ________
Revision ______ Date ________ By ________
Authorized by ________ Date ________
Type—Manual ☐ Semi-Automatic ☐
Machine ☐ Automatic ☐

Company Name ________
Welding Process(es) ________
Supporting PQR No.(s) ________

**JOINT DESIGN USED**
Type:
Single ☐ Double Weld ☐
Backing: Yes ☐ No ☐
Backing Material:
Root Opening ______ Root Face Dimension ______
Groove Angle: ______ Radius (J–U) ______
Back Gouging: Yes ☐ No ☐ Method ______

**BASE METALS**
Material Spec. ________
Type or Grade ________
Thickness: Groove ______ Fillet ______
Diameter (Pipe) ________

**FILLER METALS**
AWS Specification ________
AWS Classification ________

**SHIELDING**
Flux ________ Gas ________
Composition ________
Electrode-Flux (Class) ______ Flow Rate ______
________ Gas Cup Size ______

**PREHEAT**
Preheat Temp., Min ________
Interpass Temp., Min ______ Max ______

**POSITION**
Position of Groove: ______ Fillet: ______
Vertical Progression: Up ☐ Down ☐

**ELECTRICAL CHARACTERISTICS**
Transfer Mode (GMAW) Short-Circuiting ☐
Globular ☐ Spray ☐
Current: AC ☐ DCEP ☐ DCEN ☐ Pulsed ☐
Other ________
Tungsten Electrode (GTAW)
Size: ________
Type: ________

**TECHNIQUE**
Stringer or Weave Bead: ________
Multi-pass or Single Pass (per side) ________
Number of Electrodes ________
Electrode Spacing Longitudinal ________
Lateral ________
Angle ________

Contact Tube to Work Distance ________
Peening ________
Interpass Cleaning: ________

**POSTWELD HEAT TREATMENT**
Temp. ________
Time ________

**WELDING PROCEDURE**

| Pass or Weld Layer(s) | Process | Filler Metals | | Current | | Volts | Travel Speed | Joint Details |
|---|---|---|---|---|---|---|---|---|
| | | Class | Diam. | Type & Polarity | Amps or Wire Feed Speed | | | |
| | | | | | | | | |

Form E-1 (Front)

**Figure 10.1—AWS Structural Welding Code Prequalified Procedures**

**Procedure Qualification Record (PQR) # ________**
**Test Results**

TENSILE TEST

| Specimen No. | Width | Thickness | Area | Ultimate tensile load, lb | Ultimate unit stress, psi | Character of failure and location |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

GUIDED BEND TEST

| Specimen No. | Type of bend | Result | Remarks |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |

VISUAL INSPECTION
Appearance ____________
Undercut ____________
Piping porosity ____________
Convexity ____________
Test date ____________
Witnessed by ____________

Radiographic-ultrasonic examination
RT report no.: ________ Result ________
UT report no.: ________ Result ________

FILLET WELD TEST RESULTS
Minimum size multiple pass Macroetch
1. ______ 3. ______
2. ______

Maximum size single pass Macroetch
1. ______ 3. ______
2. ______

Other Tests

All-weld-metal tension test
Tensile strength, psi ____________
Yield point/strength, psi ____________
Elongation in 2 in., % ____________
Laboratory test no. ____________

Welder's name ____________ Clock no. ________ Stamp no. ________
Tests conducted by ____________ Laboratory
Test number ____________
Per ____________

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 4 of ANSI/AWS D1.1, (________) Structural Welding Code—Steel.
(year)

Signed ____________
Manufacturer or Contractor
By ____________
Title ____________
Date ____________

Form E-1 (Back)

**Figure 10.1 (Continued)—AWS Structural Welding Code Prequalified Procedures**

## Table 10.1
## Welding Procedure Specification and Welder Qualification Factors Which May Require Requalification

NOTE: This table is shown FOR ILLUSTRATION PURPOSES ONLY to indicate the general nature of code requirements governing requalification of welding procedures, welders, and operators. It cannot be used by an inspector to determine whether requalification is required in a specific instance. For that information reference should be made to the particular code or specification applicable to the work being inspected.

| | | |
|---|---|---|
| Procedure factor | Procedure requalification may be required when the welding practices are changed to the extent indicated below. | Welder or welding operator requalification may be required for the practice changes indicated below. |
| Type, composition, or process condition of the base material | When the base metal is changed to one not conforming to the type, specification, or process condition qualified. (Some codes and specifications provide lists of materials which are approximately equivalent from the standpoint of weldability and which may be substituted without requalification). | Usually not required, unless a marked change is made in the type of filler metal used or covering thereon, e.g., ferritic to austenitic or nonferrous metal; cellulosic to low-hydrogen type electrode covering, etc. |
| Thickness of base metal | When the thickness to be welded is outside the range qualified. (The various codes and specifications may differ considerably in this respect. Most provide for qualification on one thickness within a reasonable range; e.g., 3/16 in. to 2T, 1/2T to 2T, 1/2T to 1.1T, etc. Some may require qualification on the exact thickness or on the minimum and maximum). | When the thickness to be welded is outside the range qualified. |
| Joint design | When established limits of root openings, root face, and included angle of groove joints are increased or decreased; i.e., basic dimensions plus tolerances. (Some codes and specifications prescribe definite upper and lower limits for these dimensions, beyond which requalification is necessary. Other permit an increase in the included angle and root opening and a decrease in the root face without requalification. Also, requalification is often required when a backing or spacer strip is added or removed or the basic type of material of a backing or spacer strip is changed). | When changing from a double-welded joint or a joint using backing material to an open root or to a consumable insert joint. |
| Pipe diameter | Usually not required. In fact, some codes permit procedure qualification on plate to satisfy the requirements for welding to be performed on pipe. | When the diameter of piping or tubing is reduced below specified limits. (It is generally recognized that smaller pipe diameters require more sophisticated techniques, equipment, and skills). |

**Table 10.1 (Continued)**
**Welding Procedure Specification and Welder Qualification Factors Which May Require Requalification**

*(Continued)*

| | | |
|---|---|---|
| Type of current and polarity (if dc) | Usually not required for changes involving electrodes or welding materials adapted for the changed electrical characteristics, although sometimes required for change from ac to dc, or vice versa, or from one polarity to the other. | Usually not required for changes involving similar electrodes or welding materials adapted for the changed electrical characteristics. |
| Electrode classification and size | When electrode classification is changed or when the diameter is increased beyond that qualified. | When the electrode classification grouping is changed and sometimes when the electrode diameter is increased beyond specified limits. |
| Welding current | When the current is outside of the range qualified. | Usually not required. |
| Position of welding (For definitions, see Appendix A) | Usually not required, but desirable. | When the change exceeds the limits of the position(s) qualified is only required by some codes; others only when employing vertical-up position. |
| Deposition of weld metal. | When a marked change is made in the manner of weld deposition; e.g., from a small bead to a large bead or weave arrangement or from an annealing pass to a no annealing pass arrangement, or vice versa. | Usually not required. |
| Preparation of root of weld for second side welding | When method or extent is changed. | Usually not required. |
| Preheat and interpass temperatures | When the preheat or interpass temperature is outside the range for which qualified. | Usually not required. |
| Preheat treatment | When adding or deleting postheating or when the postheating temperature or time cycle is outside the range for which qualified. | Usually not required. |
| Use of spatter compound, paint, or other material on the surfaces to be welded. | Usually not required, but desirable when employing unproven materials. | Usually not required. |

prequalifications. It should be noted that only a few codes, such as AWS D1.1, recognize the concept of prequalified welding procedures.

**10.3.2 Employment of Standard Qualification Tests.** Such tests may or may not simulate the actual welding condition anticipated for a given project. Usually, such standard tests involve conventional butt joints on pipes or plates, or fillet welds between two plates. Base metals, welding consumables, and thermal treatments follow production welding plans within specific tolerances. Variables such as joint geometry, welding position, and accessibility are not considered essential by Section IX of the *ASME Boiler and Pressure Vessel Code.*[4] Thus, the variables used to qualify the welding procedure may bear little resemblance to production conditions and should be changed by revision of the welding procedure specification. Other documents, such as API 1104, *Standard for Welding Pipelines and Related Facilities*, require qualification tests that resemble production conditions closely.

**10.3.3 Employment of Mock-up Tests.** Such tests simulate actual production conditions to the extent necessary to ascertain that a sound plan with proper tooling and inspection has been selected. While few of the conventional welding codes and specifications mandate such mock-up qualifications, contractual documents or trouble-shooting activities may require such tests. Especially for the latter, a mock-up qualification is a valuable tool to demonstrate specific skill levels under difficult or otherwise restrictive welding conditions.

The controls used to ensure the production of satisfactory welds are (1) qualification of a welding procedure, (2) qualification of the welders and welding operators to determine their ability to deposit sound weld metal using the qualified procedure, (3) suitable supervision and monitoring of production welding, and (4) suitable inspection prior to, during, and following completion of welding. All four are vital elements in the quality production chain. Through these controls, it is possible to achieve, repeatedly, welds of suitable quality and known physical and chemical properties.

4. See Chapter 17 for addresses of standards development organizations.

## 10.4 Description

There are five basic steps in the qualification of a welding procedure:

(1) Preparation and welding of suitable samples

(2) Testing of representative specimens

(3) Evaluation of overall preparation, welding, testing, and end results

(4) Possible changes in procedure

(5) Approval

**10.4.1 Preparation of Procedure Qualification Test Joints.** Plate or pipe assemblies with a representative welded joint are used for procedure qualification testing. The size, type, and thickness are governed by the thickness and type of material to be welded in production and the type, size, and number of specimens to be removed for testing. The latter are usually prescribed by the applicable code or specification. The materials used and all details associated with the welding of the test joints should be in accordance with the particular welding procedure specification that is to be qualified.

Whether the procedure is qualified or prequalified, it has to address the essential, nonessential, and supplementary essential variables for that process which is to be qualified.

**10.4.2 Testing of Procedure Qualification Welds.** Test specimens are usually removed from the test joint for examination to determine strength, ductility, and soundness. The type and number of specimens removed and the tests made thereto depend upon the requirements of the particular code or specification. Typically, the tests include tensile and guided bend specimens to determine strength, ductility, soundness, and adequacy of fusion. If only fillet welds are tested, shear tests and break specimens or macroetch specimens are usually employed.

Additional tests may be specified by the applicable codes or contract documents to meet specific needs. These may include:

(1) Impact tests to determine notch toughness (resistance to brittle fracture) of the weld and the HAZ at specified temperatures. While Charpy-V-notch specimens are most commonly used for such tests, many other concepts, including drop weight and crack-tip-opening-displacement (CTOD) tests, are sometimes employed.

(2) Nick-break tests to determine weld soundness.

(3) Free Bend tests to determine the elongation of deposited weld metal, and weld ductility.

(4) Shear tests to determine the shear strength of fillet welds or clad bonding.

(5) Hardness tests to determine adequacy of heat treatment and suitability for certain service conditions. Such tests may be performed on surfaces or on cross sections of the weld.

(6) All-weld-metal tension tests to determine the mechanical properties of the deposited weld metal with minimum influence due to base metal dilution.

(7) Elevated temperature tests to determine mechanical properties at temperatures resembling service conditions.

(8) Restraints or "torture" tests to determine crack susceptibility and the ability to achieve sound welds under highly restrained conditions.

(9) Corrosion tests to determine the properties needed to withstand aggressive environments including high temperature, hydrogen, chlorides, etc.

(10) Nondestructive examinations and macro or micro samples to determine the soundness of a weld and to evaluate the inspectability of production welds.

(11) Delayed cracking tests to detect resistance to hydrogen cracking in HSLA (high strength, low-alloy) steels and some other materials.

Most of the detailed specimen preparation and testing procedures can be found in other chapters.

**10.4.3 Evaluation of Test Results.** Once a welding procedure has been prequalified or has been tested in accordance with the applicable code and contractual documents, the relevant data should be recorded in detail. Recommended forms are offered by some specifications and representative samples have been reproduced in the chapter. Figure 10.2 illustrates the Procedure Qualification Record suggested by AWS B2.1, while Figure 10.3 is a copy of the ASME Section IX Procedure Qualification Record (PQR).

In evaluating any welding procedure or any test results, the applicable codes provide general guidance and some specific acceptance-rejection criteria. For instance, the minimum tensile strength and the maximum number of inclusions or other discontinuities is specified by many documents. In general, it is best if the weld matches the mechanical and metallurgical properties of the base metal, but this is not always possible. In addition to the weld metal and base metal being different product forms, they often have somewhat different chemical compositions and mechanical properties. It requires engineering judgment to select the most important properties for each individual application. This is especially important for service at high or low temperature, and under corrosive conditions.

**10.4.4 Changes in a Qualified Procedure.** If a fabricator that has qualified a welding procedure desires at some later date to make a change in the procedure, it may be necessary to conduct additional qualifying tests. These tests establish that the revised welding procedure will produce satisfactory results.

Such requalification tests are not usually required when only minor details of the original procedure have been changed. They are required, however, if the changes might alter the properties of the resulting welds.

**Form A.7.2** **SUGGESTED PROCEDURE QUALIFICATION RECORD (PQR)** **Page 1 of 2**

WPS no. used for test ______ Welding process(es) ______
Company ______ Equipment type and model (sw) ______

**JOINT DESIGN USED (2.6.1)**

Single ( ) Double weld ( )
Backing material ______
Root opening ______ Root face dimension ______
Groove angle ______ Radius (J-U) ______
Back gouging: Yes ( ) No ( ) Method ______

**BASE METALS (2.6.2)**

Material spec. ______ To ______
Type or grade ______ To ______
Material no. ______ To material no. ______
Group no. ______ To group no. ______
Thickness ______
Diameter (pipe) ______
Surfacing: Material ______ Thickness ______
Chemical composition ______
Other ______

**FILLER METALS (2.6.3)**

Weld metal analysis A no. ______
Filler metal F no. ______
AWS specification ______
AWS classification ______
Flux class ______ Flux brand ______
Consumable insert: Spec. ______ Class. ______
Supplemental filler metal spec. ______ Class. ______
Non-classified filler metals ______
Consumable guide (ESW) Yes ( ) No ( )
Supplemental deoxidant (EBW) ______

**POSITION (2.6.4)**

Position of groove ______ Fillet ______
Vertical progression: Up ( ) Down ( )

**PREHEAT (2.6.5)**

Preheat temp., actual min ______
Interpass temp., actual max ______

**WELD INCREMENT SEQUENCE**

**POSTWELD HEAT TREAMTENT (2.6.6):**

Temp. ______
Time ______
Other ______

**GAS (2.6.7)**

Gas type(s) ______
Gas mixture percentage
Flow rate ______
Root shielding gas ______ Flow rate ______
EBW vacuum ( ) Absolute pressure ( )

**ELECTRICAL CHARACTERISTICS (2.6.8)**

Electrode extension ______
Standoff distance
Transfer mode (GMAW) ______
Electrode diameter tungsten ______
Type tungsten electrode ______
Current: AC ( ) DCEP ( ) DCEN ( ) Pulsed ( )
Heat input ______
EBW: beam focus current ______ Pulse freq. ______
Filament type ______ Shape ______ Size ______
Other ______

**TECHNIQUE (2.6.9)**

Oscillation frequency ______ Weave width ______
Dwell time ______
String or weave bead ______ Weave width ______
Multi-pass or single pass (per side) ______
Number of electrodes ______
Peening ______
Electrode spacing ______
Arc timing (SW) ______ Lift ( )
PAW: Conventional ( ) Key hole ( )
Interpass cleaning:

| Pass no. | Filler metal size | Amps | Volts | Travel speed (ipm) | Filler metal wire (ipm) | Slope induction | Special notes (process, etc.) |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

Note: Those items that are not applicable should be marked N.A.

**Figure 10.2—Standard for Welding Procedure Qualification**

**Form A.7.2** **Page 2 of 2**

**TENSILE TEST SPECIMENS: SUGGESTED PROCEDURE QUALIFICATION RECORD** PQR No.

Type: ____________ Tensile specimen size: ____________

Groove ( ) Reinforcing bar ( ) Stud welds ( )

Tensile test results: (Minimum required UTS ________ psi)

| Specimen no. | Width, in. | Thickness, in. | Area, in.$^2$ | Max load lbs | UTS, psi | Type failure and location |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

**GUIDED BEND TEST SPECIMENS - SPECIMEN SIZE:** ____________

| Type | Result | Type | Result |
|---|---|---|---|
| | | | |
| | | | |

**MACRO-EXAMINATION RESULTS:** Reinforcing bar ( ) Stud ( )

1. ________ 4. ________
2. ________ 5. ________
3. ________

**SHEAR TEST RESULTS - FILLETS:**

1. ________ 3. ________
2. ________ 4. ________

**IMPACT TEST SPECIMENS**

Type: ____________ Size: ____________

Test temperature: ____________

Specimen location: WM = weld metal; BM = base metal; HAZ = heat-affected zone

Test results:

| Welding position | Specimen location | Energy absorbed (ft.-lbs.) | Ductile fracture area (percent) | Lateral expansion (mils) |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**IF APPLICABLE** **RESULTS**

Hardness tests: ( ) Values ____________ Acceptable ( ) Unacceptable ( )

Visual (special weldments 2.4.2) ( ) Acceptable ( ) Unacceptable ( )

Torque ( ) psi Acceptable ( ) Unacceptable ( )

Proof test ( ) Method ____________ Acceptable ( ) Unacceptable ( )

Chemical analysis ( ) Acceptable ( ) Unacceptable ( )

Non-destructive exam ( ) Process ____________ Acceptable ( ) Unacceptable ( )

Other ____________ Acceptable ( ) Unacceptable ( )

Mechanical Testing by (Company) ____________ Lab No. ____________

We certify that the statements in this Record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of the American Welding Society Standard for Welding Procedure and Performance Qualification (AWS B2.1-84).

Qualifier: ____________

Date: ____________

**Figure 10.2 (Continued)—Standard for Welding Procedure Qualification**

0784265 0513871 975



**QW-483 SUGGESTED FORMAT FOR PROCEDURE QUALIFICATION RECORD (pqr)**
**(See QW-200.2, Section IX, ASME Boiler and Pressure Vessel Code)**
**Record Actual Conditions Used to Weld Test Coupon.**

Company Name ______
Procedure Qualification Record No. ______ Date ______
WPS No. ______
Welding Process(es) ______
Types (Manual, Automatic, Semi-Auto.) ______

JOINTS (QW-402)

Groove Design of Test Coupon

(For combination qualifications, the deposited weld metal thickness shall be recorded for each filler metal or process used.)

BASE METALS (QW-403)
Material Spec. ______
Type or Grade ______
P-No. ______ to P-No. ______
Thickness of Test Coupon ______
Diameter of Test Coupon ______
Other ______

FILLER METALS (QW-404)
SFA Specification ______
AWS Classification ______
Filler Metal F-No. ______
Weld Metal Analysis A-No. ______
Size of Filler Metal ______
Other ______
Weld Metal Thickness

POSITION (QW-405)
Position of Groove ______
Weld Progression (Uphill, Downhill) ______
Other ______

PREHEAT (QW-406)
Preheat Temp. ______
Interpass Temp. ______
Other ______

POSTWELD HEAT TREATMENT (QW-407)
Temperature ______
Time ______
Other ______

GAS (QW-408)

| | Gas(es) | Percent Composition (Mixture) | Flow Rate |
|---|---|---|---|
| Shielding | | | |
| Trailing | | | |
| Backing | | | |

ELECTRICAL CHARACTERISTICS (QW-409)
Current ______
Polarity ______
Amps ______ Volts ______
Tungsten Electrode Size ______
Other ______

TECHNIQUE (QW-410)
Travel speed ______
String or Weave Bead ______
Oscillation ______
Multipass or Single Pass (per side) ______
Single or Multiple Electrodes ______
Other ______

This form (E00007) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

(Source ASME B31.1, SEC IX)

**Figure 10.3—ASME Procedure Qualification Record**

## QW-483 (Back)

**Tensile Test (QW-150)** PQR No. ____________

| Specification No. | Width | Thickness | Area | Ultimate Total Load lb | Ultimate Unit Stress psi | Type of Failure & Location |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

**Guided-Bend Tests (QW-160)**

| Type and Figure No. | |
|---|---|
| | |
| | |
| | |
| | |

**Toughness Tests (QW-170)**

| Specimen | Notch | Notch | Test | Impact | Lateral Exp. | | Drop Weight | |
|---|---|---|---|---|---|---|---|---|
| No. | Location | Type | Temp. | Values | % Shear | Mils | Break | No Break |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

**Fillet-Weld Test (QW-180**

Result - Satisfactory: Yes ____________ No ____________ Penetration into Parent Metal: Yes ____________ No ____________

Macro - Results ____________

**Other Tests**

Type of Test ____________

Deposit Analysis ____________

Other ____________

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

Welder's Name ____________ Clock No. ____________ Stamp No. ____________

Tests Conducted by: ____________ Laboratory Test No. ____________

We certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of Section IX of the ASME Code.

Manufacturer ____________

Date ____________ By ____________

(Detail of record of tests are illustrative only and may be modified to conform to the type and number of tests required by the Code.)

(Source ASME B31.1, SEC IX)

**Figure 10.3 (Continued)—ASME Procedure Qualification Record**

Reference should always be made to the governing code or specification to determine whether a given change in the welding procedure requires requalification.

**10.4.5 Approval of Qualification Tests and Procedure Specifications.** Often welding procedures will be approved by the customer or the authorized inspection agency before any production welding is performed.

QW-483 Procedure Qualification Record (PQR) (see QW-201.2, Section IX, 1974 ASME Boiler and Pressure Vessel Code).

# Chapter 11
# Qualification of Welders and Welding Operators

Welder, welding operator, and tack welder performance qualification tests are used to demonstrate the ability of those tested to produce acceptably sound welds using a qualified Welding Procedure Specification (WPS). These tests are not intended to be used as a guide for welding during actual construction, but rather to assess whether an individual has a certain minimum skill level. The tests do not determine what an individual normally will or can do in production. For this reason, complete assurance should not be placed on performance qualification testing of individuals performing welding. The quality of production welds should be determined by inspection during and following completion of the actual welding.

Various codes (such as AWS D1.1, *Structural Welding Code—Steel*) and specifications generally prescribe methods or details for qualifying welders, welding operators, and tack welders. The applicable code or document should be consulted for specific details and requirements. A detailed description of a standard system for performance qualifications can be found in AWS B2.1, *Standard for Welding Procedure and Performance Qualification*.[5]

The types of performance qualification tests that are most frequently required are described in this chapter.

## 11.1 Performance Qualification Requirements

The qualification requirements for welding pressure vessels, piping systems, structures, and sheet metal usually state that every welder or welding operator shall make one or more test welds using a qualified welding procedure. Each qualification weld is tested in a specific manner (i.e., radiography or bend tests). In addition, essential variables that influence the welding are usually limited to certain ranges, such as the thickness of material and the test positions that will qualify for welding on different thicknesses and in different positions. Some variables pertinent to performance qualification testing and the extent of qualification are the groove type, whether or not the joint has backing, and the direction of welding in depositing weld metal.

Performance qualification requirements for welding pressure pipe differ from those for welding plate and structural members chiefly in the type of test assemblies used. Whether qualifying fillet welds or groove welds, consideration for test requirements should also be considered, for the qualification requirements may differ. The test positions may also differ to some extent. As a rule, the test requires use of pipe assemblies instead of flat plate. Accessibility restrictions may also be included as a qualification factor if the production work involves welding in restricted spaces.

**11.1.1 Essential Variables.** Since it is impractical to test a welder for all the possible variables to be met in production, most codes establish limitations or ranges within which these variables are assumed not to change the results. The variables cover such items as welding process, base metal type and thickness, filler metal, shielding medium, position, and root welding technique. The following are examples of essential variable changes which may require requalification of the welder:

5. AWS standards are available from American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

(1) *Welding Process.* For example, a change from gas tungsten arc welding (GTAW) to submerged arc welding (SAW).

(2) *Filler Metal.* Filler metals are divided into groups and assigned "F" numbers. The grouping of electrodes and welding rods is based essentially on the usability characteristics that fundamentally determine the ability of a welder to make satisfactory welds with a given electrode.

(3) *Welding position.* Positions are classified differently for plate and pipe. A change in position may require requalification. For example with pipe welding, a change from rotated to fixed position requires requalification.

(4) *Joint detail.* For example, the omission of backing on joints welded from one-side only may require requalification.

(5) *Thickness.* Test plates are generally tested at two or three thicknesses. To allow the welder to weld the production thicknesses required, it may be necessary to qualify on more than one test thickness.

(6) *Technique.* A change in the welding technique may also require a welder to requalify. For example, in vertical position welding a change in the direction of welding progression normally requires requalification. Where a combination of uphill and downhill progression is to be used in production, a welder may be qualified by a single test using the same combination as specified in production welding.

## 11.2 The Test Specimen

A typical qualification test plate from AWS D1.1, *Structural Welding Code—Steel,* for unlimited thickness is shown in Figure 11.1A. The plate is 1 in. (25.4 mm) thick with a 45° groove angle and a 1/4 in. (6.35 mm) root opening.

The groove weld plate for limited thickness (less than 3/4 in. [19.05 mm]) qualification is essentially the same as the plate shown in Figure 11.1A and B except for the thickness. The plate thickness is 3/8 in. (9.5 mm).

Joint detail for groove weld qualification tests for butt joints on pipe or square or rectangular tubing should be in accordance with a qualified welding procedure specification for a single welded pipe butt joint (see Figure 11.2A). As an alternative, the following joint details are frequently used: pipe diameter-wall thickness as required, single-V-groove weld, 60 degree groove angle, and suitable root opening with backing (see Figure 11.2B).

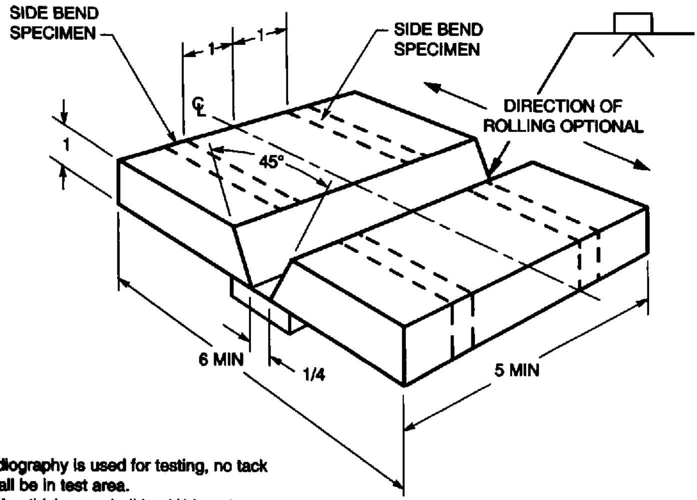
Codes and specifications nearly always require that welder qualification tests be made in one or more of the most difficult positions to be encountered in production (e.g., vertical, horizontal, or overhead) if the production work involves other than flat position welding. In most cases, qualification in a more difficult position qualifies for welding in less difficult positions (e.g., qualification in the vertical, horizontal, or overhead position is usually considered adequate for welding in the flat position). Figures 11.3A and B illustrate the ranges of positions designated for production groove and fillet welds, respectively.

Figures 11.4 through 11.7 illustrate welding positions for groove and fillet welds in test samples for both plate and tubular shapes.

## 11.3 Testing of Qualification Welds

All codes and specifications have definite rules for testing qualification welds to determine compliance with requirements. The tests most frequently required for groove welds are mechanical bend tests of which specimens are removed from specific locations in the welds. Fillet welds do not readily lend themselves to mechanical bend tests. In such cases, fillet weld break tests or macroetch tests, or both, may be required. For a description of these tests, see Chapter 13.

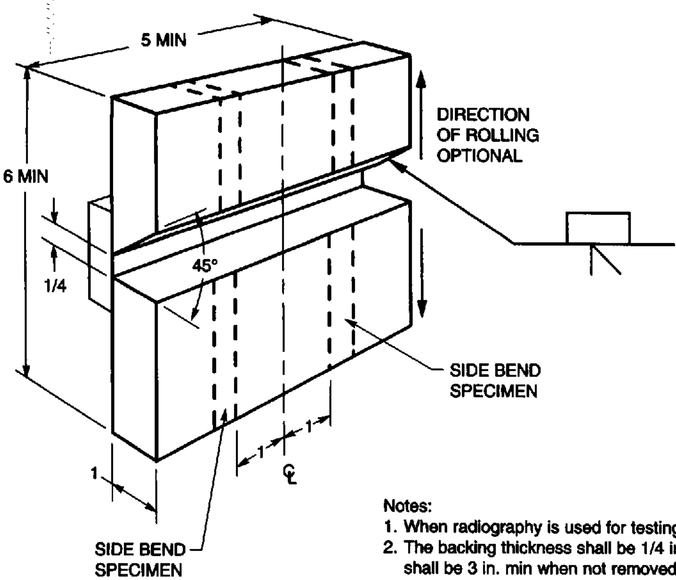
Radiographic testing is sometimes allowed as an alternative to mechanical or other tests. Penetrant examination is frequently required on welds, especially those in nonferrous and other nonmagnetic materials. Some codes have requirements and acceptance standards for visual examination or workmanship standards in addition to destructive testing and other nondestructive examinations.




| in. | mm |
|---|---|
| 1/4 | 6 |
| 3/8 | 10 |
| 1 | 25 |
| 3 | 75 |
| 5 | 125 |
| 6 | 150 |

Notes:
1. When radiography is used for testing, no tack welds shall be in test area.
2. The backing thickness shall be 1/4 in. min to 3/8 in. max; backing width shall be 3 in. min when not removed for radiography, otherwise 1 in. min.

**Figure 11.1A—Test Plate for Unlimited Thickness—Welder Qualification**




| in. | mm |
|---|---|
| 1/4 | 6 |
| 3/8 | 10 |
| 1 | 25 |
| 3 | 75 |
| 5 | 125 |
| 6 | 150 |

Notes:
1. When radiography is used for testing, no tack welds shall be in test area.
2. The backing thickness shall be 1/4 in. min to 3/8 in. max; backing width shall be 3 in. min when not removed for radiography, otherwise 1 in. min.

**Figure 11.1B—Optional Test Plate for Unlimited Thickness—Horizontal Position—Welder Qualification**

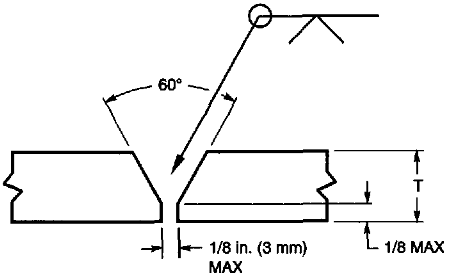



**Figure 11.2A—Tubular Butt Joint—Welder Qualification—Without Backing**

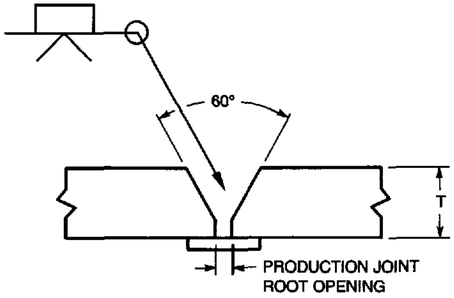



**Figure 11.2B—Tubular Butt Joint—Welder Qualification—With Backing**

Usually, the primary requirement is that the test welds be sound and thoroughly fused to the base metal. Welders who make test welds that meet the prescribed requirements are considered to be qualified to apply the process and weld with filler metals and procedures similar to those used in testing.

## 11.4 Qualification Records

Records of both the tests made for the qualification of welders and welding operators and of their usage of the process for which they were qualified are essential. An illustrative record form for welder or welding operator qualification testing is shown in Figure 11.8.

## 11.5 Standardization of Tests

The objective of welder and welding operator qualification tests is to determine whether the person has the ability to deposit sound weld metal. Examination of test specimens helps to determine this. However, the test specimen welds required for performance qualification tests do not always correspond in detail to those that will be encountered in production welding. The reason for this is that many variations exist in normal production welding, and to cover all the details would require far too many tests. In addition, it has been found that additional tests add little to the information about the welder's or welding operator's ability. For this reason, welder or welding operator qualification tests have been standardized to eliminate the need for additional qualification tests every time a procedure or production application detail is slightly altered.

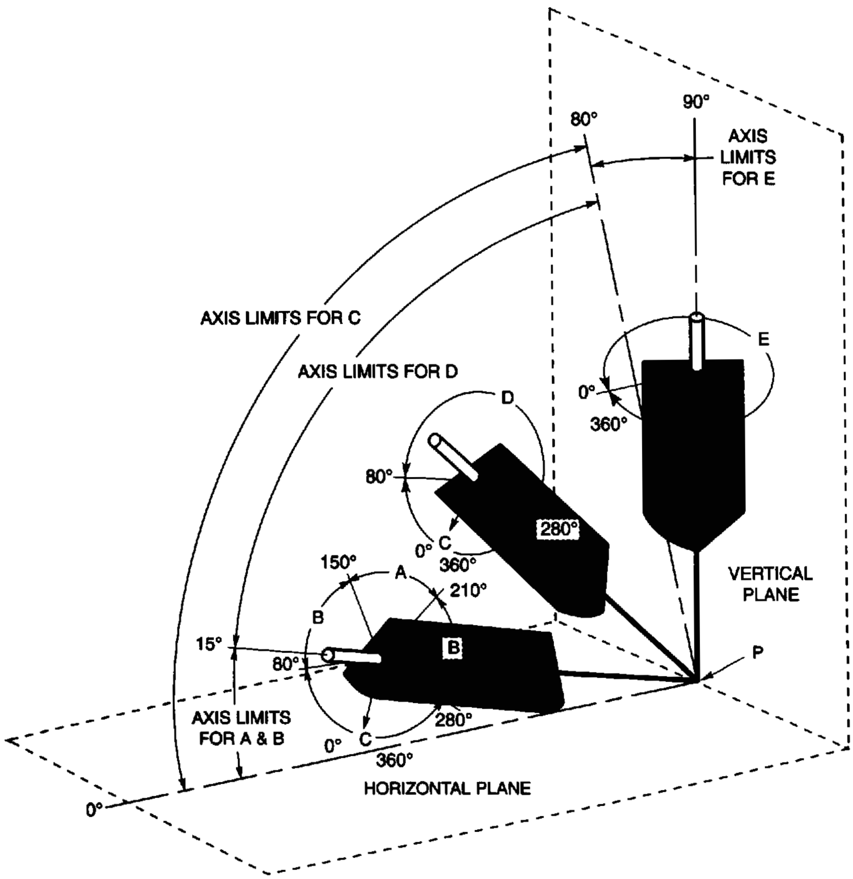
Separate requalification tests are required whenever radically different procedures or production conditions are involved. In addition, for some critical production welding applications, in-process performance tests are sometimes required.

## 11.6 Relation of Qualification Tests to Welder or Welding Operator Training

As previously noted, the welds required for qualification are not usually identical to those a welder or welding operator will be required to make during normal production work. For this reason, it is not enough to train a welder or welding operator only to the extent necessary to pass the prescribed qualification tests. Training should be broader and more extensive, sufficient to cover all procedures and joint details that will be encountered in actual production. This training is the responsibility of the fabricator.

**11.6.1 Welding Certification.** Written verification that a welder has produced welds meeting a prescribed standard of welder performance.

**11.6.2 Welder Performance Qualification.** The demonstration of a welder's ability to produce welds meeting prescribed standards.

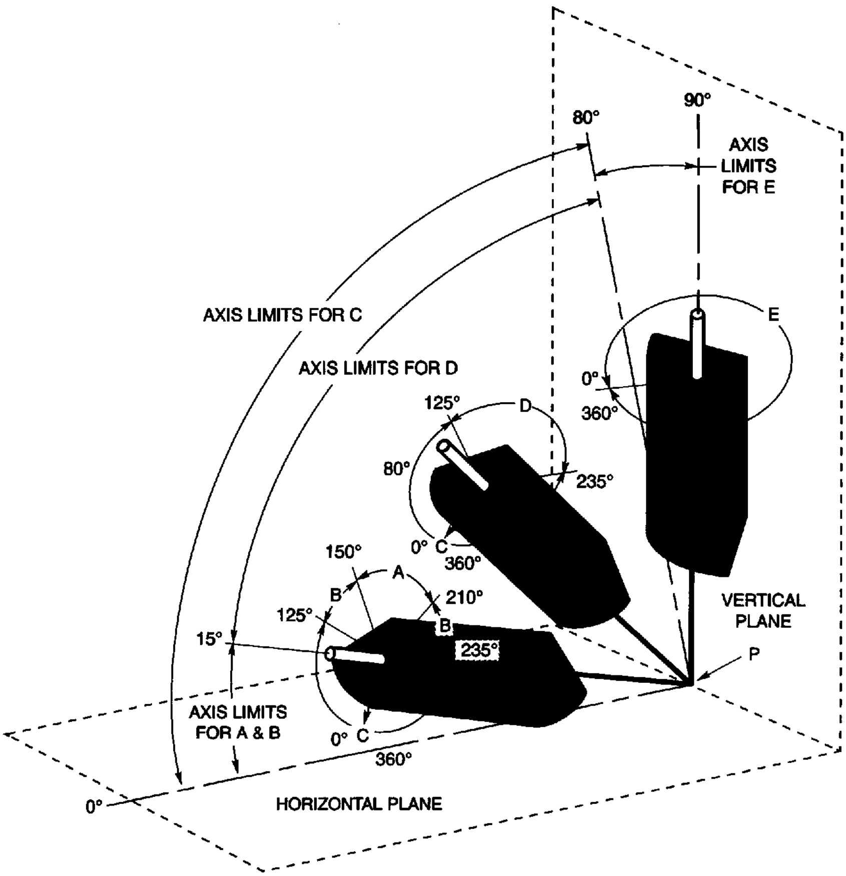



| Tabulation of positions of groove welds | | | |
|---|---|---|---|
| Position | Diagram reference | Inclination of axis | Rotation of face |
| Flat | A | 0° to 15° | 150° to 210° |
| Horizontal | B | 0° to 15° | 80° to 150°<br>210° to 360° |
| Overhead | C | 0° to 80° | 0° to 80°<br>280° to 360° |
| Vertical | D | 15° to 80°<br>80° to 90° | 80° to 280°<br>0° to 360° |

Notes:

1. The horizontal reference plane is always taken to lie below the weld under construction.
2. The inclination of the weld axis is measured from the horizontal reference plane toward the vertical reference point.
3. The axis of rotation of the weld face is determined by a line perpendicular to the weld face at its center which passes through the weld axis. The reference position (0 degrees) or rotation of the weld face invariably points in the direction opposite to that in which the weld axis angle increases. When looking at point "P," the angle of rotation of the weld face is measured in a clockwise direction from the reference position (0 degrees).

**Figure 11.3A—Positions of Groove Welds**




| Tabulation of positions of fillet welds | | | |
|---|---|---|---|
| Position | Diagram reference | Inclination of axis | Rotation of face |
| Flat | A | 0° to 15° | 150° to 210° |
| Horizontal | B | 0° to 15° | 125° to 150°<br>210° to 235° |
| Overhead | C | 0° to 80° | 0° to 125°<br>235° to 360° |
| Vertical | D<br>E | 15° to 80°<br>80° to 90° | 125° to 235°<br>0° to 360° |

Notes:

1. The horizontal reference plane is always taken to lie below the weld under construction.
2. The inclination of the weld axis is measured from the horizontal reference plane toward the vertical reference point.
3. The axis of rotation of the weld face is determined by a line perpendicular to the weld face at its center which passes through the weld axis. The reference position (0 degrees) or rotation of the weld face invariably points in the direction opposite to that in which the weld axis angle increases. When looking at point "P," the angle of rotation of the weld face is measured in a clockwise direction from the reference position (0 degrees).

**Figure 11.3B—Positions of Fillet Welds**

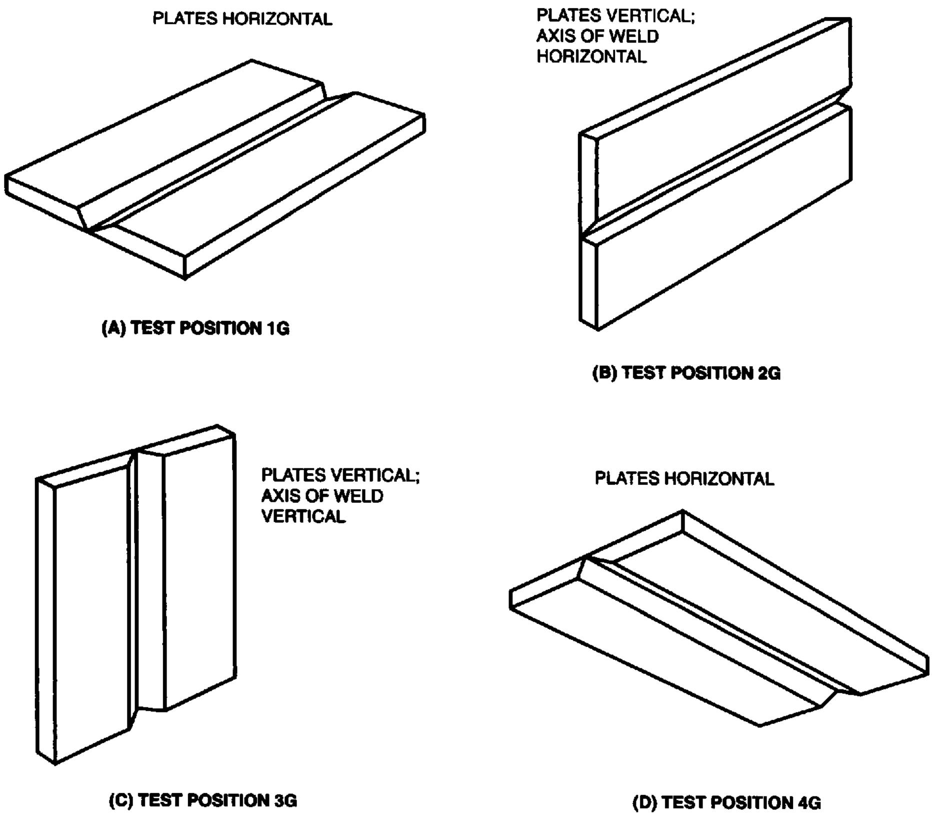



**Figure 11.4—Positions of Test Plates for Groove Welds**

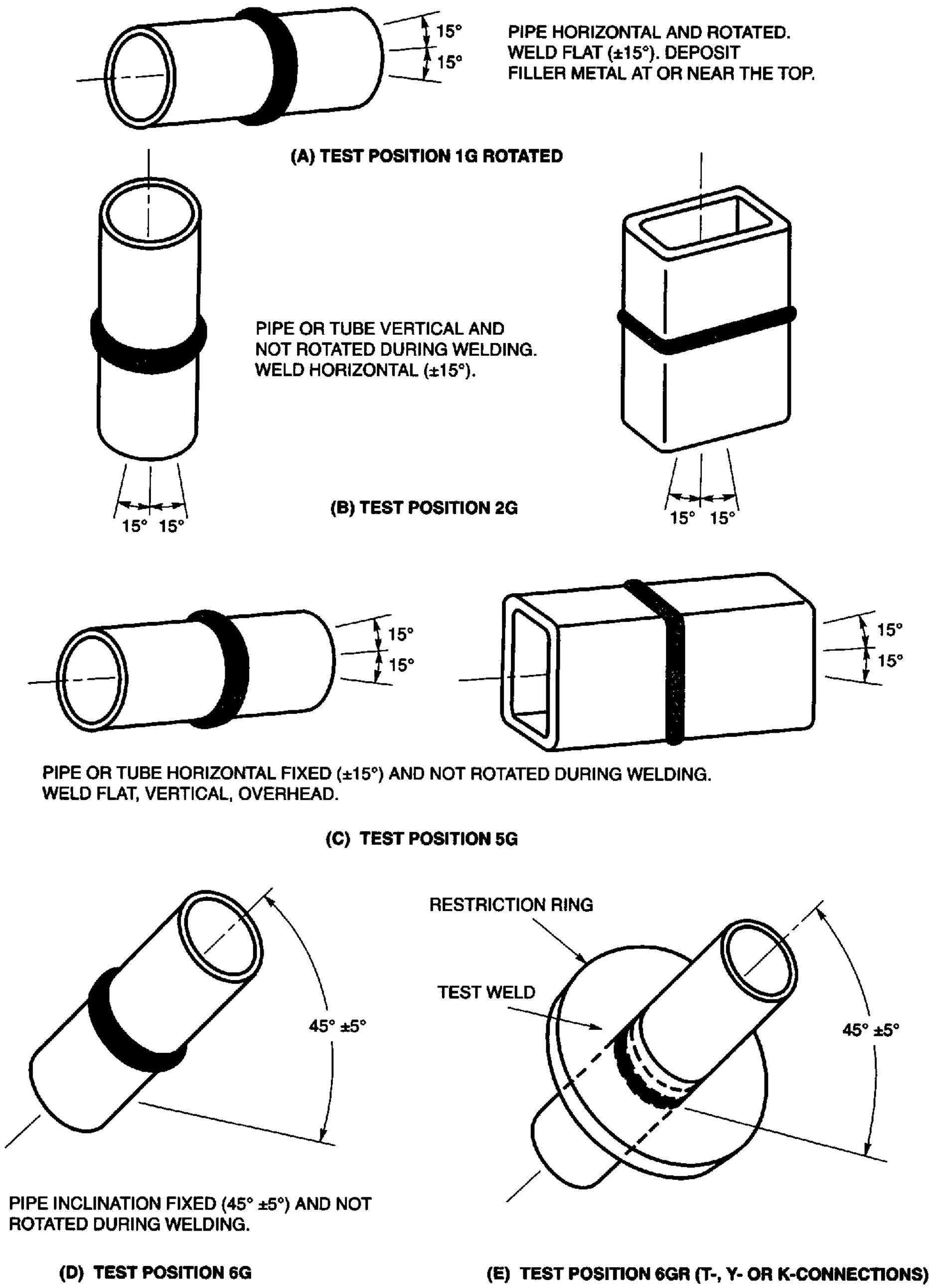
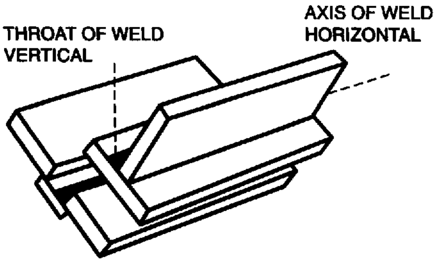
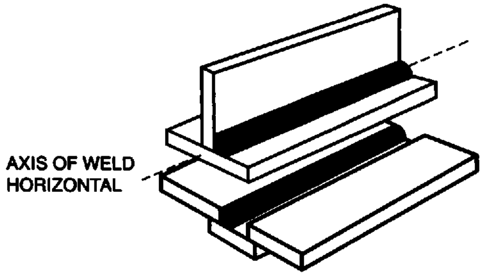


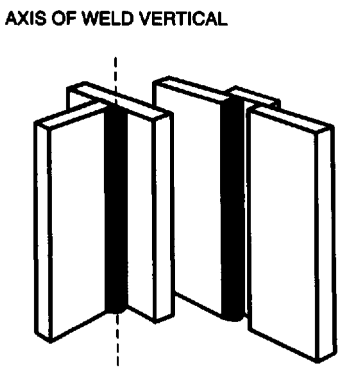

**Figure 11.5—Positions of Test Pipe or Tubing for Groove Welds**



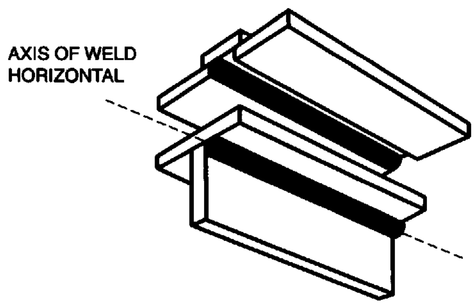

**(A) FLAT POSITION 1F**




**(B) HORIZONTAL POSITION 2F**




**(C) VERTICAL POSITION 3F**




**(D) OVERHEAD POSITION 4F**

**Figure 11.6—Positions of Test Plate for Fillet Welds**

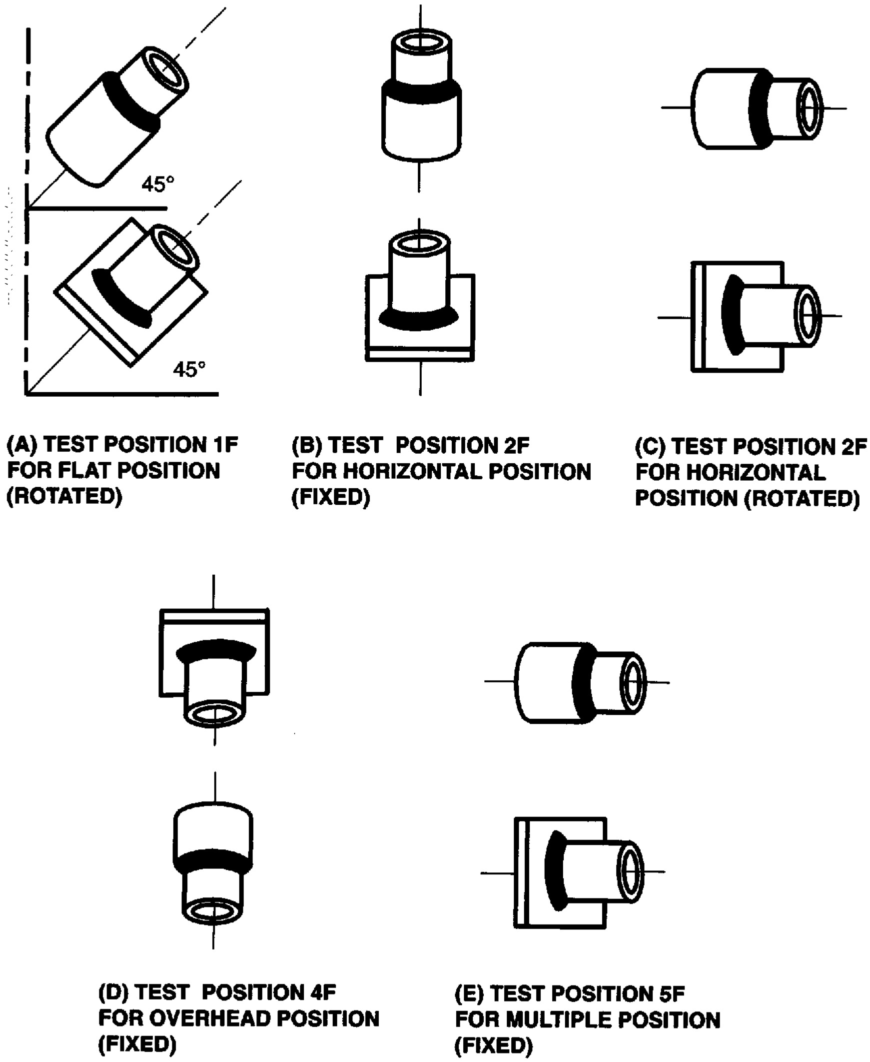



**Figure 11.7—Positions of Test Pipes for Fillet Welds**

**WELDER, WELDING OPERATOR OR TACK WELDER QUALIFICATION TEST RECORD**

Type of Welder ______________________
Name ______________________ Identification No. ______________
Welding Procedure Specification No. __________ Rev __________ Date __________

| Variables | Record Actual Values Used in Qualification | Qualification Range |
|---|---|---|
| Process/Type [Table 4.10, Item (2)] | | |
| Electrode (single or multiple) [Table 4.10, Item (9)] | | |
| Current/Polarity | | |
| Position [Table 4.10, Item (5)] | | |
| Weld Progression [Table 4.10, Item (7)] | | |
| Backing (YES or NO) [Table 4.10, Item (6)] | | |
| Material/Spec. [Table 4.10, Item (1)] | to | |
| Base Metal | | |
| Thickness: (Plate) | | |
| Groove | | |
| Fillet | | |
| Thickness: (Pipe/tube) | | |
| Groove | | |
| Fillet | | |
| Diameter: (Pipe) | | |
| Groove | | |
| Fillet | | |
| Filler Metal [Table 4.10, Item (3)] | | |
| Spec. No. | | |
| Class | | |
| F-No. | | |
| Gas/Flux Type [Table 4.10, Item (4)] | | |
| Other | | |

**VISUAL INSPECTION (4.8.1)**
Acceptable YES or NO ____

**Guided Bend Test Results (4.30.5)**

| Type | Result | Type | Result |
|---|---|---|---|
| | | | |
| | | | |

**Fillet Test Results (4.30.2.3 and 4.30.4.1)**

Appearance ______________ Fillet Size ______________
Fracture Test Root Penetration ______________ Macroetch ______________
(Describe the location, nature, and size of any crack or tearing of the specimen.)

Inspected by ______________ Test Number ______________
Organization ______________ Date ______________

**RADIOGRAPHIC TEST RESULTS (4.30.3.1)**

| Film Identification Number | Results | Remarks | Film Identifcation Number | Results | Remarks |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |

Interpreted by ______________ Test Number ______________
Organization ______________ Date ______________

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 4 of ANSI/AWS D1.1, (________) Structural Welding Code—Steel.
(year)

Manufacturer or Contractor ______________ Authorized By ______________
Form E-4 Date ______________

**Figure 11.8—Suggested Form for Welding Performance Qualification**

# Chapter 12
# Computerization of Welding Inspection and Quality

## 12.1 Control Data

The widespread application of computers throughout all industries has made a major impact on the way business functions are now accomplished. The use of computers in different work environments is prompted by a growing business need for improved performance. Computers are used by industries in a wide variety of functional areas, both for office and manufacturing applications. Computers can provide improved efficiency at reasonable costs in areas such as the following:

(1) *Office*

(a) Correspondence and letter files

(b) Payroll and financial management

(c) Management planning and control of schedules and costs

(d) Marketing and sales

(e) Purchasing

(f) Engineering design and scientific calculations

(g) Electronic mail

(2) *Manufacturing*

(a) Welding process control

(b) Shop automation

(c) Inventory control

(d) Production scheduling

(e) Quality assurance, quality control and nondestructive examination

Personal computer software for general use is readily available for word processing, spreadsheet data base management applications, and statistical analysis. Much of the paperwork connected with welding inspection and quality control can be eliminated by storing information in computerized data bases that organize it and allow the user to recall it in a useful order. Compared to hard-copy archiving, the benefits of computerized storage are numerous: it speeds data recording by substituting keypad input or bar-code reading for handwriting; can avoid errors in data recording and retrieval inherent with manual entry; gives easy and comprehensive access to information; keeps up-to-the minute records; and single entries can simultaneously update all affected documents.

Additionally, computer programs can benefit the user by acting as a teaching tool. Training personnel in the use of computers and software is crucial to successful integration of workplace computerization. Such training can be performed on-site at a central training facility sponsored by software vendors, or in some cases, with computer software training modules.

This chapter will highlight welding inspection and quality-control improvements gained through the use of computers and software and will provide an overview of welding and inspection data management and the use of statistics as a tool to control variability of processes.

**12.1.1 Welding Inspection Applications.** Statistics, computers, and commercially available software can provide valuable assistance in the welding inspection and documentation functions. Through the proper use of these tools, quality and productivity can be gained with cost savings. These improvements can be achieved through the establishment of a welding inspection data base for regularly performed welding processes. This inspection data base can be used in control charts for identification of in- and out-of-control conditions, and to aid in the establishment of realistic and accurate process control limits.

When welding inspection data is thus organized so that it can be readily analyzed to provide meaningful information, the quality of the welding process can be improved. The following are some representative attributes for monitoring:

(1) Classification of defects by grading of types

(2) Severity and number of occurrences observed

(3) Weld process, operator, and equipment used

(4) Ambient environment, including temperature, humidity, etc.

(5) Article welded

(6) Condition of joint prior to welding

(7) Joint cleanliness

(8) Repair and rework

(9) Variables of weld processes

The use of weld reject data in the form of bar charts, by deficiency type and frequency of occurrences can be a powerful tool in improving quality and reducing the number of rejected welds by directing attention to the greatest offenders. Such charting can be facilitated by the computerized data base.

A welding inspection data base can be used to store technical project information for welding procedures, welder performance and inspection data as shown in Figure 12.1. This data can include welding procedure specification and welder performance information, inspection results, accept/reject rates, process use, NDE procedures, inspector/tester certifications, and instrument calibration control systems.

Hands-free computer technology exists which allows for remote accessing of the computer as through a headset, thus reducing time and effort. Storage and retrieval of information can occur through a verbal dialogue between the inspector and the computer. Currently this technology may be available at high cost and in limited applications.

On-line computer hardware and software programs are available that take data directly

| File: NUCMD | Record Number: 248 | Change Weld Information? Yes No |
|---|---|---|

**PERSONAL DATA**

I.D. Number 37136
Name JOE SMITH
Date of Birth 01/23/56
Initial Date 01/23/88
Primary Update 01/23/88
Secondary Update 01/23/88
Renewal Date 01/23/88

**TEST DATA**

Conducted By L. MCDUFFIE, SR.
Type of Test (RT/Btr/Bln/Fil/Ten)
BTR
Proc. No./PQT No. LHC36
Revision Number 2
Test Report Number TR345

**WELDING DATA**

Process GMAW Type Semi-Automatic
Current (AC/DCRP/DCSP/NA) DCRP
Joint Type PIPE GROOVE—ONE SIDE
Weld Metal Thk. (In.) 0.093
Weld Filler F No. 6
Base Metal Thk. (In.) 0.218
Base Metal P No. 1
Type of Fuel Gas N/A
Backing METAL Insert N
Position 6G
Pipe Size (In.) 2.000
Weld Progression UP
Arc Trans. Method SARC
Part No N/A
Travel Speed (ipm) N/A
Fil. Metal Desc. E70T 1
Base Metal Desc. A106 Grade B

This formatted screen represents a complete welder-qualification record. All new records and modifications should fit this format, a sure way to keep consistent, complete records.

**Figure 12.1—A Welding Inspection Data Base**

from instrumentation on resistance welding machines and evaluates the data to determine weld quality. Some will print out images of heat patterns within a weld nugget to give an image of the nugget and will rate the weld as acceptable or rejectable.

**12.1.1.1 Quality Assurance and Inspector Computer Interfaces.** Inspectors should use a common means of classifying welding and inspection data. This classification system should be based on clearly defined terms to enable the inspector to identify the specific or relative quality observed during the inspection. This is necessary to achieve uniformity among inspectors' observations and to provide the basis for data organization statistics correlation accuracy, or at least consistency. Nonstandard terms, adjectives, or classifications would not be recognized by the data base software.

Real-time computer hardware and software can provide for direct analysis of nondestructive examination. An example of this type of application is when electronic test signals go directly to the computer for analysis by the inspector.

**12.1.1.2 Use of Computers.** QA and QC organizations can generate essential data which should be accessible and can be usefully analyzed. Computers can be used to go from a manual paper filing system to an electronic filing system, thereby realizing cost savings by eliminating the need to microfilm. Increased productivity and improved quality can be realized through the use of Computer Aided Drafting (CAD), Computer Aided Manufacturing (CAM), and coordinate measuring machines which provide automated measurement of dimensions. Other potential reasons to manage data are the following:

(1) Customer complaints
(2) Field service reports
(3) Weld process stability and control
(4) Reliability and trend analysis
(5) Quality cost data

Commercially available software and hardware allow users to tailor the system to their own application. A basic approach to incorporating computers into the inspection area includes:

(1) Start small—it's easier to justify the cost, and it provides insight into what is really needed.

(2) Consider computer compatibility with other office equipment.

(3) Use commercial software and hardware—don't reinvent the wheel.

(4) Select a reliable vendor that has a good reputation and provides good service and support for personnel training and maintenance of the equipment.

(5) Start with inspection areas such as incoming inspection of weld material and vendor control.

(6) Evaluate the human factor. A change in the way people work can affect processes and organizational relationships.

(7) Initial development of the data entry and analysis system should be performed by the same individuals.

(8) Developed programs can be operated by properly trained personnel.

**12.1.1.3 Hardware.** A computerized quality control system may be a stand alone work station or it may be connected to other systems or to a central main computer. In any case, the QC work station will require, at minimum, a dedicated or shared processing unit (the computer); a data input device (keyboard, optical reader, or other); an alphanumeric readout device (video monitor, digital alphanumeric display, or other); a printer to produce hard copies for signoffs and other purposes; and a modem for plant-to-plant or shop-to-field communications.

**12.1.1.4 Software.** Software (computer application programs) selection should follow an analysis of the actual applications. Good computer software is readily available. The following general software categories will be useful in the quality assurance and inspection environment:

**12.1.1.4.1 Word Processing Programs—Applications of Word Processing Software.** Word Processing software allows the computer to replace the typewriter as a typing tool. Advantages of word processing include:

(1) Typing can be done and corrections made before anything is put on paper, minimizing typographical errors.

(2) Editing can be done simply and easily. Major changes can be made without cutting and pasting or use of correction fluids.

(3) Using the computer the author can compose, edit and print letters, or reports. This eliminates many steps in composing on paper, having it typed, correcting errors and editing, retyping, etc.

(4) Model letters, reports, etc., can be used as blanks and can be modified as necessary to produce new ones. This eliminates retyping everything from scratch for repetitive operations.

(5) Originals can be stored electronically, taking up much less space than paper copies.

Word processing can be used in almost any way that the typewriter can. It can be used to produce letters, reports, viewgraphs, lists, procedures, and forms.

**12.1.1.4.2 Spreadsheet Programs—Applications of Spreadsheet Software.** Spreadsheets are used when forms, lists, tables, and graphs are to be prepared. They specialize in areas where calculations are to be performed on tables or lists of numbers, or where sorting is desired. With most software programs, graphs can be produced from the tables or lists of data that are being manipulated. Advantages of spreadsheet software include the following:

(1) Tables of numbers can be added, multiplied, etc., quickly by the computer, then printed.

(2) Data entry errors can be corrected easily without spoiling the calculation as when using a calculator.

(3) A set of numbers can be used for many different calculations without having to enter the data more than once.

(4) Graphs based on the data can be prepared automatically.

(5) Data can be sorted by magnitude or alphabetized automatically by the computer.

Spreadsheet software is used when repetitive calculations are to be performed to complete forms, tables, or graphs. It is especially useful when the form of the table is constant, but the data is updated periodically, and where several calculations are to be performed on the same data.

**12.1.1.4.3 Database Management—Applications of Database Management Software.** Database management software is used for the ordered storage of related pieces of data, and excels at maintaining files of information that have a constant form such as phone directories, personnel files, etc. Once the data is entered, the database can be searched to find information that is related in any of various ways. Advantages of this software include the following:

(1) Needs less storage in much less space than paper.

(2) Searches of the database can be done for needed information without poring over large quantities of paper; the computer does the searching.

(3) Information can be updated at any time, so that it is always current.

(4) Changes to the data do not require the production of new pieces of paper.

**12.1.1.5 Special Purpose Programs.** The market offers dozens of quality control programs. Companies may either design their own programs or purchase software packages that can be customized to specific operations. Almost without exception, users of QC computer programs require that the software conform to existing operations.

QC software programs commonly duplicate record-keeping formats used by manufacturers. A flashing cursor signal prompts the user through QC-record pages item by item, to enter the data. The software acts as a teaching and QC tool, assuring that every item necessary to a procedure is recorded, thus avoiding oversights and errors. The following are examples of special purpose QC software programs:

(1) Welder performance and welding procedure qualification record keeping software includes lists of welders who are qualified to given procedures, and can identify and maintain welders' names and requalification dates.

(2) QC functions such as tracking of defect and reject rates by the welder, by the job, or by the procedure.

(3) Code specific, and user assistance software.

(4) Libraries of prequalified and recommended welding procedures

(5) Computer-aided inspection record systems which combine visual and ultrasonic inspection methods with computer aided drafting and records management of actual repairs and schedule priority.

**12.1.1.6 Statistical Process Control.** Computers make possible the use of statistical process control (SPC), a technique that allows for collection and analysis of large amounts of data. There are numerous companies that make software products for statistical process control. These products frequently support statistical analyses, quality cost analysis, gauge repeatability monitoring, data acquisition, graphics, and plotting. Software products can vary in hardware compatibility and costs. The use of software products for SPC can provide a valuable tool in properly interpreting the large amounts of data that quality departments generally produce. Several evaluation criteria for selecting SPC software for a quality program are

(1) Ease of use,

(2) Good documentation,

(3) Comprehensiveness,

(4) Service/support,

(5) Reputation of supplier,

(6) Price,

(7) Quality of output (i.e., graphs, charts),

(8) Portability of software between different types of hardware for information retrieval and analysis between different work locations.

**12.1.1.7 Quality Trends Identification and Control Charts.** In-process inspection provides important information for achieving quality and is the first point of contact with the product or process. To assure quality, inspection cannot be the end objective, rather it is a way of reducing waste and improving product quality. Replacing the "conformance-to-specification limits" criteria with the idea of reducing product variability, is a viable way to improve the overall quality. The inspection function provides data gathering to recognize quality trends, analyze data and establish achievable control limits. There are many types of control charts.

Control charts can be used as a tool for tracking inspection information and identifying out-of-bounds situations or product variability. Control charts allow variations to be separated into common or system causes, which need to be brought to management's attention, or local variations, which are the workers' responsibility. Control charts can track weld reject causes and point out when attention or change is needed and minimize process adjustment.

To set up a control chart, the following steps will assist in determining the information that is needed:

(1) Decide what and how frequently to measure.

(2) Collect a representative sample of data.

(3) Determine the upper and lower control limits.

Quality is built into the product and cannot be inspected into the product. SPC and simple control charts can be used as tools to help identify nonconforming welding trends so appropriate attention can be applied to achieve a stable process, obtain information on important variables, reduce manufacturing and inspection costs, and promote process/product understanding.

**12.1.1 Summary.** The computer can provide valuable assistance to the welding inspector in helping to carry out job functions in a more effective and efficient manner. Perhaps the greatest benefits that can be realized through the use of computers includes improved cycle time, reduced cost of performing processing operations, greater production, and improved quality, consistency and accuracy of information. Personnel could have improved access to appropriate information necessary to perform their job function. Both computer software and hardware are increasingly user-friendly so that the benefits mentioned above are achievable without extensive technical computer skills.

# Chapter 13
# Destructive Testing of Welds

Historically, the testing of welds in welded structures is as old as welding. Early testing was directed toward detecting gross defects and evidence of ductility. This evolved into tests designed to determine specifics such as chemical, mechanical, and metallurgical properties, and to locate defects such as cracks, porosity, incomplete fusion, inadequate joint penetration, entrapped slag, etc.

Most of these tests are, of necessity, destructive in nature. They are generally performed on sample weldments made with procedures duplicating as close as possible those used in the fabrication of the actual welded structure.

Tests are conducted for the qualification of welding procedures, the qualification of welders and welding operators, and for quality control. These destructive tests may be chemical tests, metallographic tests, mechanical tests, or any combination thereof. The tests specified should be those that provide reasonable assurance of the required performance of the weldment in service.

The ideal test would, of course, be one that exactly duplicates the service conditions. However, the difficulty and cost of applying such tests is obvious; thus, certain standard tests are alternatively used. Details of destructive tests of welded joints and deposited filler metals can be found in the latest edition of AWS B4.0, *Standard Methods for Mechanical Testing of Welds*.[6]

The inspector has the responsibility to confirm that specified tests are conducted properly and that test results are in compliance with required specifications. The inspector needs to be thoroughly familiar with the testing procedures, the effect of revealed defects on the test results, and the interrelation of defects in the test sample with the same types of defects in the production weldment. With a thorough background in these, one will be able to discuss test results with engineering personnel to gain final acceptance or rejection of production work. No matter how carefully codes and specifications are written, much is left to the judgment of the inspector. In fairness to oneself, the manufacturer, and the employer, one should be equipped with a thorough knowledge on which to base decisions. The inspector has the sole responsibility of confirming that the weld joint properties are in accordance with the specification. Acceptance of material that does not conform to specification requirements can only be made by an authorized engineer.

Brief descriptions of various types of standard destructive tests applied to welds and weldments follow. The effect of defects on the results of these tests is presented briefly. It is realized that much more could be written, but is hoped that interested inspectors will avail themselves of opportunities for further study of the technical literature.

Tests should be performed with careful attention to specimen preparation and the test procedure. The quality and reliability of test results is in direct proportion to the care taken in the test. In general, the term *destructive testing* is used to describe an evaluation process of a weld by a technique that of necessity destroys the test specimen or destroys its ability to function in its design application. The destructive testing technique should, therefore, be used with some form of partial sampling, rather than complete sampling (see Chapter 14).

6. Available from American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

The destructive testing techniques can be classified as three general types: chemical, metallographic, and mechanical.

## 13.1 Chemical Tests

Usually, chemical tests are conducted on a specimen to determine its chemical composition or its resistance to corrosion.

**13.1.1 Chemical Composition Tests.** Tests for chemical composition are often required to ascertain whether the base metal and the weld metal meet the requirements of the codes or specifications. Special analyses of base metal and weld metal are used for special service requirements. Experience indicates what range of composition is suitable for a particular service condition. A chemical composition of the base metal and filler metal should be selected that will perform satisfactorily in service.

Weld defects are sometimes caused by variations in chemical composition of the base or filler metals. Variations in composition such as high sulfur or phosphorous, or residual elements such as tin, can cause weld discontinuities, defects, or both. Complete chemical analysis of the material and weld composition should be made and thoroughly reviewed when cracking persists.

In general, deposited composition of the weld metal should match as closely as possible that of the base metal. However, if no heat treatment of the weldment is performed, sometimes, depending upon the service requirements of the joint, a weld metal of significantly different composition from that of the base metal is specified.

**13.1.2 Corrosion Tests.** Corrosion of welds and weldments is a great concern for the manufacturer and customer of numerous items ranging from welded equipment for the chemical industry and refineries, automobile bodies, welded ship hulls, metal containers, etc., which should perform satisfactorily in various environments, many of which are corrosive. Many tests have been devised to simulate the type of corrosion anticipated in corrosive environments. These tests can accelerate trans- or intergranular corrosion, pitting corrosion, stress corrosion cracking, and other preferential types of attack. Tests are conducted under laboratory conditions and can provide a reasonably accurate forecast of the weldment performance in service.

Welding is used for joining a wide range of metals, including iron, nickel, copper, aluminum, magnesium, titanium, and their alloys. Corrosion tests are available for all alloys used in construction. No effort will be made in this text to describe any specific test. Details of test procedures for conducting corrosion tests can be found in ASTM standards (refer to the *Annual Index to Standards* for specific test procedures).

## 13.2 Metallographic Tests

Metallographic examination is sometimes required in specifications for weldments. It is used to determine the following:

(1) The soundness of welds

(2) The distribution of nonmetallic inclusions in the weld

(3) The number of weld passes

(4) The metallurgical structure in the weld and fusion zone

(5) The extent and metallurgical structure of the heat-affected zone

(6) The location and depth of penetration of the weld

These tests may involve merely visual examination, in which case the prepared specimens (called *macro-specimens*) are etched to bring out the gross structure and bead configuration and are examined by the unaided eye or at magnifications below 10X; or they may involve microscopic examination, in which case the specimens (called *micro-specimens*) are prepared and etched for examination at magnifications over 10X.

Samples may be secured by sectioning test welds or production control welds including run-off tabs. They can be prepared by cutting, machining, grinding, or polishing to reveal the desired surface for etching.

Sectioning production welds by core drilling or trepanning has been used for years as a quality-control tool. However, the rewelding of the cored or trepanned areas was often more difficult than the original welding and frequently produced defects in the repair area. This concern, together with the extensive improvements in nondestructive examination, have made obsolete the sectioning of production welds as a quality-control tool. In fact, many users prohibit sectioning for such purposes. However, sectioning remains an important tool for failure analysis.

**13.2.1 Macro Specimens.** For macroscopic examination, different metals require different methods of preparation. As an example, for plain-carbon steel welds, the surface to be examined may be prepared by one of the following methods:

(1) After sectioning the weld, and preparing a relatively smooth finish on the surface to be examined, place in a 50 percent solution of hydrochloric acid in water at 150°F (66°C) until there is a clear definition of the macro structure of the weld. This will require approximately one-half hour immersion.

(2) Another type of macro specimen is prepared by grinding and polishing smooth specimens with an emery wheel or emery paper, and then etch by treating with a solution of one part by weight ammonium persulphate (solid) and nine parts of water. The solution should be used at room temperature and should be applied by swabbing the surface to be etched with a piece of cotton that is always saturated with the solution. The etching process should be continued until there is a clear definition of the macro structure of the weld.

After being etched, the specimens are washed in clear water and the excess water is quickly removed. The specimens are then washed with propyl or ethyl alcohol and dried. The etched surface may be preserved by the application of a thin, clear lacquer. Figure 13.1 shows two typical macroetched samples (see also illustrations of weld flaws in Chapter 9).

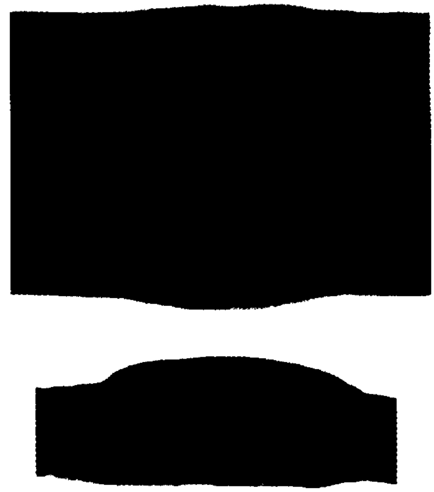


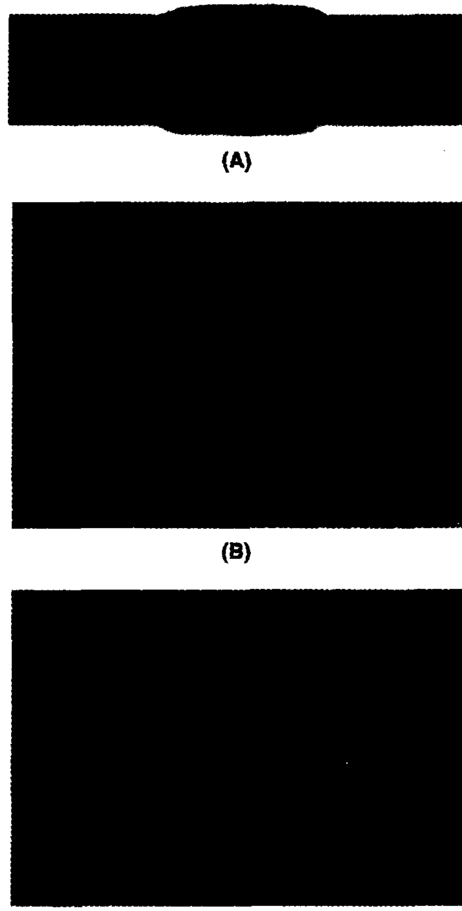
**Figure 13.1—Typical Photomacrographs**

Macroscopic examination is used to reveal the number of weld passes, the penetration of the weld, the extent of weld undercut, the extent of the heat-affected zone (HAZ), and gross discontinuities. Defects shown to exist by various nondestructive examinations can be exposed for further evaluation by using macroscopic examination.

**13.2.2 Micro Specimens.** When examining for exceedingly small defects or for metallurgical structure at high magnification, specimens should be cut from the actual weldment or from welded test specimen samples. These micro specimens are given a highly polished mirror-like surface and etched for examination with a metallograph at an appropriate magnification to reveal the structure of the base metal, HAZ, fusion zone, weld metal deposit, segregation, small discontinuities, etc.

Figure 13.2 shows a photomicrograph of a crack in the heat-affected zone. Figure 13.3 illustrates the weld metal, HAZ, and the base metal of an electroslag weld.

**Figure 13.2—Photomicrograph Illustrating the Appearance of a Crack in the Heat-Affected Zone (Approximately 100X)**



(A)

(B)

(C)

**Figure 13.3**
**(A)—Photomacrograph 1 in. Thick Electroslag Weld in ASTM A236**
**(B)—Photomicrograph (100X) of Heat-Affected Zone of Same Weldment**
**(C)—Photomicrograph (100X) of Weld Metal, Same Weldment**

Samples such as these may be required in some codes and specifications; they are frequently useful in identifying problems and in determining solutions. A qualified metallographer can read a great deal from microscopic examinations. However, the procedure is complicated; considerable skill is necessary to properly polish the samples and to use the proper etchants and technique to show what is desired. (For a detailed discussion of microscopic examination procedures, reference may be made to ASTM Standards E2 and E3.)

## 13.3 Mechanical Tests

For any welded product, the determination of the quality of welds depends to a large extent on competent inspection and adequate testing. In general, specifications and codes call out the mechanical tests for weld strength and other weld and HAZ properties to determine the quality of welds and adjacent areas. In addition, other tests (both destructive and nondestructive) may be required.

Mechanical tests for welds are similar to the mechanical tests applied to base metals, altered as necessary to determine the properties of the areas of the welds. There are other specialized tests used to determine material properties; however, these are beyond the scope of this section.

This section gives suggested requirements for mechanical testing, and the methods of obtaining the desired information. It is not a specification. Those who call for mechanical tests as a portion of a specification for a welded product should state definitely:

(1) The one or more tests that are required

(2) The AWS or other applicable standard that covers the procedures for testing

(3) The limiting numerical values of the properties and the minimum and maximum limits permitted, and

(4) The interpretation, if any needed, of the test results.

Although there may be agreement among the design and welding engineers on properties to be determined and, in general, on test procedures, there has been of necessity a wide divergence relative to the shape and size of the specimens and the details of the test procedures.

In preparing this section, no attempt has been made to cover the use of new or unused tests.

This section will describe tests that are most frequently used for determining the mechanical properties of weld metal and welded joints, including the standard hardness tests, tension tests, shear tests, and some other tests that are commonly used, though somewhat specialized.[7]

If there are specifications for the base metal, tests should be conducted in accordance with these specifications. If no such base metal specifications have been listed, yet a test is desired, the tests should be conducted in accordance with the standards of ASTM.

The terminology used in this section conforms to the ASTM Standard E6, *Standard Definitions of Terms Relating to Methods of Testing*. The term *soundness* as used here means a degree of freedom from defects discernible by visual inspection of any exposed surface of weld and or adjacent metal after testing. In reports of tests made in accordance with this section, nomenclature should conform to the above standards and definitions.

**13.3.1 Mechanical Properties.** The weld metal properties most generally required by specifications (hardness, tensile strength, yield point, yield strength, and ductility) will be described briefly. (Reference may be made to AWS or ASTM standards for detailed definition and explanation of these properties, as well as for others not covered.)

**13.3.2 Hardness Tests.** The hardness of a weldment or a weld is determined by forcing a hardened steel ball or diamond point into a flat surface on the weldment or welded specimen, with a predetermined load, in a calibrated hardness testing machine, and measuring the size of the resultant indentation. Hardness is affected by the composition of the base metal and the weld metal, the metallurgical effects of the welding process and cooling rate, cold working of the metal, heat treatment, and many other factors. Certain codes, specifications, and other standards, as well as experience has dictated that limitations be placed on the hardness range of one or more of the following: the base metal, HAZ, fusion line, and weld metal of certain metals (usually higher carbon and alloy steels). If too hard, they will not have sufficient ductility for the service conditions, their corrosion resistance may be impaired, or some other factor may dictate this limitation.

The following are the most widely used methods of measuring hardness, and with them, a brief discussion of their limitations and the factors that should be considered to obtain as accurate as possible readings. The three most widely used scales for hardness measurement are the Brinell, the Rockwell, and the Vickers.

Equipment used for hardness testing differs in many respects, as indicated in subsequent paragraphs. For the welding inspector, the most important difference involves the size of the indentor, which may range from a 0.394 in. (10 mm) diameter ball to a small diamond tip. When such tools are used, the metal indentation may range between

7. All tests described should be carried out in accordance with applicable ASTM and AWS standards. Some of these are as follows: (1) Tension Testing of Metallic Materials, (2) Notched Bar Impact Testing of Metallic Materials, (3) Guided Bend Test for Ductility of Welds.

0.197 in. (5 mm) and a small fraction of a millimeter. For reasonably homogenous base metal and weld metal, the size of the indentation has little effect on the test results. However, when an HAZ that may be 0.118 in. (3 mm) wide and contains several metallurgically differing zones is tested, the size of the indentation is of major importance. A small indentor may detect the hardened zone or the soft or tempered zone, while the 0.394 in. (10 mm) ball represents an average value. Thus, any test requirement that includes HAZ hardness should specify and record the size of the indentor employed.

**13.3.2.1 Brinell.** The Brinell hardness test consists of impressing a special hardened steel ball into the specimen under test, using a definite load for a definite time and accurately measuring the diameter of the impression. The specimen should be thick enough so that deflection of the specimen is minimized. Stationary machines employ hydraulic pressure to impress a 0.394 in. (10 mm) ball into the specimen. The load for steel is 6615 lb (3000 kg) and for softer metals, 1100 lb (500 kg).

The diameter of the impression is measured by the eye, using a special, high-power Brinell microscope graduated in tenths of millimeters. The average of two diameters at right angles to each other is determined, and the Brinell hardness number, obtained from a chart or table of diameters of impression related to hardness numbers.

An alternate portable method of Brinell testing is available when the configuration of the weldment size, or both, prevents it from being placed on a Brinell testing machine. This test consists of impressing a 0.394 in. (10 mm) ball simultaneously into a specimen of known hardness and the test piece. To obtain a hardness number, the tester is held in such a way that the ball is between the bar of known hardness and the specimen. The anvil is struck a sharp blow with a hammer, the diameters of the indentations made in the bar, and the specimen is measured. The hardness is calculated from tables or a special slide rule. Brinell hardness numbers can be multiplied by 500 to obtain the approximate tensile strength of the material being tested. Considerable operator skill is required to obtain consistent and accurate hardness measurements with use of this and other portable hardness testing instruments.

Several precautions should be taken to ensure obtaining true hardness values. The surface to be tested should be flat and reasonably smooth. Impressions should be taken at representative locations. The specimen should be firmly supported in such a way that the load is applied at a right angle to the surface of the specimen. The test should not be used on specimens of soft steel that are less than about 1/2 in. (13 mm) thick, or on specimens so small as to produce flow of metal at the edges as a result of the ball impression. Impressions should not be taken closer than about two indentor diameters from each other, else the cold work caused by the previous impression will produce erroneous data.

**13.3.2.2 Rockwell.** The Rockwell hardness tester measures the depth of penetration made by a small hardened steel ball or a diamond cone. The test is performed by applying a minor load of 10 kg which seats the penetrator in the surface of the specimen and holds it in position. A major load is then applied. After the pointer comes to rest, the major load is released, leaving the minor load on. The Rockwell hardness number is read directly on the dial.

As Rockwell hardness numbers are based on the difference between the depths of penetration at major and minor loads, it will be evident that the greater this difference, the less the hardness number and the softer the material. This difference is automatically registered when the major load is released (the minor load still being applied) by a reversed scale on the indicator dial, from which the Rockwell hardness number may be read directly. Hardened steel balls of 1/8 in. or 1/16 in. (3.2 mm or 1.6 mm) diameter are used for the softer metals, and a cone-shaped diamond penetrator is used for hard metals.

Several precautions should be taken to ensure obtaining true values. Surfaces that are ridged by rough grinding or coarse machining offer unequal support to the penetrator. Both the surface at the penetrator side and the underside should be free of perceptible ridges. The specimen should seat solidly, with no rocking, and should be of such thickness that the underside of the specimen does not show a perceptible impression. This thickness will vary greatly according to the hardness of the material treated. Softer material requires a greater thickness of specimen, or lighter load, or both. Results from tests on a curved surface may be in error and should not be reported without stating the radius of curvature. In testing round specimens, the effect of curvature may be eliminated by filing a small flat spot on the specimen. Impressions should not be made within about two penetrator diameters of the edge of the specimen, nor closer than that to each other. When changing from one scale to another, a standard test block of a specified hardness in the range of the new scale should be used to check whether all the required changes have been made and whether the penetrator has seated properly. Care should be taken not to damage the penetrator or the anvil by forcing them together when a specimen is not in the machine. The minor load should be applied carefully so as not to overshoot the mark. The loading level should be brought back gently. The ball penetrator tends to become flattened by use, especially in testing hardened steels, and should be checked occasionally and replaced when necessary. In the same manner, the diamond cone penetrator should be examined frequently and replaced when it is found to be blunted or chipped.

**13.3.2.3 Vickers.** The Vickers hardness test is another of the class of tests that measure resistance to penetration. It is generally used as a laboratory tool by a technician or engineer to determine hardness of the room-temperature metallurgical constituents and regions of the welded joint.

The Vickers hardness test consists of impressing a square-based pyramid penetrator into the surface of a specimen under a predetermined load. The penetrator is forced into the specimen, and the diagonals of the square impression are measured and averaged.

*DPH* (diamond pyramid hardness) =

$$1.854 \frac{P}{D^2} \qquad \text{(Eq. 13-1)}$$

where

$P$ = load in kilograms

$D$ = average of the measured diagonals of the indentation expressed in mm.

The application and removal of the load after a predetermined interval are controlled automatically. Since the Vickers indentor is a diamond, it can be used in testing the hardest steels and remains practically undeformed. The load is light, varying from 1 to 120 kg., according to requirements. A normal loading of 30 kg is used for homogeneous materials, and 10 kg is used for soft, thin, or surface-hardened materials. The specimen surface preparation is very important; it should approach a metallographic polish.

Section C2 of AWS B4.0, *Standard Methods for Mechanical Testing of Welds*, gives further information on hardness testing.[8]

Portable Brinell and shore scleroscope machines using the same or very similar principles are used on welded configurations that cannot be placed in one of the Brinell, Rockwell, or Vickers standard instruments. However, their accuracy leaves much to be desired, and should be used only for base metal evaluation. The inspector should be acquainted with the use and limitations of the several types.

**13.3.2.4 Summary.** Each of the above hardness tests supplements the others. The Brinell impression, being large, can only be

8. Refer to footnote 6 on page 99.

used for obtaining hardness values over a relatively large area such as the face of a weld or the base metal. The Rockwell test and the Vickers test, however, can be applied to survey the hardness of small zones such as the cross section of a weld, the fusion line, the heat-affected zone or various individual beads. Conversion data from the Rockwell to the Brinell to the Vickers are available. Table 13.1 shows a typical conversion chart. In using this chart, however, it should be remembered that the data were obtained from a large number of tests and represent average values. The scattering obtained in the actual tests was considerable and depended greatly upon the analyses of materials and their condition.

**13.3.3 Tensile Strength.** Since a large proportion of design is based on tensile properties, it is important that the tensile properties of the base metal, the weld metal, the bond between the base metal and weld metal, and the HAZ conform to the design considerations of the weldment. Where butt joints are used, the weld metal should usually develop the minimum tensile properties of the base metal. In the case of fillet welds, plug welds, and spot welds, shear strength is usually the significant factor. Tensile strength of weld metal or weld joints is obtained by pulling a specimen to failure. All-weld-metal specimens are usually cylindrical (0.505 in. diam. [12.7 mm]). Welded joint specimens are usually rectangular, reduced cross-section specimens, as shown in AWS B4.0, *Standard Methods for Mechanical Testing of Welds*. Tensile strength is determined by dividing the maximum load by the cross-sectional area before deformation. The result will be in units of stress per cross-sectional area.

**13.3.4 Yield Point and Yield Strength.** These properties are determined with the same specimens that determine tensile strength. Yield properties are usually obtained for individual parts of the welded joints, such as base metal or weld deposit.

**13.3.4.1 Yield Point.** Yield point is defined as the stress per square inch of the original cross-sectional area that causes a marked increase in extension without increase in the load. The yield point may be determined by one of the methods described in the following paragraphs.

(1) *Drop of the Beam Method.* In this method the load is applied to the specimen at a steady rate of increase. The operator keeps the beam in balance by running out the poise at an approximately steady rate. When the yield point of the material is reached, the increase of load stops, and the beam of the machine drops for a brief but appreciable interval of time. In a machine fitted with a self-indicating, load-measuring device, there is a sudden halt of the load-indicating pointer. This point corresponds to the drop of the beam. The load at the "halt in the gauge" or the "drop of the beam" is recorded, and the corresponding stress is taken as the yield point. This method of determining yield point requires only one operator to conduct the test.

(2) *Total Strain Method Using Extensometer.* An extensometer reading to 0.0001 inch per inch of gauge length is attached to the specimen at the gauge marks. When the specimen is in place and the extensometer attached, the load is increased at a uniform rate. The observer watches the elongation of the specimen as shown by the extensometer and notes for this determination the load at which the rate of elongation shows a sudden increase.

*Note: The strain method is more sensitive and may show the start of the yield elongation at a slightly lower stress than that given by the first method.*

**13.3.4.2 Yield Strength.** Yield strength may be defined as the load per square inch of cross-sectional area that caused a specific set of the specimen as determined by either the offset method or the extension-under-load method.

(1) *Offset Method.* For nearly all metals, if at any point on the stress-strain diagram the load is released, the curve of decreasing load will be approximately parallel to the initial portion of the curve of increasing load (see

## Table 13.1
## Typical Hardness Conversion Table (Approximate) (for Carbon and Low-Alloy Steels in Accordance with ASTM E-140 and ASTM A-370)

| Approximate Tensile Strength, psi | Rockwell C Diamond Cone | Rockwell A Diamond Cone | Rockwell B Hardened Steel Ball | Shore Scleroscope Number | Approximate Brinell Number* | Brinell mm Impression |
|---|---|---|---|---|---|---|
| 310 000 | 56 | 79.0 | | 75 | 577 | 2.55 |
| 301 000 | 55 | 78.5 | | 74 | 560 | 2.59 |
| 292 000 | 54 | 78.0 | | 72 | 543 | 2.63 |
| 283 000 | 53 | 77.4 | | 71 | 525 | 2.67 |
| 273 000 | 52 | 76.8 | | 69 | 512 | 2.71 |
| 264 000 | 51 | 76.3 | | 68 | 496 | 2.75 |
| 255 000 | 50 | 75.9 | | 67 | 481 | 2.79 |
| 246 000 | 49 | 75.2 | | 66 | 469 | 2.83 |
| 237 000 | 48 | 74.7 | | 64 | 455 | 2.87 |
| 229 000 | 47 | 74.1 | | 63 | 443 | 2.91 |
| 222 000 | 46 | 73.6 | | 62 | 432 | 2.94 |
| 215 000 | 45 | 73.1 | | 60 | 421 | 2.98 |
| 208 000 | 44 | 72.5 | | 58 | 409 | 3.02 |
| 201 000 | 43 | 72.0 | | 57 | 400 | 3.06 |
| 194 000 | 42 | 71.5 | | 56 | 390 | 3.10 |
| 188 000 | 41 | 70.9 | | 55 | 381 | 3.13 |
| 181 000 | 40 | 70.4 | | 54 | 371 | 3.17 |
| 176 000 | 39 | 69.9 | | 52 | 362 | 3.21 |
| 170 000 | 38 | 69.4 | | 51 | 353 | 3.25 |
| 165 000 | 37 | 68.9 | | 50 | 344 | 3.29 |
| 160 000 | 36 | 68.4 | (109.0) | 49 | 336 | 3.33 |
| 155 000 | 35 | 67.9 | (108.5) | 48 | 327 | 3.37 |
| 150 000 | 34 | 67.4 | (108.0) | 47 | 319 | 3.42 |
| 147 000 | 33 | 66.8 | (107.5) | 46 | 311 | 3.45 |
| 142 000 | 32 | 66.3 | (107.0) | 44 | 301 | 3.51 |
| 139 000 | 31 | 65.8 | (106.0) | 43 | 294 | 3.55 |
| 136 000 | 30 | 65.3 | (105.5) | 42 | 286 | 3.60 |
| 132 000 | 29 | 64.7 | (104.5) | | 279 | 3.64 |
| 129 000 | 28 | 64.3 | (104.0) | 41 | 271 | 3.68 |
| 126 000 | 27 | 63.8 | (103.0) | 40 | 264 | 3.73 |
| 123 000 | 26 | 63.3 | (102.5) | 38 | 258 | 3.77 |
| 120 000 | 25 | 62.8 | (101.5) | | 253 | 3.81 |
| 118 000 | 24 | 62.4 | (101.0) | 37 | 247 | 3.85 |
| 115 000 | 23 | 62.0 | 100.0 | 36 | 243 | 3.89 |
| 112 000 | 22 | 61.5 | 99.0 | 35 | 237 | 3.93 |
| 110 000 | 21 | 61.0 | 98.5 | | 231 | 3.97 |
| 107 000 | 20 | 60.5 | 97.8 | 34 | 226 | 4.02 |
| 103 000 | 18 | | 96.7 | 33 | 219 | 4.10 |
| 100 000 | 16 | | 95.5 | 32 | 212 | 4.15 |
| 97 000 | 14 | | 93.9 | 31 | 203 | 4.25 |
| 93 000 | 12 | | 92.3 | 29 | 194 | 4.33 |
| 90 000 | 10 | | 90.7 | 28 | 187 | 4.40 |

*A 10 mm Tungsten Carbide ball should be used on all steels over $R_{C\,46}$.

Figure 13.4 for a typical stress-strain diagram). These curves may, however, be offset after the release of load. The value of this offset is expressed in terms of the percentage of original gauge length. Yield strength may be determined by the offset method as follows:

On the stress-strain diagram shown in Figure 13.4, a straight line is drawn parallel to the initial straight line portion of the diagram and at a distance to the right corresponding to the value of the offset specified. The load corresponding to the point where this straight line intersects the initial curve, divided by the original cross-sectional area of the specimen, is the value of the "yield strength."

In reporting values of yield strength obtained by this method, the specified value of offset used should be stated in parentheses after the term *yield strength.* Thus, "52 000 psi yield strength (0.2 percent)" indicates that at a stress of 52 000 psi, the approximate permanent set of the metal is 0.2 percent of the original gauge length. This method is devised for determining a stress corresponding to a well-marked plastic deformation.

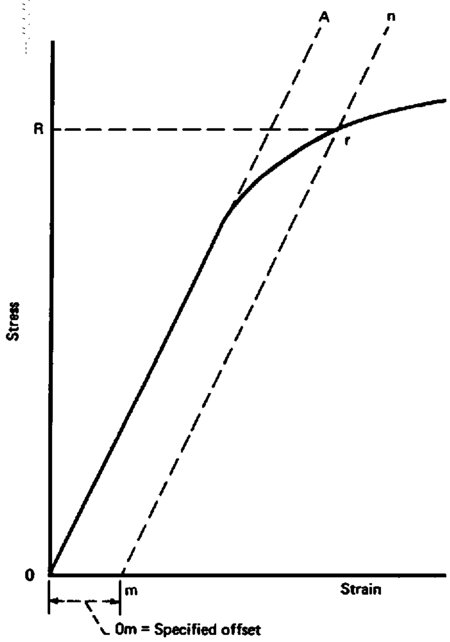



**Figure 13.4—Typical Stress-Strain Diagram Used in the Offset Method**

(2) *Extension Under Load Method.* For tests to determine the acceptance or rejection of material whose stress-strain characteristics are well known from previous tests of similar material in which stress-strain diagrams were plotted, the total strain corresponding to the stress at which the specified permanent set occurs will be known within acceptable limits.

Therefore, in such tests, a specified total strain may be used, and the stress on the specimen, when this total strain is reached, is the value of the yield strength. To determine yield strength by this method, the initial reading of the extensometer for the initial load is recorded, and the load increased until the extension in the specimen is that prescribed. The corresponding load divided by the original cross-sectional area of the specimen is the yield strength.

**13.3.5 Ductility.** Ductility, or percentage elongation and reduction of area, may also be obtained from the tensile test. Ductility values are not usually used in designing a structure; nevertheless, minimum values are included in most specifications because they indicate the quality of the weld metal.

Percentage elongation is obtained by placing gauge marks on the specimen (usually using a double center punch with the points accurately distanced to the gauge length required) before testing. After testing, the broken specimen is fitted tightly together and the final distance between gauge marks measured. The difference between the final and original gauge lengths, divided by the original gauge length and multiplied by 100, gives the percentage elongation in the specified gauge length. Sometimes, because of defective machining or some other factor, the specimen will not break in the center portion of the gauge length and may even break completely outside the gauge length. In such cases, the test results are usually not acceptable, because most of the elongation has taken place at a position other than where originally intended.

Elongation of a specimen under tensile load is uniform until necking occurs. Thereafter, elongation is confined almost exclusively to the small area of the neck. This area of localized necking would be a greater proportion of a short gauge length than of a long gauge length. Other things being equal, the shorter the gauge length, the higher the percent elongation obtained from any given specimen.

Reduction of area is determined by carefully fitting together the ends of the fractured specimen and measuring the dimensions of the smallest cross section. The difference between this area and the original cross-sectional area, expressed as a percentage of the original area, is defined as the reduction of area.

**13.3.5.1 Standard Tension Test.** The standard tension test specimen should comply with the requirements of Figure 13.5. The standard specimen should be used unless the size of the welded joint or deposited weld is such that a specimen of this size cannot be machined from it. In this case, the 0.350 in. (8.90 mm) or 0.250 in. (6.35 mm) round specimen with the largest test and grip may be used, choosing the specimen with the largest diameter that can be machined from the material to be tested. The portion of the specimen included in the gauge length G should consist entirely of metal from the deposited zone of the joint. End preparation of tension specimens may be of any shape to fit the type jaws used in the tension testing machine.

All three specimens are geometrically similar in all significant dimensions. Therefore, the properties determined from any one of them tend to be approximately the same as the properties determined from the others. However, it is desirable that comparisons be made only between specimens of the same size. Percent elongation is particularly affected by the gauge length used for the test.

The apparatus, material, methods, and rate of depositing the weld metal in the test plate should, so far as practicable, be the same as those used in making welds with the given filler metal.

*Note: Due to unavoidable differences in the method of depositing the filler metal and the rates of cooling, the properties of the weld metal determined from a specimen will depend upon the dimensions of the adjacent metal. Therefore, it is preferred that the test specimens be removed from a weldment geometrically similar to the production weldment. For thermit welds, a suitable refractory material may be used for a trough in which the weld metal is allowed to solidify.*

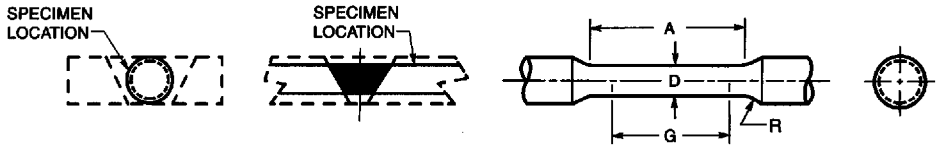
In the standard tension test procedure, the diameter of the specimen at the middle of the reduced section should be measured in inches and the gauge length defined by a gauge mark at each end. The specimen is then ruptured under tensile load and the maximum load in pounds determined.

As a result of this type of test, the tensile strength, yield strength, percent elongation, and reduction in area may be determined.

## 13.4 Tests of Welded Joints

**13.4.1 Test Specimens.** Individual specifications may designate which specimens described in this section are to be used and the order in which they will be cut from any prepared pipe or plate sample. Specimens removed from the test piece should be located no closer than 1 in. (25.4 mm) from the start or end of the weld being tested.

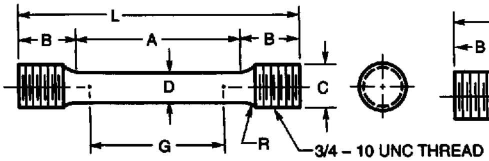
**13.4.2 Bend Specimens.** Bend ductility specimens for pipe or plate should be in accordance with those shown in Figure 13.6. Soundness and ductility specimens include face, root, side, and longitudinal guided bends. (See AWS B4.0, *Standard Methods for Mechanical Testing of Welds*, for additional information.)



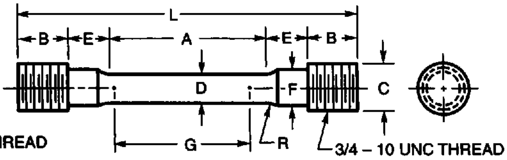

| | Dimensions | | | | |
|---|---|---|---|---|---|
| | Standard Specimen | Small-size specimens proportional to standard specimen | | | |
| Nominal Diameter | in. 0.500 | in. 0.350 | in. 0.250 | in. 0.160 | in. 0.113 |
| G. gauge length | 2.000 ± 0.005 | 1.400 ± 0.005 | 1.000 ± 0.005 | 0.640 ± 0.005 | 0.450 ± 0.005 |
| D. diameter | 0.500 ± 0.010 | 0.350 ± 0.007 | 0.250 ± 0.005 | 0.160 ± 0.003 | 0.113 ± 0.002 |
| R. radius of fillet, min | 3/8 | 1/4 | 3/16 | 5/32 | 3/32 |
| A. length of reduced section min | 2-1/4 | 1-3/4 | 1-1/4 | 3/4 | 5/8 |

Notes:
1. The reduced section may have a gradual taper from the ends toward the center with the ends not more than 1 percent larger in diameter than the center (controlling dimension).
2. If desired, the length of the reduced section may be increased to accommodate an extensometer of any convenient gauge length. Reference marks for the measurement of elongation should nevertheless be spaced at the indicated gauge length.
3. The gauge length and fillets shall be as shown but the ends may be of any form to fit the holders of the testing machine in such a way that the load shall be axial. If the ends are to be held in wedge grips it is desirable to make the length of the grip section great enough to allow the specimen to extend into the grips a distance equal to 2/3 or more of the length of the grips.
4. The use of specimens smaller than 0.250 diameter shall be restricted to cases when the material to be tested is of insufficient size to obtain larger specimens or when all parties agree to their use for acceptance testing. Smaller specimens require suitable equipment and greater skill in both machining and testing.
5. For transverse weld specimens, the weld shall be approximately centered between gauge marks.
6. Any standard thread is permissible that provides for proper alignment and aids in assuring that the specimen will break within the reduced section.
7. On specimen 5 (see page 19), it is desirable to make the length of the grip section sufficient to allow the specimen to extend into the grips a distance equal to 2/3 or more of the length of the grips.
8. The use of UNF series of threads (3/4 in. by 16, 1/2 in. by 20, 3/8 in. by 24, and 1/8 in. by 28) is recommended for high-strength, brittle materials to avoid fracture in the threaded portion.
9. Surface finish within the gauge length shall be no rougher than 63 microinches $R_a$.
10. On the round specimens in this figure, the gauge lengths are equal to 4 times the nominal diameter. In some product specifications other specimens may be provided for but unless the 4 to 1 ratio is maintained within dimensional tolerances, the elongation values may not be comparable with those obtained from the standard test specimen. Note that most metric based codes use a 5 to 1 ratio of gauge length to diameter.

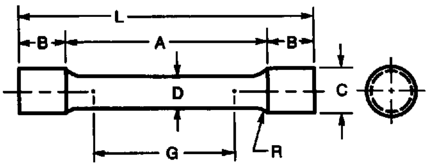
**Figure 13.5—Standard Tension Specimens**



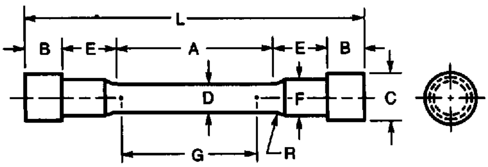

SPECIMEN 1



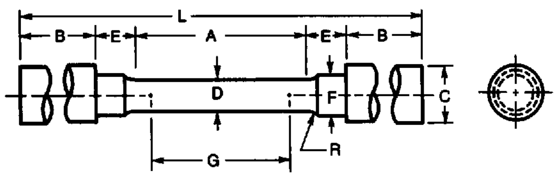

SPECIMEN 2




SPECIMEN 3



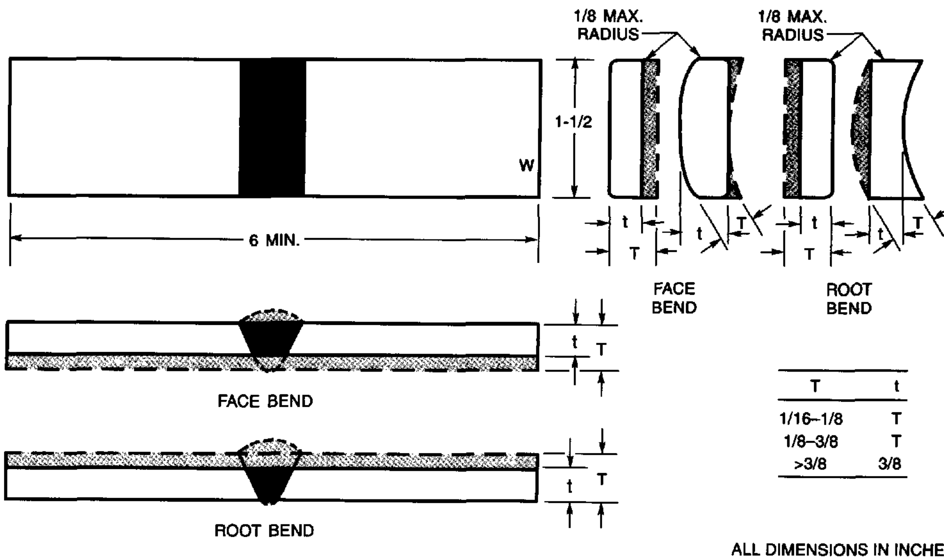

SPECIMEN 4




SPECIMEN 5

| Dimensions | | | | | |
|---|---|---|---|---|---|
| | Specimen 1 in. | Specimen 2 in. | Specimen 3 in. | Specimen 4 in. | Specimen 5 in. |
| G — gauge length | 2.000 ± 0.005 | 2.000 ± 0.005 | 2.000 ± 0.005 | 2.000 ± 0.005 | 2.000 ± 0.005 |
| D — diameter (Note 1) | 0.500 ± 0.010 | 0.500 ± 0.010 | 0.500 ± 0.010 | 0.500 ± 0.010 | 0.500 ± 0.010 |
| R — radius of fillet, min. | 3/8 | 3/8 | 1/16 | 3/8 | 3/8 |
| A — length of reduced section (Note 2) | 2-1/4 min | 2-1/4 min | 4 approx | 2-1/4 min | 2-1/4 min |
| L — over-all length approx. | 5 | 5-1/2 | 5-1/2 | 4-3/4 | 9-1/2 |
| B — length of end section | 1-3/8 approx | 1 approx | 3/4 approx | 1/2 approx | 3 min |
| C — diameter of end section | 3/4 | 3/4 | 23/32 | 7/8 | 3/4 |
| E — length of shoulder and fillet section, approx. | — | 5/8 | — | 3/4 | 5/8 |
| F — diameter of shoulder | — | 5/8 | — | 5/8 | 19/32 |

**Figure 13.5 (Continued)—Standard Tensile Specimens**



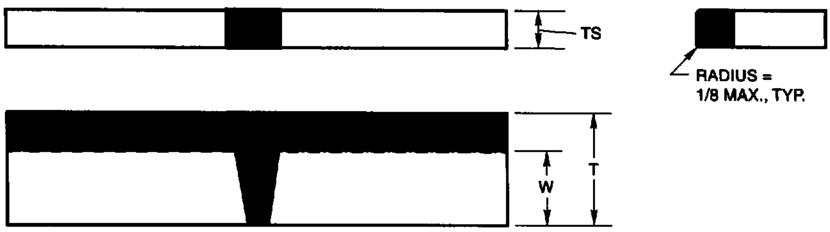

| T | t |
|---|---|
| 1/16–1/8 | T |
| 1/8–3/8 | T |
| >3/8 | 3/8 |

| in. | mm |
|---|---|
| 1/16 | 1.6 |
| 1/8 | 3.2 |
| 3/8 | 9.5 |
| 1-1/2 | 38 |
| 6 | 152 |

| | Specimen Thickness (TS) | |
|---|---|---|
| Thickness of Base Materials (T) | M-23 & M-35 All F-23 Welds | All Other Materials |
| 1/16 to 1/8 | T | T |
| 1/8 to 3/8 | 1/8 | T |
| Over 3/8 | 1/8 | 3/8 |

Notes:
1. Weld reinforcement and backing strip or backing ring, if any, shall be removed flush with the surface of the specimen.
2. For pipe diameters of 2 through 4 in. NPS, the width of the bend specimen may be 3/4 in. For pipe diameters of 3/8 to 2 in. NPS, the bend specimen width may be 3/8 in., with an alternative (permitted for pipe 1 NPS in. and less) of cutting the pipe into quarter sections, in which case the weld reinforcement may be removed and no other preparation of the specimens is required.

**Figure 13.6(A)—Transverse Face- and Root-Bend Specimens**




| | Specimen Thickness (TS) | | |
|---|---|---|---|
| Weld Thickness | M-23 & M-35 and Any F-23 Welds | All Other M Numbers | Width of Specimen (W) |
| 3/8 to 1-1/2 | 1/8 | 3/8 | T |
| Over 1-1/2 | 1/8 | 3/8 | See Note 3 |

Notes:
1. Weld reinforcement and backing strip or backing ring, if any, shall be removed flush with the surface of the specimen. If a recessed ring is used, this surface of the specimen may be machined to a depth not exceeding the depth of the recess to remove the ring, except that in such cases the thickness of the finished specimen shall be that specified above.

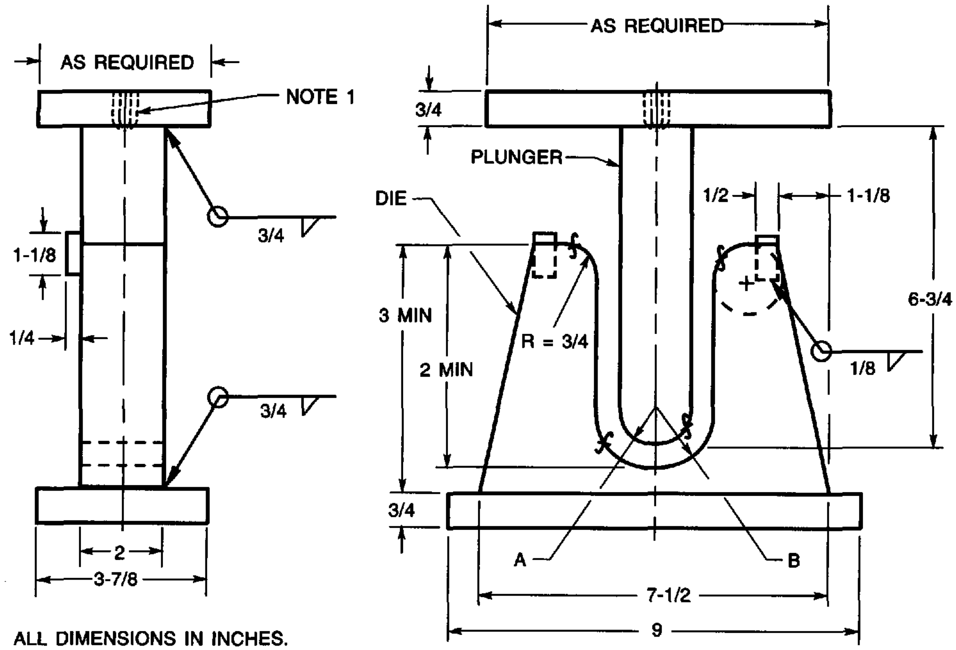
**Figure 13.6(B)—Transverse Side-Bend Specimens**

Face and root bends are generally used for materials 3/8 in. (10 mm) or less in thickness. Pipe and plate specimen preparation and dimensions are shown in Figure 13.6(A). Side bends are used for materials 3/8 in. and greater in thickness. Specimen preparation and dimensions are shown in Figure 13.6(B). Longitudinal bends may be used for welded joints having differing mechanical properties. Specimens are prepared with the longitudinal axis of the weld running parallel to the long dimension of the specimen. Specimen preparation should be in accordance with dimensions and details shown in Figure 13.6. Tool marks, if any, should be parallel to the long dimension of the specimen.

*Note: Tests have shown that the severity of the guided bend test increases to some extent with increasing width-to-thickness ratio of the specimen. Results of the side bend test are therefore not directly comparable when obtained on specimens shown in Figure 13.6, having different widths, W. Other materials such as aluminum and copper alloys may be subject to different requirements.*

**13.4.2.1 Procedure.** Each specimen should be bent in a fixture with the working contour shown in Figure 13.7, and otherwise substantially in accordance with that figure. However, steels and other materials with a tensile strength over 100 000 psi (690 MPa) require that rollers be used instead of hardened and greased shoulders. For higher yield strength steels and other materials, the plunger radius is sometimes increased to three times the thickness of the material, or more. Any convenient means may be used to move the plunger member with relation to the die member.

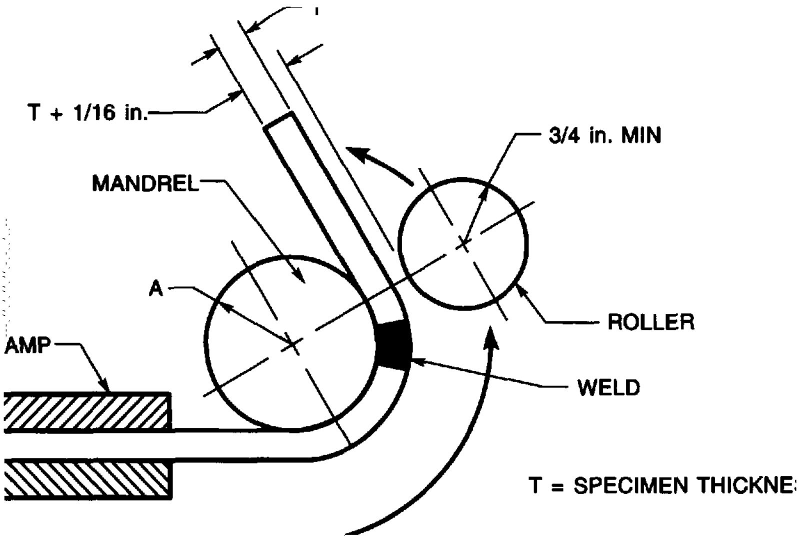
In performing this test, the specimen is placed on the die member of the fixture with the weld at midspan. Face-bend specimens are placed with the face of the weld directed




| Fixture Dimensions for 20% Elongation of Weld | | |
|---|---|---|
| Specimen Thickness, T in. | Plunger Radius, A in. | Die Radius, B in. |
| 3/8 | 3/4 | 1-3/16 |
| T | 2T | A + T + 1/16 |

Notes:
1. Tapped hole of appropriate size, or other suitable means for attaching plunger to testing machine.
2. Either hardened and greased shoulders or hardened rollers free to rotate shall be used in die.
3. The plunger and its base shall be designed to minimize deflection and misalignment.
4. The plunger shall force the specimen into the die until the specimen becomes U-shaped. The weld and heat-affected zones shall be centered and completely within the bent portion of the specimen after testing.
5. Weld sizes indicated are recommendations. The actual size is the responsibility of the user to ensure rigidity and design adequacy.

**Figure 13.7—Fixture for Guided Bend Test**




Notes:
1. It is essential to have adequate rigidity so that the bend fixture will not deflect during testing. The specimen shall be firmly clamped on one end so that it does not slide during the bending operation.
2. Test specimens shall be removed from the bend fixture when the roller has traversed 180° from the starting point.

**Figure 13.7 (Continued)—Fixture for Guided Bend Test**

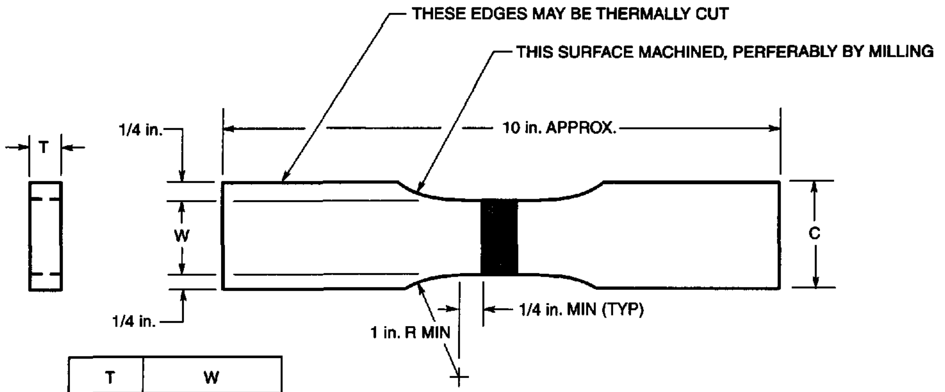
toward the gap. Root-bend specimens are placed with the root of the weld directed toward the gap. Side-bend specimens are placed with that side showing the greater defects, if any, directed toward the gap.

The two members of the fixture are forced together until the specimen attains a specified angle of bend. For steels containing less than approximately 2% alloying elements, the final shape is usually a "U" and the plunger is continued downward until a 1/8 in. (3.2 mm) diameter wire cannot be placed between the specimen and any point on the curvature of the plunger member of the fixture. Welds with more than this alloy content, or tensile strengths in excess of 100 000 psi (690 MPa), seldom have sufficient ductility to make a complete "U" bend without fracture.

Materials having yield strength over 50 000 psi (345 MPa) minimum may be tested by bending the specimen to increased radii.

**13.4.2.2 Results.** The convex surface of the specimen is examined for the appearance of cracks or other open defects. Any specimen in which cracks or other open defects are present after the bending, in excess of a specified number and size, is considered as having failed. Cracks that occur on the corners of the specimens during testing generally are considered irrelevant.

**13.4.3 Tensile Strength Specimens.** For welded butt joints in plate, the tension specimen should comply with the requirements of Figure 13.8(A) and (B). Circumferentially welded joints in pipe may be tested as sectioned specimens or a complete pipe or tube, depending on the diameter of the test piece. Pipe or tubing 2 in. (50 mm) in diameter and larger may be tested using tension specimens as in Figure 13.8. The ends of the specimens may be modified to accommodate the testing machine jaws. Pipe and tubing less than 2 in.




| T | W |
|---|---|
| < 1 in. | 1.50 ± 0.01 in. |
| ≥ 1 in. | 1.00 ± 0.01 in. |

Notes:
1. Thin base metal being tested tends to tear and break near the shoulder. In such cases, dimension C shall be no greater than 1-1-3 times the width of the reduced section.
2. Weld reinforcement and backing strip, if any, shall be removed flush with the surface of the specimen.
3. When the thickness, t, of the test weldment is such that it would not provide a specimen within the capacity limitations of the available test equipment, the specimen shall be parted through its thickness into as many specimens as required.
4. The length of reduced sections shall be equal to the width of the widest portion of weld, plus 1/4 in. minimum on each side.
5. All surfaces in the reduced section should be no rougher than 125 microinches $R_a$.
6. Narrower widths (W and C) may be used when necessary. In such cases, the width of the reduced section should be as large as the width of the material being tested permits. If the width of the material is less than W, the sides may be parallel throughout the length of the specimen.

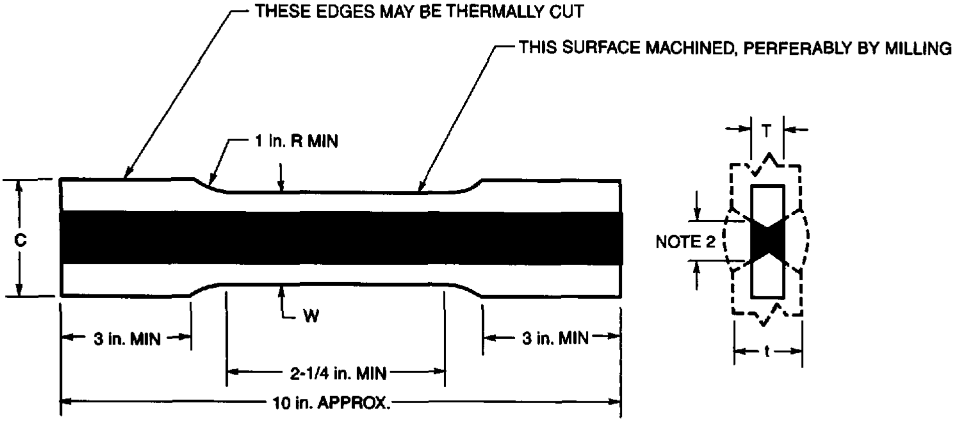
**Figure 13.8(A)—Transverse Rectangular Tension Test Specimen (Plate)**

(50 mm) in diameter may be tested using the complete welded specimen without sectioning. Weld reinforcement may or may not be removed depending upon the governing code or specification.

**13.4.3.1Procedure.** For reduced tension specimens the least width and corresponding thickness of the reduced section is measured in inches (or millimeters). For small tube specimens, the average outside diameter (O.D.) of the base metal, at a distance not exceeding 1/2 in. (13 mm) from the boundary between the base metal and the weld metal, and the average inside diameter (I.D.) of the base metal at either end of the specimen are measured in inches (or millimeters). The specimen is ruptured under tensile load and the maximum load in pounds (or kg) is determined.

**13.4.4 Fillet Weld Test.** The fillet weld soundness test is used to evaluate procedures and welders for T-or lap joints.

**13.4.4.1 Specimen.** The fillet weld break specimen should be prepared as shown in Figure 13.9. Material used for the test plate should have sufficient yield strength to cause fracture in the weld zone without bending. The

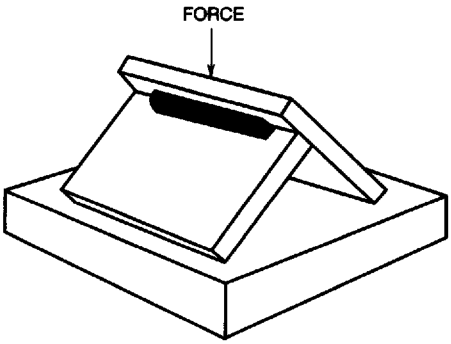


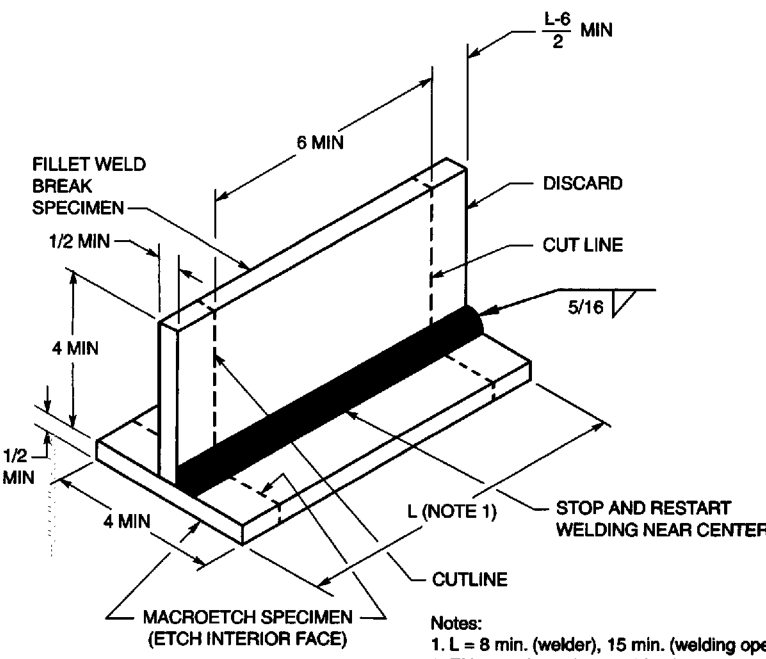

| Dimensions | | |
|---|---|---|
| | Specimen 1 in. | Specimen 2 in. |
| W = width | 1 ± 0.05 | 1-1/2 ± 0.125 |
| B = width of weld | 1/2 approx | 3/4 approx |
| nominal C = width of grip section | 1-1/2 | 2 |

Notes:

1. The weld reinforcement and backing, if any, shall be removed, flush with the surface of the specimen.
2. The width of the weld may be varied to approximate 1/2 W by selecting an appropriate specimen thickness, T, and its location within the weld.
3. The width, W, may be varied within reason to accommodate the width of the weld if it is not possible to meet the requirements of Note 2.
4. The grip sections of the specimen shall be symmetrical with the center line of the reduced section, within 1/8 in.
5. All surfaces in the reduced section should be no rougher than 125 microinches $R_a$.
6. Narrower widths (W and C) may be used when necessary. In such cases, the width of the reduced section should be as large as the width of the material being tested permits. If the width of the material is less than W, the sides may be parallel throughout the length of the specimen.

**Figure 13.8(B)—Longitudinal Rectangular Tension Test Specimen (Plate)**




| in. | mm |
|---|---|
| 5/16 | 8 |
| 1/2 | 13 |
| 4 | 100 |
| 6 | 150 |
| 15 | 380 |

Notes:
1. L = 8 min. (welder), 15 min. (welding operator)
2. Either end may be used for the required macroetch specimen, The other end may be discarded.

**Figure 13.9—Typical Fillet Weld Break and Macroetch Test for Fillet Welder or Welding Operator Qualification**

weld is deposited using the material, position, and procedure intended for production welds.

**13.4.4.2 Procedure.** The test plate is welded on one side of the T joint. Specimens for evaluation are removed for break and macroetch tests as shown in Figure 13.9. The fillet weld break specimen is broken by applying pressure to cause the fracture to occur at the welded joint. The macroetch specimen is prepared by polishing and etching the cross section with a suitable reagent.

**13.4.4.3 Results.** The surfaces of the fracture are examined for compliance with the applicable code or specification. The macroetched specimen is examined for bead configuration and evidence of defects.

**13.4.5 Fracture Toughness Tests.** Fracture toughness is a term for the resistance to the extension of a crack in metal. The most common method used in the U.S. for measuring the fracture toughness of a welded joint is the Charpy V-notch Impact Test (CV). Other types or fracture toughness tests of welds that are used to some extent are the Dynamic Tear (DT), the Plain-Strain Compact Tension Fracture Toughness ($K_q$), and the Drop Weight Nil-Ductility Temperature (DWNDT) tests. The procedure for these tests of welds are given in AWS B4.0.

Impact testing of ferritic steels is necessary because certain types fail by brittle fracture at service temperatures even though they exhibit normal properties during the standard tensile test. This failure by brittle fracture may occur when the material is used in the notched condition. Notched conditions include restraint due to deformation in directions perpendicular to the major stress, multi-axial stress, and stress concentrations. It is in this field that the impact tests prove useful to determine susceptibility of the steels to notch-brittle behavior. However, test results cannot be used directly to appraise the serviceability of a structure.

Notched impact tests, such as Charpy V-notch, bring out notched behavior by applying a single overload of stress. The absorbed energy "values" determined are quantitative comparisons based on a selected specimen; they cannot be converted into energy values that would serve for engineering design calculations.

Whenever possible, testing should be performed using the standard size specimen. Increasing either the width or depth of the specimen increases the volume of metal subject to distortion and the energy absorption when the specimen is broken. However, any increase in size, particularly in width, also tends to increase the degree of restraint and, by increasing the tendency to induce brittle fracture, may decrease the amount of energy absorbed. Thus, while a standard size specimen may be on the verge of brittle fracture, a double-width specimen may actually require less energy to rupture than one of standard width. For these reasons, correlation of the energy values obtained from specimens of different size or shape is, in general, not feasible.

Testing conditions also affect the notched behavior. So pronounced is the effect of temperature on the behavior of notched steel, that comparisons are frequently made by examining specimen fractures and plotting energy value and fracture appearance against temperature from tests of notched bars at a series of temperatures. When the test temperature has been carried low enough to start cleavage fracture, there may be either an extremely sharp drop in impact value or a relatively gradual falling off toward the lower temperatures. The transition temperature at which this embrittling effect takes place varies considerably with chemical composition, welding procedure, and postweld heat treatment.[9]

---

9. Some of the many definitions of transition temperature currently being used are:

(1) The lowest temperature at which the specimen exhibits a fibrous structure

(2) The temperature at which the specimen fracture shows a 50 percent crystalline and a 50 percent fibrous appearance

(3) The temperature corresponding to the energy value that equals 50 percent of the difference between values obtained at 100 percent fibrous and zero fibrous

(4) The temperature corresponding to a specific energy value

(5) Lateral expansion at hinge of at least 0.010 in. (0.25 mm)

**13.4.5.1 Specimens.** The Charpy specimens are machined as shown in Figure 13.10. It is important that the root of the notch has the proper radius, and is machined with sharp (preferably carbide) cutters to minimize tearing and other nonuniform notch contours.

The energy absorption is related to the notch geometry. A sharp crack started in the notch can reduce the energy absorption significantly. For example, if the notch is machined with a flat bottom, then a crack can form at the sharp corner where the flat bottom intersects the side wall. This reduces the reported energy absorption, but the test is invalid because the standard notch tolerances were not present.

**13.4.5.2 Procedure.** Testing is performed on a pendulum-type apparatus. The supports and striking edge should be of the form and dimensions shown in Figure 13.11. Other dimensions of the pendulum and support should be such as to minimize interference between pendulums, supports, and broken specimens.

The support should be such that the center of gravity of the test specimen is on a line tangent to the arc of travel of the striking point of the pendulum, drawn at the position of impact.

The machine should be furnished with scales graduated either in degrees, joules, or foot-pounds force. Percentage of error in energy of blow caused by variations in the weight of the pendulum, height of fall, or friction should not exceed ±0.4 percent. Several machines of this type are made commercially and should be calibrated at least once a year with standard specimens. These may be obtained from the National Institute of Standards and Technology (NIST). A complete description of notched-bar impact testing is contained in ASTM Standard A370.

**13.4.5.3 Results.** After testing all specimens, the complete report should contain the following:

(1) the type and model of machine used,

(2) the type of specimen used,

(3) machine calibration date,

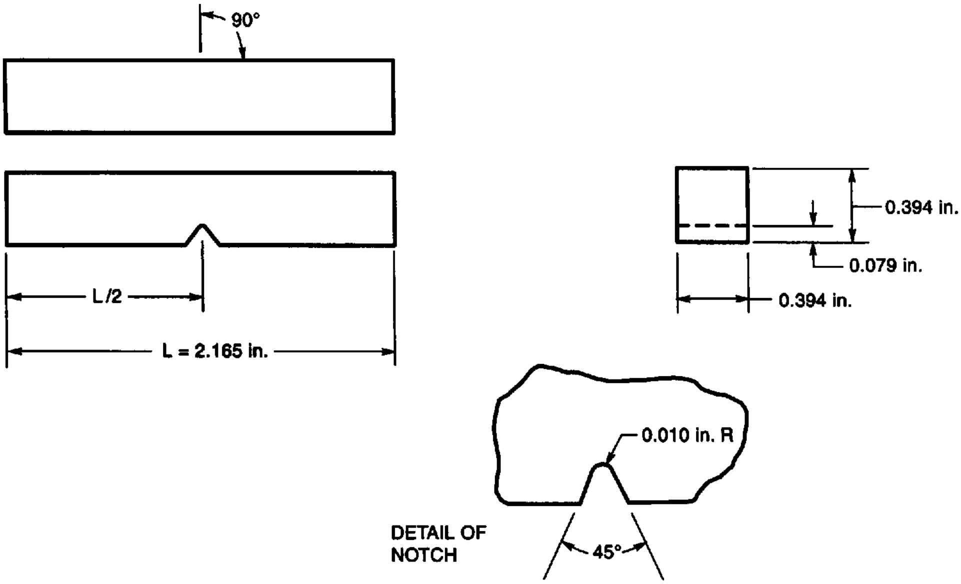
(4) the temperature of the specimen, or the room condition if both are the same,

(5) the energy actually absorbed by the specimen in breaking reported in total joules or foot-pounds force,

(6) appearance of fractured surface [(percent shear (dull)], percent cleavage or crystalline (shiny)],

(7) the number of specimens failing to break, and

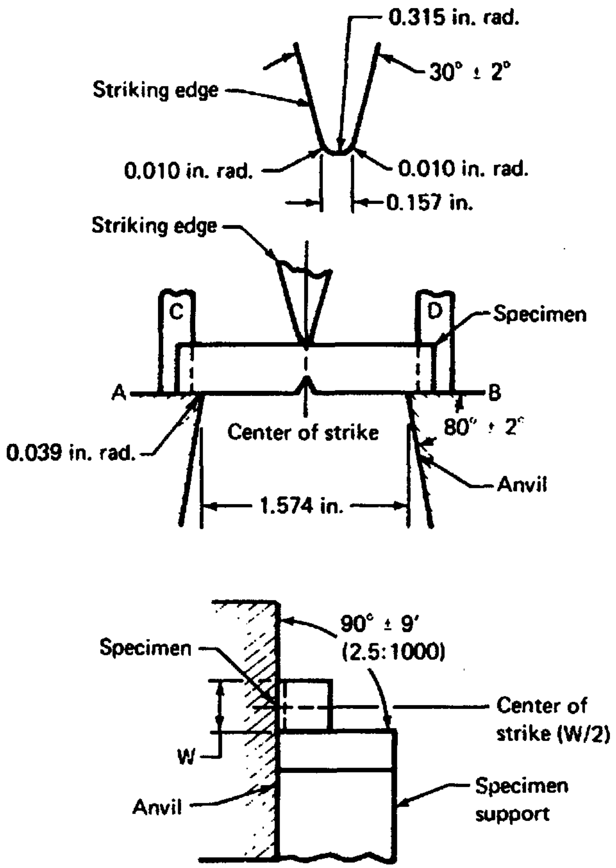
(8) lateral expansion at hinge of impact specimen.




NOTE—Dimensional Tolerances shall be as follows:

| | |
|---|---|
| Notch length to edge | 90° ± 2° |
| Adjacent sides shall be at | 90° ± 10 minutes |
| Cross section dimensions | ±0.003 in. |
| Length of specimen (L) | +0, −0.100 in. |
| Centering of notch (L/2) | ±0.039 in. |
| Angle of notch | ±1° |
| Radius of notch | ±0.001 in. |
| Notch depth | ±0.001 in. |
| Finish requirements | 63 microinches $R_a$ on notched surface and opposite face; 125 microinches $R_a$ on other two surfaces |

**Figure 13.10—Charpy (Simple-Beam) Impact Test Specimens**




All dimensional tolerances shall be ± 0.05 mm (0.002 in.) unless otherwise specified.

Notes:

1. A shall be parallel to B within 2:1000 and coplanar with B within 0.002 in. (0.05 mm).
2. C shall be parallel to D within 2.0:1000 and coplanar with D within 0.005 in. (0.125 mm).
3. Finish on unmarked parts shall be 125 μin. (4 μm).

**Figure 13.11—Charpy (Simple-Beam) Impact Test**

# Chapter 14
# Proof Tests

A *Proof Test* is a test of an object's ability to withstand the applicable service forces. Proof testing can use many different methods to determine that the object will meet the requirements imposed. Hardness test, pressure test, chemical test, tensile test, bend test, load test, spin test, leak test, and peel test are some of the many standard tests used to determine the quality/usability (proof test) of the object. The leak test is a specific proof test and the subject of leak testing is covered in Chapter 15.

## 14.1 Nondestructive Examination

Visual inspection (see Chapter 15) may also be a part of the proof test. In most cases, proof tests are applied in connection with "visual" examination (or at least some form of visual examination is required). Details of any required test or examination are usually specified by the drawings, specifications, or contract for the object.

Many welded components are proof tested during or subsequent to fabrication. This may involve overloading the component or testing for leaks or both. The proof test may be a destructive test of one object or a series of identical objects, or a object may be proof tested by applying specific loads without failure or permanent deformation. Such tests are usually designed to subject the parts to stresses exceeding those anticipated during service. However, the stresses are maintained below or at the minimum specified yield strength of the materials.

Structural members are often proof tested by demonstrating their ability to carry loads equal to or larger than any anticipated service conditions. This can be accomplished by statically loading with a testing machine, sand bags, or scrap iron, or by dynamically loading with special testing equipment. Acceptance is based on freedom from cracking, or objectionable permanent deformation.

## 14.2 Hardness Test

A Hardness Test is a test (proof) to determine if the material and the weld, or both, meets the specified requirements. Hardness testing of welds and materials is in Chapter 13, Destructive Testing of Welds.

Pneumatic testing, hydrostatic testing, and vacuum box testing are testing methods used to proof test containments such as pacemakers, autoclaves, cross-country pipelines, etc. A leak in a pacemaker is unacceptable, and a leak in a city water main can occur and be unacceptable to city residents impacted by the leak. The inspector is guided by Federal, National, State, and City codes and other standards, and project requirements when evaluating if a leak is tolerable. See Chapter 15 for the leak testing guidelines.

Open containers may be tested hydrostatically (by filling with water) and visually examined for leakage. Examples are water or oil storage tanks, or containers for other liquids. Watertight bodies for amphibious vehicles are usually tested by running the vehicle fully loaded into water and examining the seams for leakage while the vehicle is floating.

Weldments associated with rotating machinery parts or equipment are proof tested by overspinning the component and permitting centrifugal force to provide the desired stress levels, such as "150% design stress." Visual and nondestructive examination plus dimensional measurements are employed to determine the acceptability (function properly) of the part.

Most fabrication standards and codes do not specify proof tests to obtain "Reliability or Quality." The American Welding Society (AWS) standards and codes do not specify proof tests, but rely on Nondestructive Examinations to maintain the standard or code quality. The American Society of Mechanical Engineers' Boiler and Pressure Vessel codes use proof tests to only establish the Maximum Allowable Working Pressure (MAWP).

Contract specifications generally include specific requirements for testing, inspection, and repair in accordance with applicable codes and specifications.

If repair welding is to be done after testing, reference is made to AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers that Have Held Hazardous Substances*, to ensure that hazardous environments are not present.

# Chapter 15
# Nondestructive Examination Methods

## 15.1 Introduction

Nondestructive Examination (NDE) is a general term used in this text to identify methods that permit evaluation of welds and related materials without destroying their usefulness. Nondestructive Examination (NDE), Nondestructive Inspection (NDI), and Nondestructive Testing (NDT) are synonymous terms also used to identify these evaluation methods. The majority of prospective weld inspectors already know that visual examination certainly meets this criterion, but there are other NDE inspection methods. The purpose of this chapter is to acquaint the welding inspector with some of the more commonly used NDE methods and the fundamental conditions for their use.

The essential elements common to most all NDE methods include the following:

(1) A probing medium

(2) A test specimen that is appropriate for the medium being used so that discontinuities may be detected

(3) A detector capable of measuring the distributions or alterations in the media

(4) A technique for recording or displaying information received from the detector, suitable for evaluation.

(5) The operator who should be trained to interpret detector feedback to evaluate results.

Many types of media have been used in NDE methods; similarly, many properties of materials have been the fundamental basis for selecting a particular NDE technique. For purposes of this text only the following basic NDE methods will be discussed:

(1) Visual examination

(2) Radiographic examination

(3) Ultrasonic examination

(4) Magnetic particle examination

(5) Penetrant examination

(6) Eddy current examination

(7) Acoustic emission examination

(8) Leak examination

(9) Ferrite content examination

Nondestructive examination methods are not intended as a replacement for destructive tests. The welding inspector should be advised that destructive tests frequently are used to complement nondestructive examination and that each method may provide support for the other. It is not uncommon for the acceptance-rejection criteria of an NDE method to be developed by destructive test investigations correlated with NDE results. It is not within the scope of this chapter to offer comparative advantages between specific NDE methods, nor to present a full handbook of information on the numerous NDE techniques. Table 15.1 contains a brief summary of typical considerations generally used in selecting an NDE method for weld inspection. The general knowledge presented in this chapter should be of valuable assistance to the inspector as it provides an overview of the inspection methods available without unnecessary detail. Also contained within this chapter is a brief section on NDE procedures and the highlights of those requirements that complement the decision to establish written procedures.

## 15.2 Inspection by Visual Examination

For many types of welds, integrity is verified principally by visual examination. Even for weldments with joints specified for examination throughout by other nondestructive examination methods, visual examination is performed. Visual examination constitutes an

**Table 15.1**
**Considerations when Selecting an NDE Method**

| Equipment Needs | Applications | Advantages | Limitations |
|---|---|---|---|
| **Visual** | | | |
| Magnifiers, color enhancement, projectors, other measurement equipment, i.e., rulers, micrometers, optical comparators, light source. | Weld preparations and weld surfaces for dimensional and surface conditions. | Economical, expedient and relatively little equipment for many applications. | Limited to external or surface conditions only. Limited to the visual acuity of the observer/inspector. |
| **Radiography (Gamma)** | | | |
| Gamma ray sources, gamma ray camera projectors, film holders, films, lead screens, film processing equipment, film viewers, exposure facilities, radiation monitoring equipment, shielding material. | Most weld discontinuities including cracks, porosity, lack of fusion, incomplete penetration, slag, as well as corrosion and fit-up conditions. | Permanent record—enables review by parties at a later date. Gamma sources may be positioned inside of accessible objects, i.e., pipes, etc., for panoramic technique radiographs. Energy efficient source requires no electrical energy for production of gamma rays. | Radiation is safety hazard—requires control of facilities or areas where radiation will be used and requires special monitoring of exposure levels and dosages to personnel. Sources (gamma) decay over their half-lives and should be periodically replaced. Gamma sources have a constant energy of output (wavelength) and cannot be adjusted. Requires access to opposite sides of welds. Gamma source and related licensing requirements are expensive. Radiography requires highly skilled operating and interpretive personnel. |
| **Radiography (X-Rays)** | | | |
| X-ray sources (machines), electrical power source, same general equipment as used with gamma sources (above). | Same applications as above. | Adjustable energy levels, generally produces higher quality radiographs than gamma sources. Offers permanent record as with gamma (above). | High initial cost of X-ray equipment Not generally considered portable, radiation hazard as with gamma sources, skilled operational and interpretive personnel required. |

*(Continued)*

**Table 15.1 (Continued)**
**Considerations when Selecting an NDE Method**

| Equipment Needs | Applications | Advantages | Limitations |
|---|---|---|---|
| | | **Ultrasonic** | |
| Pulse-echo instrument capable of exciting a piezoelectric material and generating ultrasonic energy within a test piece, and having a suitable cathode ray tube capable of displaying the magnitudes and locations of received sound energy. Calibration standards, liquid couplant. | Most weld discontinuities including cracks, slag, lack of fusion, lack of bond, accurate thickness measurements possible. Poisson's ratio may be obtained by determining the modulus of elasticity. | Most sensitive to planar type defects. Test results known immediately. Portable. Ultrasonic flaw detectors do not require an electrical power outlet. High outlet. High penetration capability. Requires access from only one surface. | Surface condition should be suitable for coupling of transducer. Couplant (liquid) required. Small, thin welds may be difficult to inspect. Reference standards are required. Requires a relatively skilled operator/inspector, and skilled interpretive personnel. Resolution of small defects near surface difficult. |
| | | **Magnetic Particle** | |
| Prods, yokes, coils suitable for inducing magnetism into the test piece. Power source (electrical). Magnetic powders, some applications require special facilities and ultraviolet lights. Gauge meters and field indications. | Most weld discontinuities open to or near the surface. Most suitable for cracks and other linear conditions. | Relatively economical and expedient. Inspection equipment is considered portable. Unlike liquid penetrants, magnetic particle can detect some near surface discontinuities. Can inspect through thin coatings. | Applicable only to ferromagnetic materials. Parts should be clean before and after inspection. Thick coatings may mask rejectable indications. Some applications require parts to be demagnetized after inspection. Magnetic particle inspection requires use of electrical energy for most applications. Some potential for arc strikes on surface. |
| | | **Liquid Penetrant** | |
| Fluorescent or visible dye. Penetrant, developers, cleaners (solvents, emulsifiers, etc.). Suitable cleaning gear. Ultraviolet light source and darkened area if fluorescent dye is used. | Weld discontinuities open to surface, i.e., cracks, porosity, seams. | May be used on all nonporous materials. Portable, relatively inexpensive equipment. Expedient inspection results. Results are easily interpreted. Requires no electrical energy except for light source. Indications may be further examined visually. | Surface films such as coatings, scale, smeared metal mask or hide rejectable defects. Bleed out from porous surfaces can also mask indications. Parts should be cleaned before and after inspection. |

*(Continued)*

**Table 15.1 (Continued)**
**Considerations when Selecting an NDE Method**

| Equipment Needs | Applications | Advantages | Limitations |
|---|---|---|---|
| | | **Eddy Current** | |
| An instrument capable of inducing electromagnetic fields within a test piece and sensing the resulting electrical currents (eddy) so induced with a suitable probe or detector. Calibration standards. | Weld discontinuities near the surface (i.e., cracks, porosity, fusion). Alloy content, heat treatment variations, wall thickness, and plating or coating thickness. | Relatively expedient, with instantaneous results. Automation possible for symmetrical parts. No couplant required. Probe does not have to be in intimate contact with test piece. Skilled interpretive personnel. | Limited to conductive materials. Shallow depth of penetration. Some indications may be masked by part geometry due to sensitivity variations. Reference standard required. |
| | | **Acoustic Emission** | |
| Emission sensors, amplifying electronics, signal processing electronics including frequency gates, filters. A suitable output system for evaluating the acoustic signal (audio monitor, visual monitor, counters, tape recorders, X-Y recorder.) | Internal cracking in welds during cooling, crack initiation and growth rates. In service monitoring of welds. | Real time and continuous surveillance inspection. May be inspected remotely. Portability of inspection apparatus. Can identify source of emissions. | Requires the use of transducers coupled on the test part surface. Part should be in "use" or stressed. More ductile materials yield low amplitude emissions. Noise should be filtered out of the inspection system. |
| | | **Leak Test** | |
| Exact equipment depends upon the leak test method used (see text). Generally needs equipment capable of inducing a pressure differential and some form of detection device capable of sensing the leak. Some applications will require special leak test medium. | Welds which have defects extending through the weld volume. | Many components may be "real time" inspected in conjunction with a proof test. Some applications utilize relatively little operator training. Test results are usually expedient. | Some methods require special facilities and are time consuming to inspect. Applications requiring high levels of sensitivity are usually uneconomical and require personnel extensively trained. |

important part of practical quality control. Therefore, visual examination is of the first order of importance.

The most extensively used of any method of nondestructive examination, visual examination is easy to apply, quick, relatively inexpensive, requires good eyesight, and gives important information regarding the general conformity of the weldment to specifications.

For convenience of presentation, visual examination is discussed under five main headings: visual examination practice, examination prior to welding, examination during welding, examination after welding, and marking welds for repairs. The welding engineer data sheet checklist for visual inspection (see Figure 15.1) identifies points to consider during each welding phase.

## 15.3 Visual Examination Practice

The inspector should be familiar with the applicable documents, workmanship standards, and all phases of good shop practice. The weld to be examined should be well lighted. Inaccessible areas can be viewed with a borescope, and, when so required by a customer, a low power magnifier may be used. A low power magnifier should be used with caution since it does accentuate the surface and can make decisions arguable.

Welds that are inaccessible in the finished product should be examined during the progress of the work. Scales and gauges (see Figure 15.2) are used for checking the fit-up of pieces and the dimensions of the weld bead. Although visual inspection is the simplest of the inspection methods, a definite procedure should be established in order to insure adequate coverage.

**Before Welding**

__ Review applicable documentation
__ Check welding procedures
__ Check individual welder qualifications
__ Establish hold points
__ Develop inspection plan
__ Develop plan for recording inspection results and maintaining those records
__ Develop system for identification of rejects
__ Check condition of welding equipment
__ Check quality and condition of base and filler materials to be used
__ Check weld preparations
__ Check joint fit-up
__ Check adequacy of alignment devices
__ Check weld joint cleanliness
__ Check preheat, when required

**During Welding**

__ Check welding variables for compliance with welding procedure
__ Check quality of individual weld passes
__ Check interpass cleaning
__ Check interpass temperature
__ Check placement and sequencing of individual weld passes
__ Check backgouged surfaces
__ Monitor in-process NDT, if required

**After Welding**

__ Check finished weld appearance
__ Check weld size
__ Check weld length
__ Check dimensional accuracy of weldment
__ Monitor additional NDT, if required
__ Monitor postweld heat treatment, if required
__ Prepare inspection reports

**Figure 15.1—Welding Engineer Data Sheet**

**15.3.1 Examination Prior to Welding.** Inspection starts with examination of the material prior to fabrication, a practice that can eliminate conditions that tend to cause weld defects. Scabs, seams, scale, or other harmful surface conditions may be detected during visual examination. Plate laminations may be observed on cut edges. Plate dimensions may be determined by measurement. Identification of material type and grade should be made.

After the parts are assembled in position for welding, the inspector should check root openings taking into account structural tolerances, edge preparation, and other features of joint preparation that might affect the quality of the welded joint. The inspector should

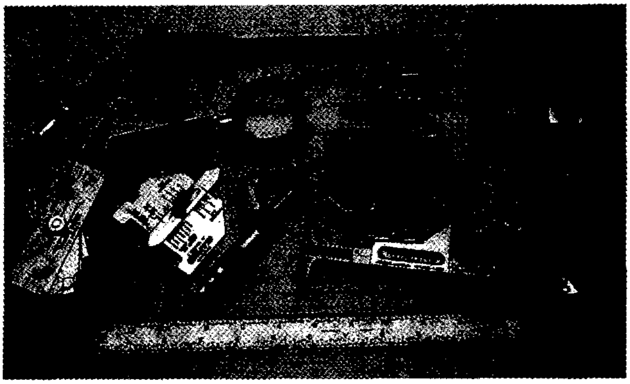


**Figure 15.2 —Scales and Gauges for Checking Fit-Up and Weld Dimensions**

check the following conditions for conformity to the applicable specifications:

(1) Joint preparation, dimensions, and finish

(2) Clearance dimensions of backing strips, rings, or backing filler metal

(3) Alignment and fit-up of the pieces being welded

(4) Verification of cleanliness

(5) Approved/qualified weld procedure specification and welders/welding operators

**15.3.2 Examination During Welding.** Visual examination checks details of the work while fabrication is in progress, such as:

(1) Welding process and conditions

(2) Filler metal

(3) Flux and/or shielding gas

(4) Preheat and interpass temperature

(5) Distortion control

(6) Interpass chipping, grinding, or gouging

(7) Weld bead contours (Figure 15.3)

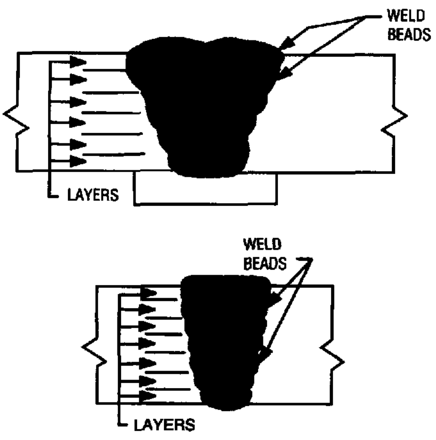



**Figure 15.3—Weld Bead Contours**

The inspector should be thoroughly familiar with all the items involved in the qualified welding procedure specification. These should be checked with particular care, especially during the early stages of production, and compliance with all details of the procedure should be verified.

Examination of successive layers of the weld deposit is sometimes carried out with the assistance of a workmanship standard. Figure 15.4 indicates how such a standard may be prepared. This is a section of a joint similar to the one in production, in which portions of successive weld layers are shown. Each layer of the production weld may be compared with corresponding layer of the workmanship standard. One should realize that this workmanship sample was made

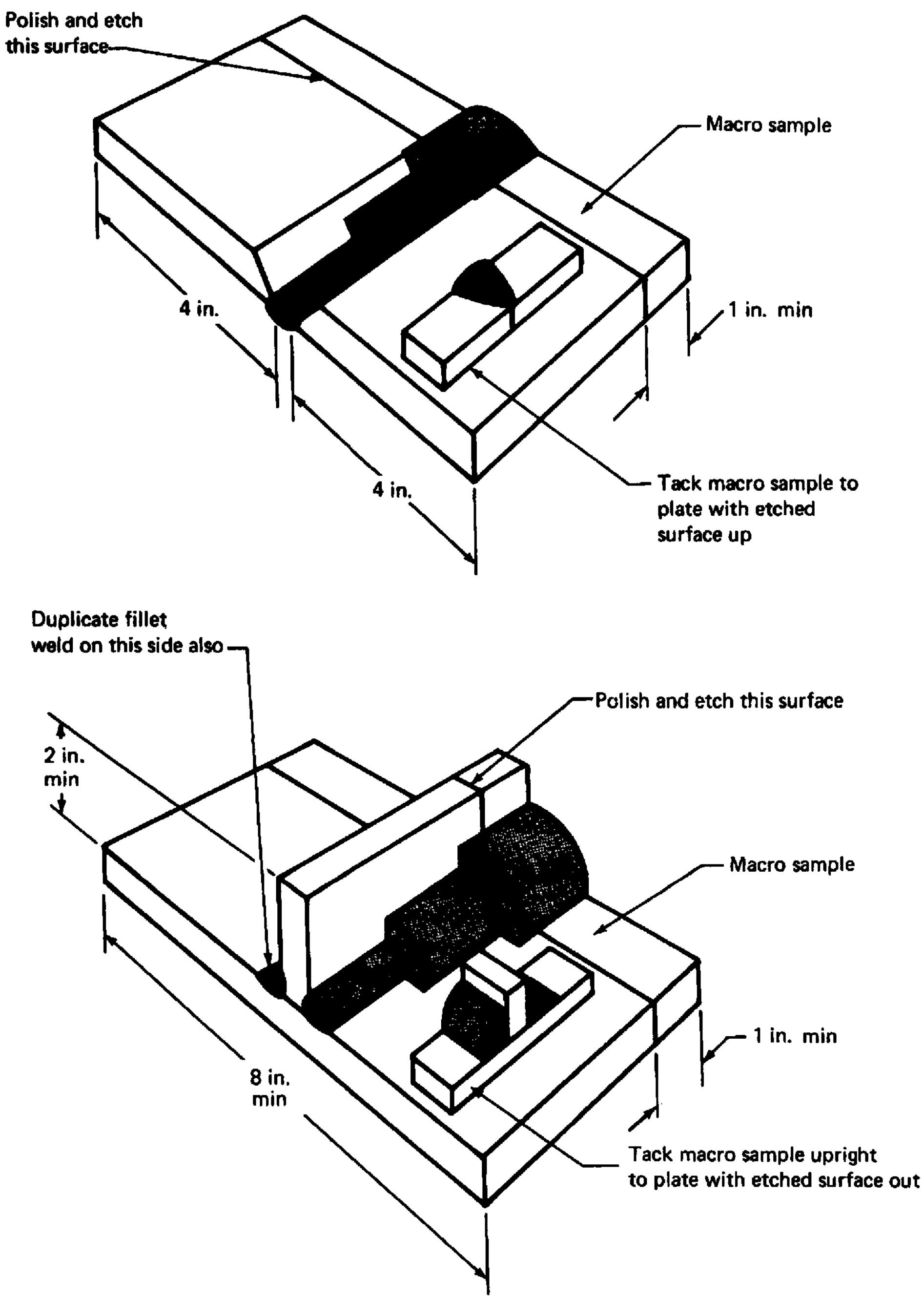



**Figure 15.4—Workmanship Standard**

under ideal conditions and may not truly represent actual job conditions; allowances should be made for production tolerances.

The first layer, or root pass of a weld, is the most important one from the point of view of final weld soundness. Because of the geometry of the joint, the relatively large volume of base metal with respect to that of the root pass weld metal, the fact that the plate may be cold, and the possibility that the arc may not strike into the root, the root pass freezes quickly. In so doing, it tends to trap slag or gas that resists removal during subsequent passes. In addition, the metal melted during this pass is particularly susceptible to cracking. Such cracks may not only remain, but may extend to subsequent layers. Examination of this pass should be thorough, and a workmanship standard can be very useful for this inspection. As will be shown later in this section, nondestructive examinations may give evidence as to conditions in the root pass, and thus serve as a verification of visual examination.

Examination of the root pass offers another opportunity to inspect for plate laminations, since these discontinuities tend to get larger because of the affects of heat incident to the welding operation.

In the case of double-groove welds, slag from the root pass on one side of the weld may be trapped in the deposit on the other side of the weld. Such deposits are usually chipped, ground, or gouged out prior to welding the opposite side. Where slag removal is incomplete, slag will remain in the root of the finished weld.

The root opening should be monitored as root pass welding progresses. Special emphasis should be placed on the adequacy of the tack welds and clamps or braces designed to maintain the root opening to assure penetration and alignment. The importance of this root opening is not limited to butt joints but also applies to branch and angle connections that are more difficult to inspect after the weld has been completed. (The inspector should take advantage of opportunities for check examinations whenever they are offered.)

**15.3.3 Inspection After Welding.** Visual inspection is useful for finished product verification of such items as:

(1) Dimensional accuracy of the weldment (including distortion)

(2) Conformity to drawing requirements (involving determination of whether all required welding has been done, and whether finished welds conform to required size and contour) (Figure 15.3)

(3) Acceptability of welds with regard to appearance includes such items as surface roughness, weld spatter, etc. (Figures 15.3 and 15.4)

(4) The presence of unfilled craters, arc strikes, undercuts, overlaps, and cracks (Figures 15.5 and 15.6)

(5) Evidence of mishandling from center punch or other inspection marking or excessive grinding

Dimensional accuracy of weldments is determined by conventional measuring methods and need not be commented upon in this section.

The conformity of weld size and contour may be determined by the use of weld gauges. The size of a fillet weld in joints whose members are at right angles, or nearly so, is generally defined in terms of the length of the leg, the thickness or "throat" and the profile (concavity or convexity). Gauges will determine

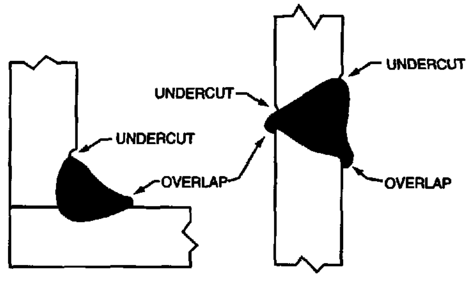



**Figure 15.5—Sketches of Weld Undercut and Overlap**

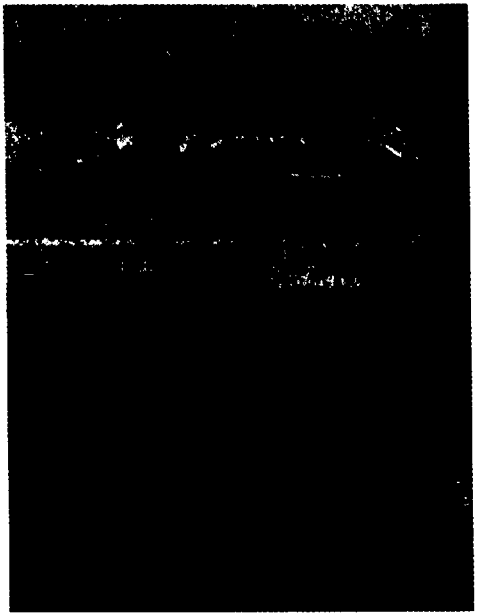


**Figure 15.6—Photographs of Weld Undercut and Overlap**

whether the size is within allowable limits and whether there is excessive concavity or convexity.

Special gauges may be made for use where the surfaces are at angles of less than or greater than 90 degrees. There are a variety of commercially available weld gauges, fillet gauges, protractors, etc. [see Figure 15.7].

For groove welds, the width of finished welds will vary in accordance with the required groove angle, root face, root opening, thickness of the material, and permissible tolerances. The height of reinforcement should be consistent with specified requirements. Requirements as to surface appearance differ widely, and, in general, the weld surface should be as specified in a code or customer's specifications. Visual standards, or sample weldments submitted by the fabricator and agreed to by the purchaser, can be used as guides to appearance. Sometimes a smooth weld, strictly uniform in size and contour, is required because the weld forms part of the exposed surface of the product and good appearance is desirable.

The presence of defects that affect service performance is, in most instances, more objectionable than those that affect appearance. The former are discussed in Chapter 9; however, the following are a few examples:

(1) Cracks
(2) Undercuts
(3) Overlap
(4) Excessive weld irregularity
(5) Dimensional inaccuracies

For accurate detection of such defects, the weld surface should be thoroughly cleaned before inspection.

**15.3.4 Marking Welds For Repair.** One of the most important details of nondestructive examination is the proper marking of the areas to be repaired. This marking should be:

(1) Positive and clear,

(2) In accordance with a method of marking established and understood, by all inspectors and by shop personnel involved in making the repair,

(3) Of a distinctive color or technique that it is not easily confused with other markings,

(4) Permanent enough to be evident until after the repair has been made and inspected,

(5) Selected so that the ink, paint, etc. will not damage the material, and

(6) Removed if not acceptable to service conditions.

The repair should be inspected, and the inspector should be able to find the markings; therefore, the marking medium should be such that the marks will survive rough handling incident to repair. After the repair has been made and inspected, it should be properly marked to indicate whether or not the repair is satisfactory.

**15.3.5 Summary.** Visual examination, as indicated above, is invaluable as an inspection method; however, some caution should be used in drawing conclusions. For example, good surface appearance is often regarded as indicative of careful workmanship and high weld quality. However, surface appearance

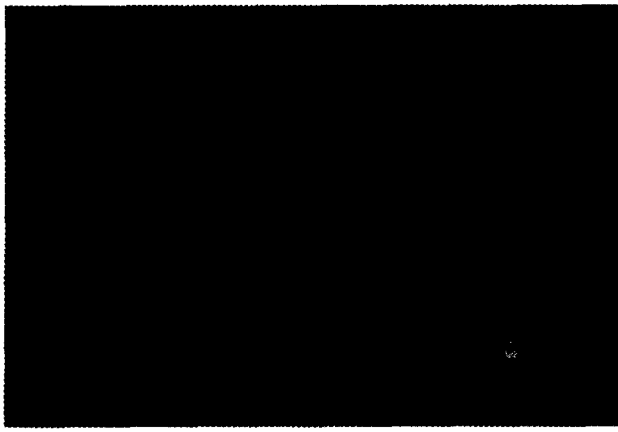


**Figure 15.7—Weld Inspection Gauges**

alone does not prove careful workmanship and is not a conclusive indication of subsurface condition. Thus, judgment of weld quality should be based on evidence that is in addition to that afforded by surface indications. Such additional evidence is afforded by observations that have been made prior to and during welding and the implementation of other NDE methods. For instance, if the inspector knows that the plate was free of laminations, that the edge preparation was correct, that the root opening was as specified, that the root pass was sound, and that the qualified welding procedure was followed carefully, the inspector may be reasonably safe in judging the completed weld on the basis of visual examination.

## 15.4 Inspection By Radiographic Examination

Radiography is a method of nondestructive examination that utilizes radiation to penetrate an object and (1) record images on a variety of recording devices such as film or photosensitive paper, (2) be viewed on a fluorescent screen, or (3) be monitored by various types of electronic radiation detectors. When an object to be examined is exposed to penetrating radiation, see Figure 15.8, some radiation will be absorbed, some will be scattered, and some radiation will be transmitted through the test object onto the recording device. Radiation will be differentially absorbed over various areas of the test object.

Most conventional radiographic processes used today involve exposures that record a permanent image on a photographic film. Additionally, most weldment examinations performed by the radiographic method use electromagnetic radiation, such as x-rays and gamma rays. Therefore, this section will be limited to radiography of weldments with those processes mentioned above. Only a brief introduction to the theory of radiographic testing as it applies to weld inspection and a review of the general application techniques will be presented in this text. Many excellent sources of reference materials are available to the welding inspector, containing detailed and specific technique considerations, terms and definitions in general use, as well as advanced and highly specialized aspects of the various attributes of the complete radiographic examination process. Some of these sources are listed at the end of this article and are highly recommended.

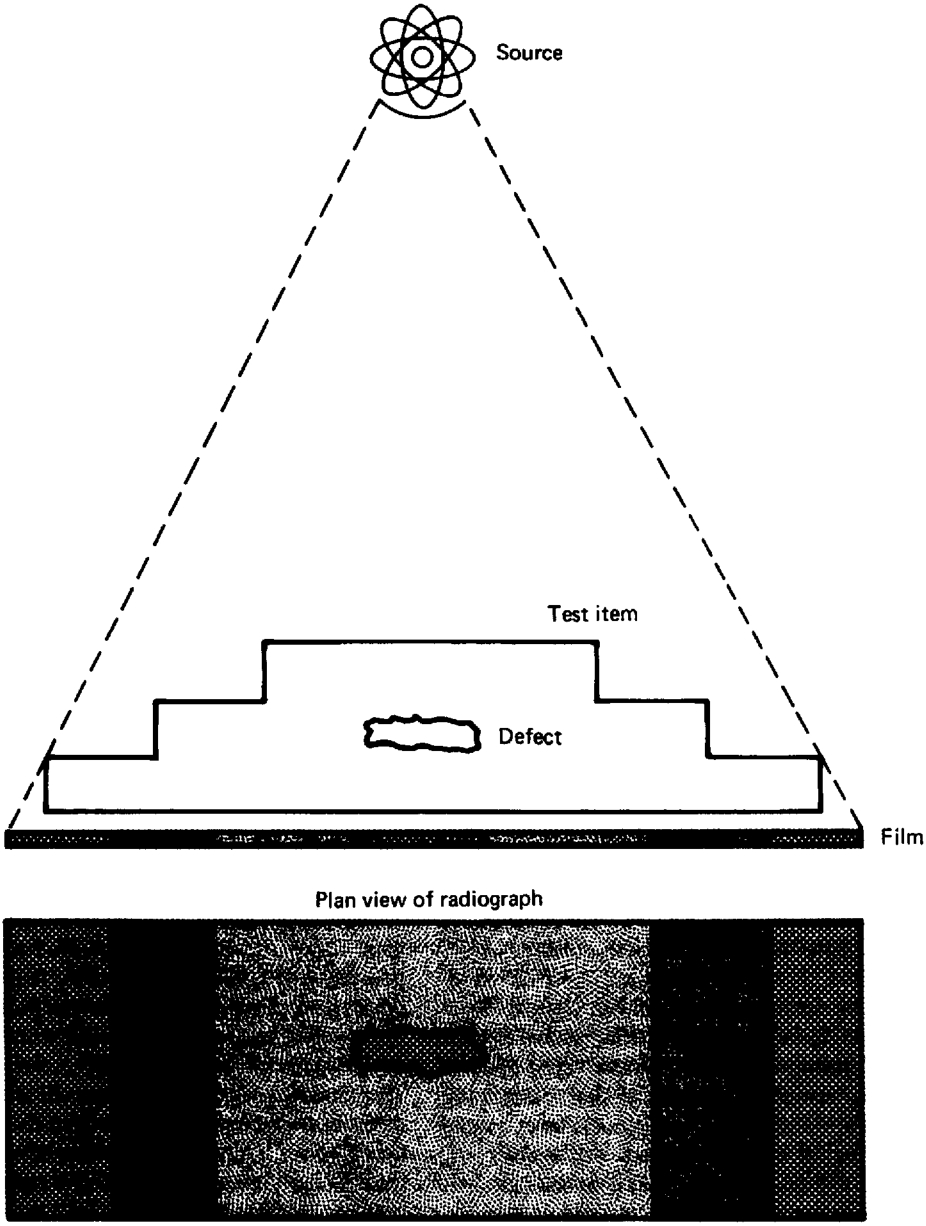



Figure 15.8—Typical "Shadow Graph"

**15.4.1 Essential Elements.** The basic process of radiographic examination involves (1) the production of the radiograph, and (2) the interpretation of the radiograph. The essential elements needed to carry out these two operations consist of the following:

(1) A source of radiation (usually gamma or x-rays) and associated accessories

(2) An object to be radiographed (weldment)

(3) An x-ray film enclosed in a lightproof film holder (cassette)

(4) A trained person to produce an acceptable radiograph

(5) A means of chemically processing the exposed film

(6) A person certified to interpret the radiographic images using adequate viewing devices

The following is a brief discussion about each of these six essential elements of the radiographic inspection process.

**15.4.1.1 A Source of Radiation.** The illustration shown in Figure 15.8 details the basic essentials in the making of a radiograph. Radiation, electromagnetic radiant energy with penetrating properties related to its energy level wavelength, is unique in that it cannot be detected by any of mankind's five natural senses: sight, touch, taste, hearing, or smell. More important to the radiographic process is the unique ability of radiation to ionize elements.

The two types of radiation sources most commonly used in weld inspection are x-ray machines and radioactive isotopes. The radiation emitted by these sources has an extremely short wavelength (about 1/10 000 of the wavelength or less than that of visible light) that enables them to penetrate materials that absorb or reflect light. X-rays are produced by x-ray tubes; gamma rays are emitted from the disintegrating nuclei of radioactive elements. Although the wavelength of radiation produced can be quite different, both x-ray and gamma radiation behave similarly for radiographic purposes.

In the past, radium (a natural emitter of gamma radiation) has been used extensively for industrial radiography; however, with the availability of artificially produced isotopes, its use has decreased greatly. Of the radioisotopes, the three in common use are cobalt 60, cesium 137, and iridium 192 shown in Table 15.2. These have been named in order of decreasing energy level (penetrating ability). Cobalt 60 and iridium 192 are more widely used than cesium 137.

Sources of x-radiation are very diversified today and consist of smaller, portable tube-type x-ray machines of the 50 KV range up to mammoth linear accelerators and betatrons in the 1 to 30 million electron volt range.

**Table 15.2**
**Radiographic Isotopes Used in Industrial Radiography**

| Isotope | Half-Life (years) | Energy Levels MEV | Approximate Mean Effective Energy Level MEV | Characteristic Intensity–Roentgens per Hour per Curie at 1 meter |
|---|---|---|---|---|
| Cobalt-60 | 5.3 | 1.17 and 1.33 | 1.2 | 1.35 |
| Cesium-137 | 33 | 0.66 | 0.39 | |
| Iridium-192 | 75 | 0.137 to 0.651 | 0.55 | |

It should be noted that each source of radiation has advantages and limitations and the welding inspector should become familiar with such terms as *curie*, *half-life*, *half-value layer*, *specific activity*, *energy or wavelength of emissivity*, and *source intensity*. Although the single most significant aspect of a radiation source is usually its image quality producing properties, other important considerations that may necessitate "trade-offs" in selecting a source include its portability and costs. Portability and costs speak for themselves. The image-quality properties will be detailed later in this section.

The welding inspector should further note that all radiation producing sources are hazardous, and special precautionary measures shall be taken when entering or approaching a radiographic area. This will also be discussed later in this section.

**15.4.1.2 An Object to be Radiographed.** The test object is an essential part of the radiographic process for rather obvious reasons; however, we should have a basic understanding about radiation interaction with the test object in order to fully appreciate the resultant film image. As was illustrated in Figure 15.8, the radiographic process is dependent upon the differential absorption of radiation as it penetrates the test object. The two key factors that determine the rates of differential absorption are (1) the amount of mass represented by the object, and (2) the penetrating power (defined by the energy) of the radiation source. The amount of mass is related to the density or object composition as well as to the amount or thickness of the object. Generally, the higher the atomic number of the object material, the more radiation will be absorbed and the less will penetrate the object to reach the film; more radiation will pass through thin sections than will pass through thick sections.

The penetrating power of the radiation source is dependent upon the kilovoltage selected on the x-ray machine or the particular isotope selected for gamma radiography. As the energy of the radiation source is increased, the more easily it will penetrate thicker or more dense materials. Table 15.3 shows the approximate radiographic equivalence factors for several metals. It is important to remember these two variables, for it is the differences in absorption occurring during the exposure process that accounts for the resultant differences in dark regions and light regions on the radiograph, i.e., contrast. The dark regions on the radiograph represent the more easily penetrated parts of the test object, while the lighter regions represent the more difficult to penetrate regions of the test object.

Discontinuity dimensions parallel to the direction of radiation are most likely to create a discernible image, while discontinuity dimensions that are normal to (planar) the direction of radiation are least likely to create a discernible image. Thus, the welding inspector should realize that orientation of radiation to test object/discontinuity is an important consideration. Radiographic exposure of the test object in multiple directions is therefore very common and often necessary. The inspector should realize there is a limit to the amount of differential absorption that is radiographically discernible (sensitivity) and that higher energy levels used for penetration produce lower sensitivity levels. Thus, the radiographer should select energy levels that will permit penetration of the object in a reasonable time period while still achieving adequate sensitivity and contrast for detection and interpretation of defects.

**15.4.1.3 An X-Ray Film Enclosed in a Lightproof Film Holder (Cassette).** Film is an essential for radiography. While the general makeup of the film itself is relatively simple, its behavior characteristics are much more complicated, and the latter are of concern to the radiographer, since the success and quality of the work will depend upon knowledge and correct use of films that are manufactured with many different properties.

An industrial radiographic film is a thin, transparent, flexible plastic base that has been coated with gelatin-containing microscopic crystals of silver bromide. Some films have one side coated and some have both sides of

**Table 15.3**
**Approximate Radiographic Equivalence Factors of Several Metals**

| Metal | X-Rays (kV) | | | | | | | | Gamma Rays | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | 100 | 150 | 220 | 400 | 1000 | 2000 | 14-24 MEV | Iridium-192 | Cesium-137 | Cobalt-60 |
| Magnesium | 0.6 | 0.6 | 0.05 | 0.08 | | | | | | | |
| Aluminum | 1.0 | 1.0 | 0.12 | 0.18 | | | | | 0.35 | 0.35 | 0.35 |
| 2024 (aluminum alloy) | 1.4 | 1.2 | 0.13 | 0.14 | | | | | 0.35 | 0.35 | 0.35 |
| Steel | | 12.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 18-8 (steel) alloy | | 12.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Copper | | 18.0 | 1.6 | 1.4 | 1.4 | | | | 1.1 | 1.1 | 1.1 |
| Zinc | | 18.0 | 1.4 | 1.3 | 1.3 | | | | 1.1 | 1.0 | 1.0 |
| Brass* | | | 1.4* | 1.3* | 1.3* | 1.2* | 1.2* | | 1.1* | 1.1* | 1.1* |
| Lead | | | 1.4 | 12.0 | | 5.0 | 2.5 | | 4.0 | 3.2 | 2.3 |

Note: Aluminum is taken as the standard metal at 50 kV, and 100 kV, and steel at the higher voltages and gamma rays. The thickness of another metal is multiplied by the corresponding factor to obtain the approximate equivalent thickness of the standard metal. The exposure applying to this thickness of the standard metal is used. Example: To radiograph 0.5 in. of copper at 200 kV, multiply 0.5 in. by the factor 1.4, obtaining an equivalent thickness of 0.7 in. of steel. Therefore, give the exposure required for 0.7 in. of steel.

*Tin or lead alloyed in the brass will increase the factors given here.

the base coated with a layer of silver bromide crystals, approximately 0.001 in. (0.02 mm) thick. The silver emulsion is not only sensitive to x-radiation and gamma radiation but is also sensitive to light. For this reason, the film is enclosed in a light-tight holder loaded in a photographic darkroom and remains in this holder (cassette) until the exposure process is completed and the film is ready for development. At that time, it is unloaded in the darkroom so that the film is never "exposed to" light until the development processing is completed. Films will be discussed in more detail later in this section.

**15.4.1.4 A Trained Person to Produce an Acceptable Radiograph.** In addition to the basic "material" components of the radiographic process, the production of successful radiographs is highly dependent upon a trained person capable of safely making reliable exposures. Radiography may be related to photography as there are some similarities between the two processes. Figure 15.9 shows some of the basic geometric principles of penumbral "shadow formation" or image projection common to most all image recording processes. Figure 15.10 shows the basic geometrical requirements for producing shadow images which are not blurred, i.e., unsharp. In general, the following rules apply to exposure geometry:

(1) The radiation source should be as small as possible. Sharpness in a radiograph is closely related to the physical size of the source of radiation.

(2) The distance from the source of radiation to the film should be as great as is practical.

(3) The film should be as close to the specimen as possible. Ideally the cassette or film holder should be in contact with the specimen.

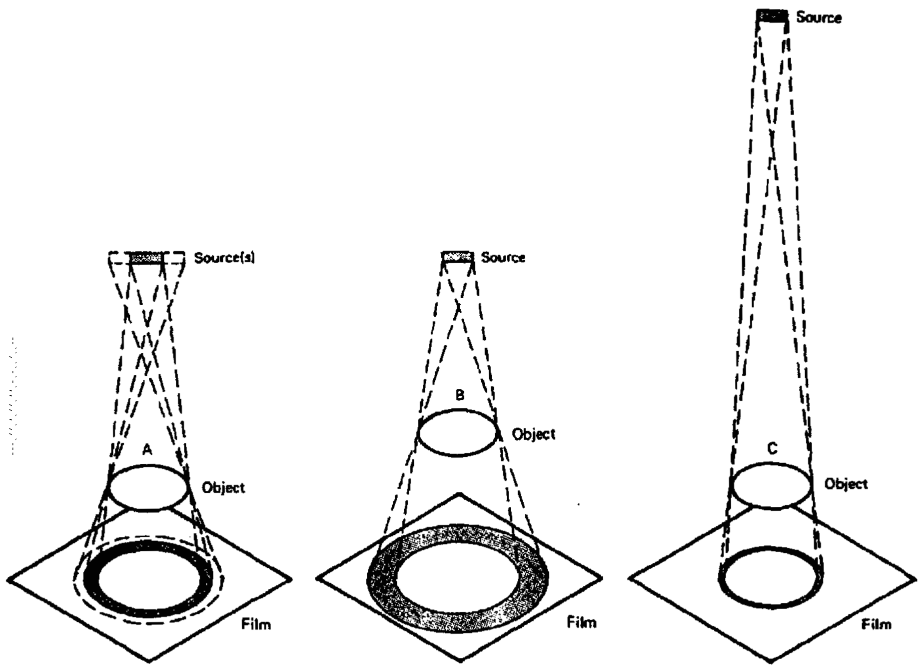
(4) The primary source alignment axis of the radiation beam should be directed perpendicular to the film plane where possible. This will minimize distortion of the specimen and flaw images.

(5) The plane of maximum interest on the specimen should be parallel to the plane of the film.

The art of establishing successful radiographic techniques is highly dependent upon the knowledge of all of these as well as other principles. Through judgment and experience, the radiographer should develop a "feel" for the geometry of the exposure technique. Arrangement of the position of the radiation source, the specimen, and the film relative to one another will determine the geometric projections and "sharpness" of the radiographic images. The radiographic exposure sharpness obtained is referred to as *definition* and exposures that show images resulting from poor definition will be blurred much the same as a photograph made with an out-of-focus lens.

To achieve maximum effectiveness, the radiographer should be capable of selecting the proper film, intensifying screens, filters, and materials to reduce radiation scatter. During the handling and exposure of the film, the radiographer should exercise extreme care to avoid the introduction of film artifacts such as crimp marks, scratches, pressure marks, static electricity, etc. that will interfere with subsequent interpretation of the radiographic image. Other film "artifacts" are discussed under film processing.

It was mentioned earlier that radiation sources can be hazardous and that special precautions should be taken while working with radiation. The radiographer or qualified person making the exposure should be trained in the aspects of radiation safety. In this country, the Nuclear Regulatory Commission (NRC) of the federal government has jurisdiction over certain isotopes, whereas x-ray exposure devices are usually controlled by state governments. In either instance, exposure dosages to radiation are controlled by strict rules and regulations, and one of the most—if not the most—important responsibilities of the authorized person making the exposure is to see that no unwarranted radiation exposure is received by anyone. The welding inspector should be aware of the possibly harmful affects of radiation.



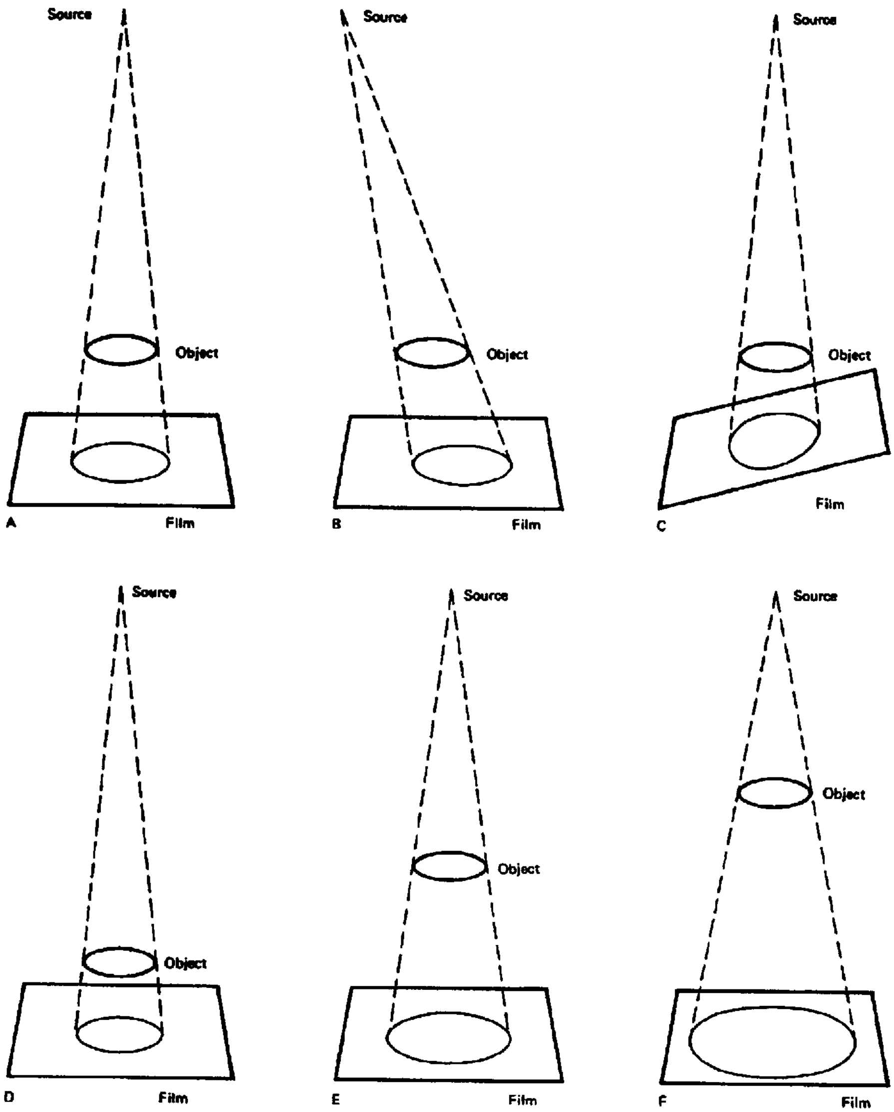

1. Figure A displays penumbra sizes when object is near film with different source sizes.
2. Figure B displays a large penumbra when the object-to-film distance is increased.
3. Figure C displays an extremely small penumbra when source-to-film distance is increased.

**Figure 15.9—The Penumbral Shadow**

It should also be mentioned that most fabrication specifications and codes in use today in this country require that personnel engaged in nondestructive examination activities, including radiographic personnel, be certified as to their abilities and levels of technical competence. In more recent developments in this country, some states now require specific radiation safety training for radiographers followed by certification testing prior to performance of gamma radiography. The American Society for Nondestructive Testing (ASNT) (Ref. 15.9) has published a recommended practice for such certifications and is an example of the increasing emphasis being placed on inspection personnel certifications. Inspection personnel usually should obtain minimum levels of education, training, experience, pass a written an examination, and have a tested minimum visual acuity. The welding inspector should ensure that all necessary requirements have been satisfactorily met.

**15.4.1.5 Processing the Film.** The radiographic process is only partially completed once the exposure has been made. Proper chemical processing of the film to develop the latent image of the object is an essential element of the process. Improper processing may make it impossible to read the film and may render useless the most careful radiographic exposure work.

Processing the radiographic film converts the latent invisible image (produced in the




A, B, and C show principles of shadow projection.
D, E, and F show principles of shadow enlargement.

**Figure 15.10—Geometric Principles of Shadow Formation**

film emulsions by exposure to x-ray, gamma ray, or light) to a visible, permanent image. Processing, as well as the handling of radiographic films is carried out in a darkroom under special lighting (safe light) of a color to which the film is relatively insensitive. Radiographic films are only as good as the processing they receive.

The first step in processing films is immersion in a developer solution. This causes the exposed portions of the film to become dark; the amount of darkening of the film will depend upon the degree of development and the degree of exposure to radiation the film has received.

A second optional step is either a water rinse or an acid stop bath to reduce or stop the developing action on the film.

The third step is the fixing bath. The function of the fixer is to dissolve unexposed silver bromide from the areas not darkened by the developer solution and to harden the emulsion so that it will with stand drying temperatures.

The fourth step is a water wash bath to remove the fixer and products of the fixing action from the film emulsion.

The fifth step (optional) is immersion in a wetting solution (soap) that allows the water to run off the surface of the film to help prevent spotting.

The sixth and final step is drying.

Radiographic film development techniques are either automatic or manual (hand tanks and racks). Automatic processing cycles usually do not involve a stop bath or a specific cleaning stage or applications of a wetting agent. Modern automatic film processors transport exposed films from one chemical solution to the next and include a rapid drying cycle. In all instances involving film handling, cleanliness is of utmost importance. Dust, dirt, oily residues, fingerprints, and chemical spills, including drops of water on the film before exposure and processing, could affect the image on the finished radiograph. Indications that appear on radiographic films and are irrelevant to the weld image under examination are referred to as *artifacts.*

**15.4.1.6 A Skilled Person to Interpret the Radiograph.** The final essential element of the radiographic inspection process involves evaluation of the completed radiograph and a subsequent disposition of the test object under examination. Evaluation of the completed radiograph is usually called "film interpretation" and the person performing the interpretation is a *film interpreter* or *film reader.*

If absolute perfection were the required level of quality for all materials and assemblies, then the interpretation of radiographs would be a relatively easy task. The interpreter would simply declare the product or assembly unacceptable if any kind or amount of discontinuity was found. However, practical considerations usually allow something less than perfection for most products. Engineering design specifications will establish quality guidelines for the radiographic examination of the test object. The interpreter will be required to make judgments about the acceptability of discontinuities existing in the product under examination. The art of film interpretation, therefore, is a judgment process, and the individual who performs these judgments will need basic understanding not only of radiography, but also of the technology of the product being examined.

The essentials of film interpretation are discussed in some detail later in this section. The degree of skill required of a film interpreter is acquired through long experience or extensive training, or a combination of both. Accurate interpretation requires a broad knowledge of the characteristic appearances of weld and related discontinuities associated with the particular types of material or mechanisms in which they occur. This knowledge can only be fully gained from experience in scrutinizing a wide range of specimens radiographed and preferably correlated with sectioned or prepared workmanship samples. Secondly, it is essential that the interpreter be knowledgeable of the types of discontinuities likely to be encountered in a particular welding process and the manner in which their images are likely to vary with the angle at which they are projected onto the film by the radiation beam. Needless to say, the interpreter should possess a knowledge of the radiographic techniques used.

Some specifications and codes may require certification that the film interpreter has met minimum levels of education, training, and experience in conjunction with an examination for technical competence.

**15.4.2 Radiographic Techniques.** The radiographic process, though simple in concept, involves a large number of variables and requires well-organized techniques to obtain consistent quality.

This section presents some of those technique essentials that have been proven useful and practical in industry. For further information on radiographic techniques, see "References and Suggested Reading Material" at the end of this chapter.

The radiographic image should provide useful information regarding the internal soundness of the specimen. Image quality is governed by two categories of variables which control: (1) radiographic contrast and (2) radiographic definition. Both of these general categories may be further subdivided (see Figure 15.11) and will be briefly discussed.

**15.4.2.1 Radiographic Contrast.** In the radiograph of Figure 15.8, the various intensities of radiation passing through the test object are displayed as different film densities in the resultant image. The difference in film density from one area to another contributes to "radiographic contrast." Any shadow or detail within the image is visible by means of the contrast between it and the background images. Up to a certain degree, the greater the degree of contrast or density differences in the radiograph (between two or more areas of interest), the more readily various images will stand out. The radiographic contrast of concern here is the result of a combination of two contributing contrast components of the radiographic system, i.e., subject contrast and film contrast.

**15.4.2.2 Subject Contrast.** Subject contrast is that contribution made to the overall radiographic contrast by the range of difference in radiation absorption by the subject or test object. As mentioned earlier, the key elements in absorption are (1) the mass of the test object, including the atomic number of the absorbing substance and the thickness of the absorber, and (2) the penetrating power of the radiation used (i.e., the energy or wavelength of radiation used). A flat plate of homogeneous material with a very small thickness variation would have a very low subject contrast. Conversely, a test object with a large thickness variation would yield a large difference in absorbed radiation and would, therefore, have a high subject contrast. A given test object with a given thickness variation (such as Figure 15.11) can have a low subject contrast using high-energy radiation (short wavelength) and a high subject contrast using low-energy radiation (longer wavelength).

Subject contrast is also affected by scattered radiation. When a beam of x-rays or gamma rays strikes any object, some of the radiation will be absorbed, some will be scattered, and some will pass straight through. The electrons of the atoms constituting the object scatter radiation in all directions, much as light is dispersed by a fog. The wavelengths of much of the scattered radiation are increased by the scattering process and, hence, the scatter is always somewhat "softer" or less penetrating than the unscattered primary radiation. Figure 15.12 illustrates two basic scattering processes with which the welding inspector should be familiar: (1) internal object scattering, and (2) external reflected scattering. In the radiography of thicker, more dense materials with lower energy x-ray sources of radiation, scattered radiation forms the greater percentage of the total radiation reaching the film. For example, in the radiography of a 3/4 in. (19 mm) thickness of steel, the scattered radiation from the test object is almost twice as intense as the primary radiation reaching the film; in the radiography of a 2 in. (50 mm)

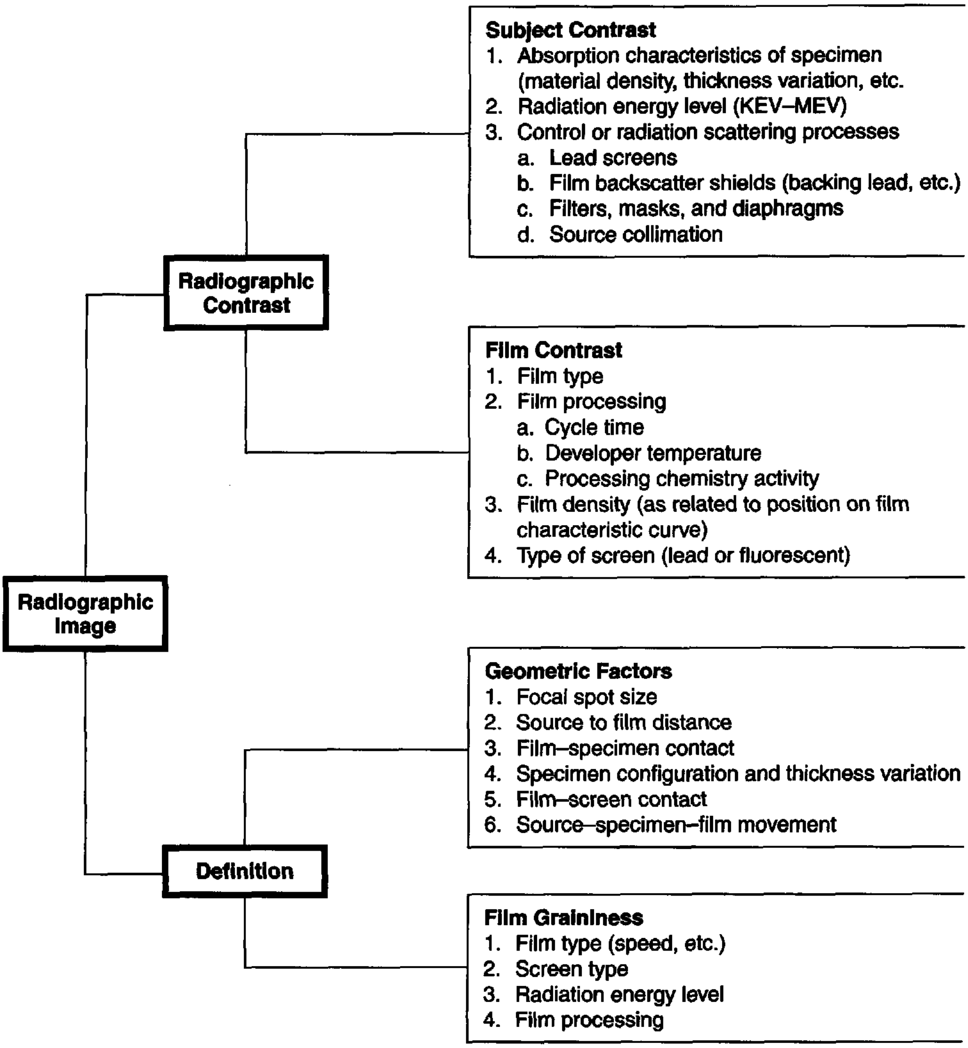



**Figure 15.11—Factors Affecting Quality of Radiographic Image**

thickness of aluminum, the scattered radiation is two and a half times as great as the primary radiation. As may be expected, preventing scatter from reaching the film markedly improves the quality of the radiographic image.

As a general rule the greater portion of the scattered radiation affecting the film is from the internals of the test being radiographed. Figure 15.12(A) illustrates internal radiation scattering effects to the film. Although this scattered radiation can never be completely eliminated, a number of means are available to reduce its effect. Lead foil screens (usually on the order of a few thousandths of an inch in thickness) are commonly employed as filters and are positioned between the test object and the film to absorb the "softer," less

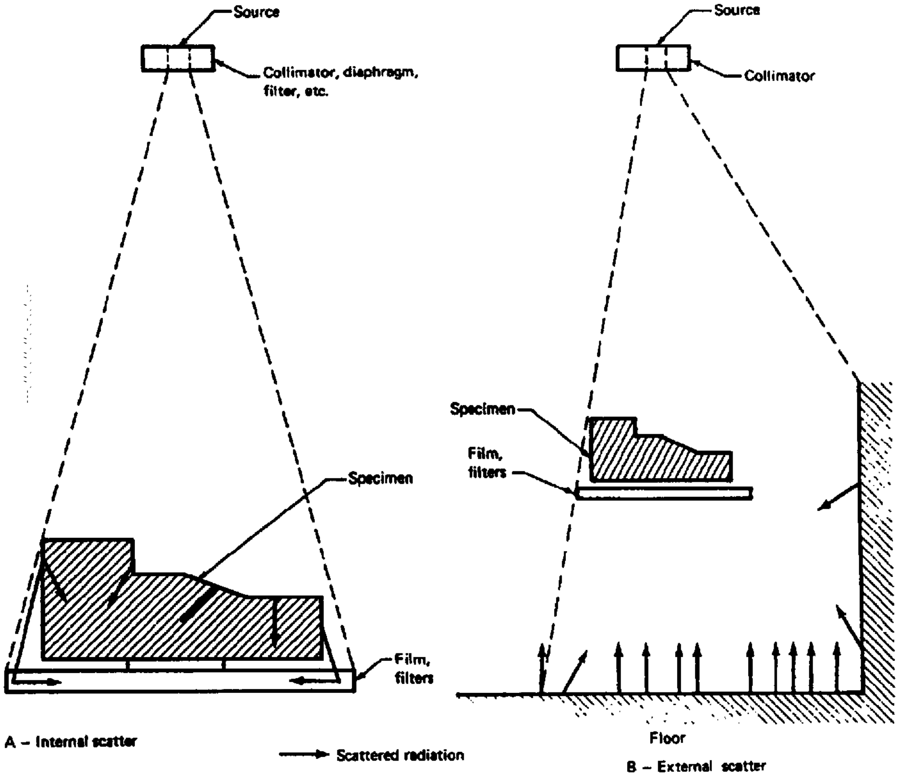



**Figure 15.12—Sources of Scattered Radiation**

penetrating scattered radiation prior to its reaching the film. In addition to improvement of the radiographic image by reduction of scattered radiation, the screens intensify the radiographic image. Lead screens intensify by emitting secondary radiation and fluorescent screens intensify by emitting visible light. As a result of this intensification characteristic, intimate film–screen contact should be maintained. Also employed are diaphragms and filters of various absorbent materials placed close to the radiation source between the source and the test object to absorb softer radiation prior to its reaching the test object. This latter method has the effect of improving the "quality" of the radiation that actually penetrates the test object and the better the radiation quality, the less problem in controlling the unwanted internal scattered radiation. As a general rule, the same principles will apply to both gamma and x-radiation; however, since gamma radiation from common industrial gamma ray sources is highly penetrating, methods used for controlling internal scattered radiation from these sources will usually necessitate different applications.

Scattered radiation originating in matter outside the test object, i.e., externally, is most serious for test objects that have a propensity for high radiation absorption. This is obviously due to the fact that scattering from external sources may be large compared to the primary image-forming radiation that reaches the film through the test object. Figure 15.12(B) illustrates the effects on a test object from common sources of external radiation scattering. Most sources of external scattering (such as walls, floors, ceilings, or nearby support apparatus) are poor absorbers of radiation and consequently reflect radiation back to the test object (back scattering) and the film. This reflected radiation, then, causes a decrease in the fundamental image contrast in much the same way as internal scattered radiation. Common industrial methods used to control this type of scattered radiation include the use of heavy (0.01 to 0.02 in. [0.2 to 0.5 mm]) lead screens in contact with the back side of the film (inside cassette). Heavy backing lead (1/4 to 1/3 in. [6 to 8 mm], depending upon the conditions) between the film and the floor; or sometimes special masks made of some highly absorbent material are placed around the test object. Diaphragms or collimators that restrict the direction of primary radiation intensity to the test object have also proven to be valuable aids in controlling external scattered radiation effects on subject contrast.

**15.4.2.3 Film Contrast.** Film contrast is that contribution made to the overall radiographic contrast by the film and its related characteristic variables. The recording process, depending upon the film type and related variables, can amplify the difference in film densities created by subject contrast. This is called *process contrast amplification* or *the degree of film contrast*. Film emulsions can be manufactured to render different degrees of film contrast in addition to other properties such as speed (the exposure duration required to achieve a certain film contrast) and the level of graininess of the emulsion. Each film type detects and records varying radiation exposure differences as significant film density changes on the radiograph. The principles of film contrast are best described and understood by the film characteristic curve, sometimes called the *H&D curve*.

Figure 15.13 illustrates a typical characteristic curve for an industrial radiographic film. This curve relates film density (the degree of darkness of the radiograph) to the logarithm of radiation exposure. The radiation exposure, *R*, of a film is defined as the product of the radiation intensity, *I*, exposing the film, and the time, t, of exposure duration. This relationship may be expressed as follows:

$$(1)\ R = I \times t \qquad \text{(Eq. 15-1)}$$

where

$R$ = radiation exposure
$I$ = source intensity
$t$ = time of exposure duration

The exposure value is expressed as a logarithm (usually base 10) for two reasons: (1) for convenience in compressing an otherwise long scale of exposure units, and (2) on a logarithmic scale, a change in exposure (a radiation or exposure difference, *R*) has a constant spread throughout the scale, whereas the same *R* would have a wider and wider spread along an arithmetic scale. A constant exposure difference is the basic "tool" that renders a characteristic curve useful.

Film density, or optical transmission density, is defined as follows:

$$(2)\ D = \mathrm{Log}_{10}\, I_o/I_t \qquad \text{(Eq. 15-2)}$$

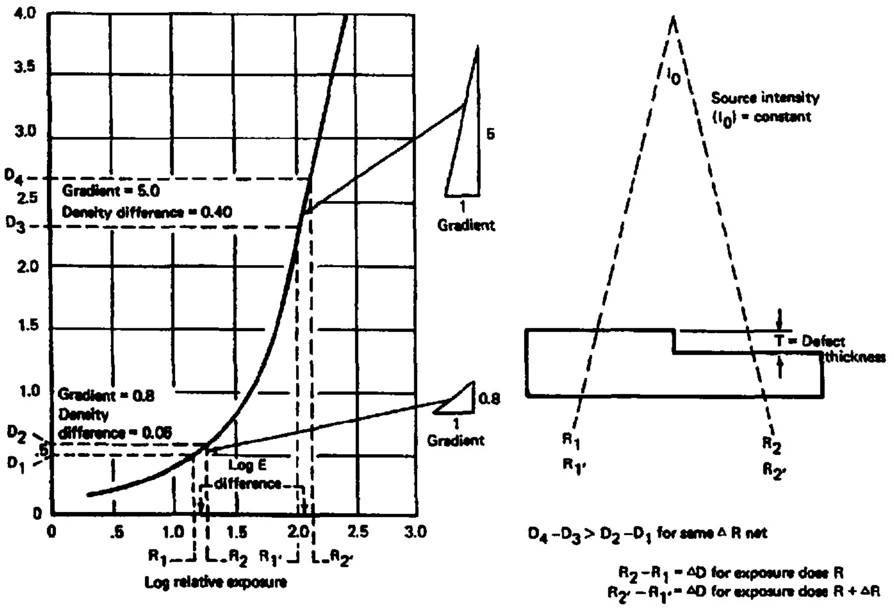
where

$D$ = film density
$I_o$ = intensity of light incident on film
$I_t$ = intensity of light transmitted through the film (as seen by the eye)

The logarithmic value is used for convenience to express the density as a small number. A film density of 1.0 H&D units means that 1 out of 10 parts of light will reach the eye after being transmitted through the film, or

$$D = Log_{10}\ units$$
$$= 1.0\ H\&D\ density\ 1\ unit \qquad \text{(Eq. 15-3)}$$

The characteristic curve shape (i.e., slope) at any particular film density is not only dependent upon the type of film selected, but is also influenced by the degree of development and the type of *intensification screens*




The specimen above illustrates a typical defect in terms of a thickness reduction, (T). $R_2$–$R_{1'}$ = the dosage of difference for a relative exposure (1): $R_2 - R_1$ = the dosage difference for a relative exposure (2). If these exposure differences are transferred to the logarithmic scale on the curve at left, the relative exposure dose difference ΔR has the same spread throughout the large scale. When ΔR is applied to the gradient curve, the slope of the curve will dictate the difference in film densities (contrast) for the corresponding areas of the specimen.

**Figure 15.13—Characteristic Curve For a Typical Industrial X-Ray Film**

*used.* Intensification screens are thin sheets of materials placed within the film cassette in intimate contact with the film for the purpose of catalyzing the photographic action on the film during exposure. There are two basic concepts used in intensification processes (1) fluorescent type screens (such as calcium tungstate) emit light when the screen is exposed to radiation, which further exposes the film; (2) lead type screens, which may also serve as scatter foils, emit electrons which expose the film. These screens are usually referred to as intensification screens. They change the shape of the characteristic curve, depending upon which type is used.

Film contrast (i.e., the difference in film densities resulting from the same percentage change in radiation exposure) then is determined by (1) the shape or slope of the characteristic curve and (2) the film density level of the radiograph. For a better understanding of the fundamentals, refer to the curve shown in Figure 15.13. The characteristic curve shows the resultant film densities ($D_1$, $D_2$, $D_3$, and $D_4$) occurring from exposure dosages $R_1$ and $R_2$. The exposure differences, $\Delta R$ or ($R_2 - R_1$), could arise from different equivalent thicknesses in the exposed specimen, caused by perhaps a discontinuity. The same dosage difference ($R_2$ – $R_1$), at various positions along the slope of the characteristic curve produces different amounts of film contrast, $\Delta D$ or ($D_2 - D_1$). The degree of film contrast, ($\Delta D$), will be lowest at the "toe" of the characteristic curve and highest where the curve is steepest.

Where the slope of the characteristic curve is 1.0, no contrast amplification will occur. Slopes less than 1.0 will actually reduce the contrast. For this reason, good radiographic techniques expose the film long enough to obtain film densities along the high gradient portion of the characteristic curve. Many radiographic specifications require a minimum film density of 1.5 H&D units. The optimum value should be sought by constructing such a film characteristic curve for the radiograph processing variables that will be experienced. Upper limits on film densities are usually imposed by the radiographer's viewing illumination. Many viewing boxes can illuminate films with densities as high as 4.0 H&D units.

Complex geometries, shapes, and changing thicknesses may require multiple film-exposure techniques. When castings are radiographed, several films with different speeds may be used in a single simultaneous exposure to ensure that adequate film densities are obtained over a desired thickness range.

**15.4.2.4 Radiographic Definition.** Radiographic definition is equal in importance to radiographic contrast. Definition concerns the sharpness of the image. *Sharpness* means the degree of abruptness of the transition from one density to another. The more abrupt this transition, the greater the ease in identifying or defining the image. It is easier to discern details in a sharp radiograph than those in an "out-of-focus" one. Two components of radiographic definition are exposure geometry and film graininess (see Figure 15.11).

**15.4.2.4.1 Exposure Geometry.** The sharpness aspect of the exposure geometry, illustrated in Figure 15.10, shows how "penumbral shadow" is affected by: (1) source size, (2) source-to-film distance, and (3) specimen-to-film distance.

Every source of radiation has physical dimensions larger than a pinpoint, casting a penumbral shadow behind any object, which thus blurs the image. For a given x-ray or gamma ray source, the radiographer usually has no way to change source size. Gamma sources generally vary from 1/16 in. (1.6 mm) diameter to slightly less than 1/2 in. (12 mm) diameter. X-ray focal spot sizes vary from several mm$^2$ (generally 6 to 8) down to a fraction of a square millimeter. However, as may be seen in Figure 15.10, the effects of penumbral shadow may be reduced and rendered less noticeable by increasing the distance between source and specimen or decreasing the distance between specimen and film. Changes in exposure conditions related to geometry (both focus and projection) are interdependent in their effect upon image sharpness. Excessive object thickness amplifies the penumbral shadow. Should the object under examination be moved or positioned farther from the film for a given source-to-film distance (S.F.D.), the penumbral shadow will noticeably increase as may be seen in Figure 15.10. The variables governing the penumbral shadow or "geometric unsharpness" may be mathematically related as follows:

$$(3)\ \frac{U_g}{D} = FT \qquad \text{(Eq. 15-4)}$$

where

$U_g$ = geometric unsharpness
$F$ = focal spot size of the largest dimension of the source
$T$ = specimen thickness
$D$ = source-to-specimen distance

Most good radiography is generally performed with a value of $U_g$ less than 0.040. Most codes will give limits of $U_g$ acceptance.

Poor definition of the radiographic image may also result from any movement of the specimen or source, especially in a transverse direction normal to the axis of exposure. If intensifying screens are used in the cassette, they should be in as intimate contact with the film as possible to avoid two undesirable consequences: (1) the specimen could be moved unnecessarily farther from the film, and (2) electron impingement onto the film from the intensifying screen could exaggerate the size of the image, reducing the sharpness.

**15.4.2.4.2 Graininess of the Film.** Film graininess is the visual appearance of irregularly spaced grains of black metallic silver deposited in the finished radiograph. The unexposed radiographic film contains an emulsion with countless grains of silver halide. The graduation in density results from the number of grains developed in each area, each grain being uniformly black. Fast films have large grains and, thus, a coarsely structured image. Slow films have finer grains and a less grainy image.

Radiographic films of all types and brands possess some amount of graininess. The following are some factors that will determine the degree of graininess on a finished radiograph:

(1) Type and speed of film

(2) Type of screens used

(3) Energy of radiation used

(4) Type and degree of development used

Fluorescent intensifying screens produce what is termed *screen mottle.* Screen mottle gives an appearance of graininess, considerably "softer" in outline than film graininess. The cause of screen mottling is a statistical variation in the absorption of radiation quanta by areas of the screen and the resulting fluctuation in intensification. In general, the smaller the number of radiation quanta absorbed by the screen, the more readily may screen mottle be observed. It is important to keep all intensification screens clean as well as in good condition, free from blemishes, cracks, or surface deterioration, in order to preclude additional statistical variations in the intensification process. Because of this potential for "mottling," some codes and other standards do not permit the use of fluorescent screens.

The energy level of the radiation source used affects film graininess. Generally, high-energy radiation produces increased graininess. This has been attributed to electron scattering within the emulsion and subsequent sensitization of adjacent silver halide grains (see Ref. 15.11).

Development or processing of the exposed radiograph beyond the manufacturer's recommended times and temperatures can cause an increase in amount of grain "clumping" and, thus, an increase in the visual impression of film graininess.

***Image Quality Indicators.*** Due to the large number of variables that affect the image quality of a radiograph (see Figure 15.11), some assurance is needed that an adequate radiographic technique has been achieved. The tool used by the radiographer to demonstrate technique is the image quality indicator (IQI) or penetrameter. Figure 15.14 illustrates typical conventional penetrameters used

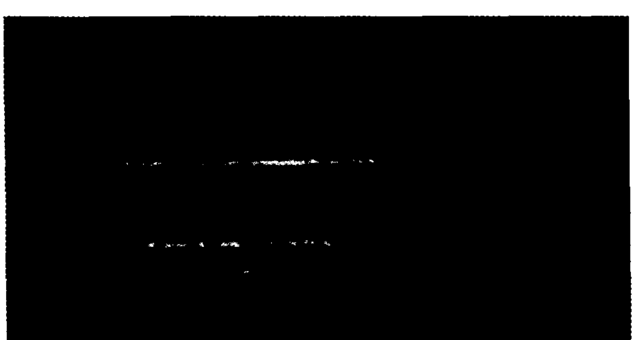
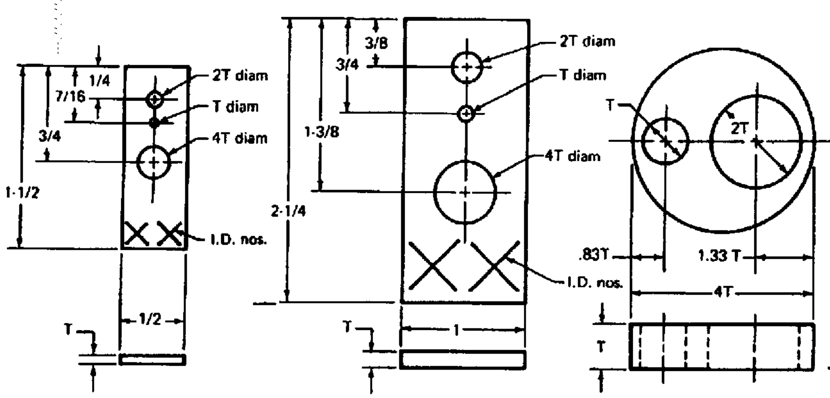


**Figure 15.14—The "Tools of The Trade" for the Radiographer**

extensively in this country. Other design types used abroad are available. The other "design types" refer primarily to wire gauges. These are now included in the ASME Code and should no longer be considered as "foreign."

Conventional penetrameters (ASTM, Military) consist of a strip of material of simple geometric shape that has absorption characteristics similar to the weld metal under investigation (see Figure 15.15). Use of this type of IQI provides information about (1) the radiographic contrast, and (2) the radiographic image quality. Each penetrameter has specific absorption characteristics. When a weldment is to be radiographed, a penetrameter with thickness equal to a specified percentage (1%, 2%, 4%, etc.) of the weld thickness is generally selected. A lead identification number at one end of the IQI shows the thickness of the penetrameter in millimeters or thousandths of an inch. Conventional penetrameters usually contain three holes drilled in the face of the plaque, the diameters of which vary in size as multiples of the plaque thickness. Most specifications and codes in use today call for an IQI with 1T, 2T, and 4T diameter holes, where "T" is the plaque thickness. As may be seen in Figure 15.15, these holes are carefully positioned on the plaque and, for each particular design of penetrameter, usually remain in the same sequence for all sizes and material groups.

Penetrameters are manufactured in standard sizes or increments of thickness. Although requirements will vary from user to user, the thickness increments are generally close enough together so that little or no significant penalty is paid when an exact thickness penetrameter is not available for a particular weld thickness. In addition, conventional penetrameters are usually manufactured in material groupings rather than in countless numbers of penetrameters for all material types. Most specifications and codes organize all major materials into a minimum of five absorption categories, ranging from lighter metals (Group I) to heavy metal (Group V). The specimen to be examined should have its penetrameter made from the same grouping as the specimen material or from a grouping of lighter metal.




| in. | mm |
|---|---|
| 1/4 | 6.4 |
| 3/8 | 9.5 |
| 7/16 | 11 |
| 3/4 | 19 |
| 1-3/8 | 35 |
| 1-1/2 | 38 |
| 2-1/4 | 57 |

Design for penetrameter thickness from 0.005 in. to and including 0.050 inch.

Design for penetrameter thickness from 0.060 in. to and including 0.160 inch. Made in .010 in. increments.

Design for penetrameter thickness from 0.180 in. and above. Made in 0.020 in. increments

Dimensions are in inches.

**Figure 15.15—Typical Penetrameter Design**

Most radiographic image quality requirements are expressed in terms of penetrameter thickness and desired hole size. For example, the requirement might be a 2-2T level of sensitivity. The first 2 requires the penetrameter thickness to be 2 percent of the thickness of the specimen; the symbol 2T requires the hole having a diameter of twice the plaque thickness to be visible on the radiograph. The 2-2T image quality level is commonly specified for routine radiography. For more sensitive radiography, a 1-2T or 1-1T could be required. More relaxed image quality requirements would include 2-4T and 4-4T.

Figure 15.14 also illustrates typical placement relationship of penetrameter and welds. It is important that penetrameter placement be controlled to obtain similar quality for the weld and the penetrameter. In most instances the penetrameter will be placed on the source side of the specimen, as this is the position of least favorable geometry. However, in some cases this will not be practical, as in the radiography of a circumferential weld in a long pipe section where the weld is inaccessible from the inside. In this case, the penetrameter may be located on the "film side" of the weldment. Most specifications and codes will specify the circumstances or conditions when a "film side" penetrameter may be used and will also stipulate how the film side penetrameter size shall be selected.

Note also in Figure 15.14 that the penetrameter has been placed on another piece of material. This piece of material is called a *shim* and is of radiographically similar material to the weldment being examined. The thickness of the shim will generally equal the thickness of weld reinforcement and backing so that the image of the penetrameter will be obtained by projection through the same thickness of material as the area of interest, which in this case is the welded joint.

In the hands of a skilled radiographic interpreter, the appearance of the penetrameter image on the radiograph will indicate the quality of the radiographic technique. It should be remembered that even if a certain hole in a penetrameter is visible on the radiograph, a void or discontinuity of the same approximate diameter and depth as the hole size may not be visible. Penetrameter holes have sharp boundaries and abrupt changes in dimensions, whereas voids or discontinuities may have a gradual or blending-in change in dimension and shape. A penetrameter, therefore, is not an indicator or gauge to measure the size of a discontinuity or the minimum detectable flaw size. A penetrameter is an image quality indicator of the success of the radiographic technique.

**15.4.3 Exposure Techniques.** In determining the most proficient arrangement of the essentials needed to make a radiograph, a radiographer should select the best locations for positioning of the radiation source and film in conjunction with the test object. The following are typical factors that should be considered:

(1) Which arrangement will provide optimization of image quality and weld coverage?

(2) Which arrangement will provide the best view for those discontinuities most likely to be present within the weldment?

(3) Will a multiple film exposure technique be required for weld coverage?

(4) Can a "panoramic" [see Figure 15.16(F)] type of exposure be used?

(5) Which arrangement will require the shortest exposure duration?

(6) Can the exposure be made safely?

Figure 15.16(A) through (G) shows typical exposure arrangements for some common types of weldments. A flat weldment (A) is one of the simplest test objects to radiograph. Most of the essentials of good radiography can be easily applied, i.e., good exposure geometry and proper positioning of radiographic tools for the most practical set-up.

Figure 15.16(B) through (F) illustrate some typical exposure arrangements for radiography of pipe weldments. If the pipe nominal diameter is relatively small (1-1/2 in. [38 mm] or less), it may be practical to expose a portion of two walls of the pipe weldment with one exposure straight through both walls, as shown in view C. Unfortu-

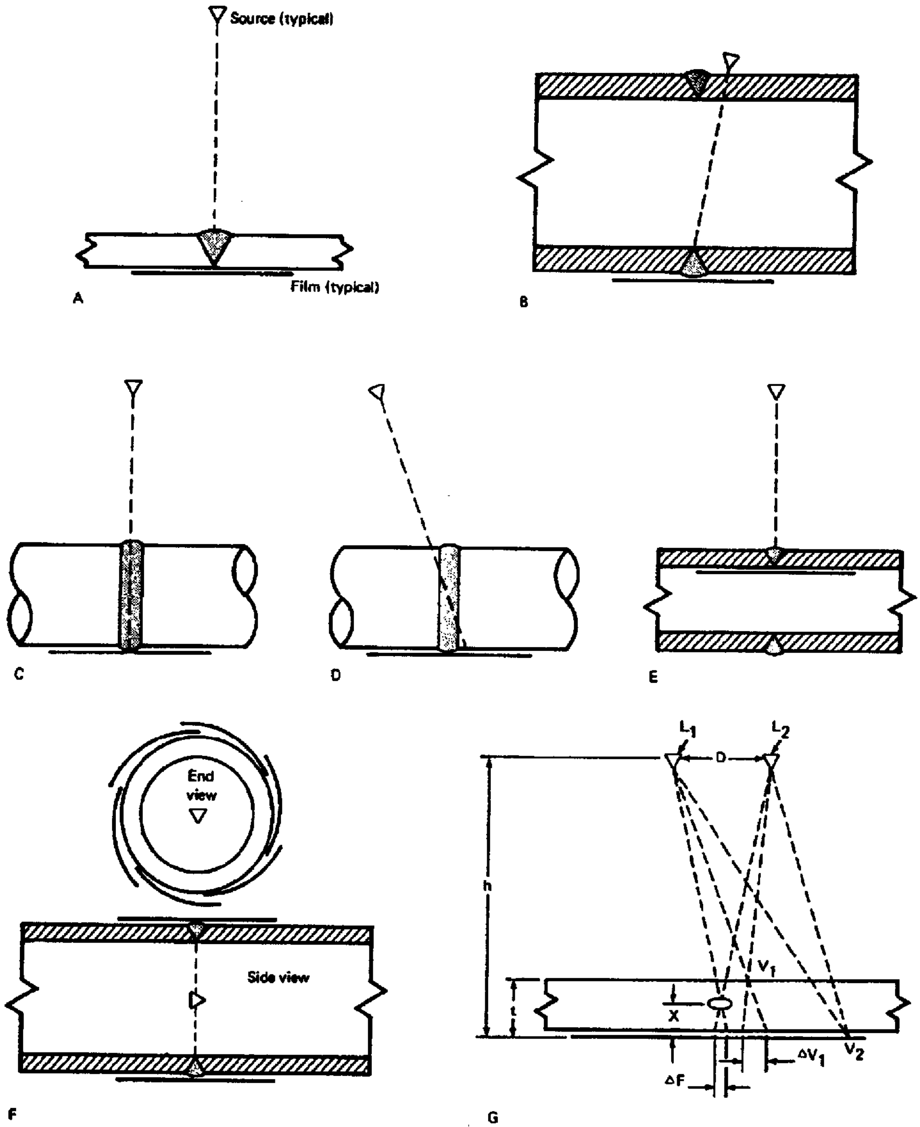



**Figure 15.16—Typical Radiographic Exposure Arrangements**

nately, in this case, the image of both walls would be projected superimposed onto the same film area. It would be difficult to determine the exact location of a discontinuity if one were present. Depending upon the wall thickness of the pipe, a better arrangement may be to position the source "offset" from the plane of the weld, as shown in view D, so that the images will be cast onto the film as an ellipse, which will improve the visibility characteristics of each wall separately. Should discontinuities exist, they could be individually located.

In some instances, trade-offs are possible that will influence the radiographer's choice of conditions. The welding inspector should be cautioned that one method may be as good as another, depending upon the variables involved. The radiographer usually has reliable information at hand when planning the setup.

Circumferential welds in slightly larger pipe sizes (2 to 3-1/2 in. [50 to 90 mm] nominal diameters), are also usually radiographed in the double-wall fashion, the radiation penetrating both walls to make the exposure. More than one exposure may be required, however, to obtain good coverage of the weldment.

Nominal pipe sizes over 3-1/2 in. (90 mm) usually are exposed for single-wall film viewing. This may be accomplished in one of three ways: (1) the radiation source may be positioned on the inside of the pipe [Figure 15.16(F)] with the film wrapped around the outside; (2) the radiation source may be positioned on the outside of the pipe with the film on the inside (view E); and (3) the radiation source may be positioned on the outside of the pipe with the film on the diametrically opposite side of the pipe so that the radiation source penetrates both walls (view B). In this latter arrangement, the wall closest to the source is treated as if it were not there (source is usually offset). In all instances, sufficient numbers of exposures should be made to ensure complete weld coverage for either single-wall or double-wall film viewing. The preferred arrangement would be that which contains the most favorable trade-off of exposure and geometry variables as determined by the radiographer for the prevailing conditions or a radiographic procedure which the radiographer should follow.

Figure 15.16(G) illustrates a technique that may be used to determine the depth of a discontinuity found in a plate type of test object. A single radiograph, which is a two-dimensional plane surface, will not indicate the depth location of a discontinuity. A double exposure provides parallax to reveal the third dimension. Essentially, lead markers $V_1$ and $V_2$ are positioned on the source and film sides of the test object as shown. Two exposures are made, the radiation source being moved left or right any convenient distance $D$ for the second exposure. The position of the images of marker $V_2$ will change very little as a result of this source shift. The shadows of the flaw $F$ and reference marker $V_1$ will change position significant amounts, $\Delta F$ and $\Delta V_1$, respectively. Depending upon the detail of the flaw, both exposures may be made on the same film; however, one exposure has a tendency to fog the other. If the thickness of the specimen is t, the distance of the flaw above the film plane is $(t\Delta F)/\Delta V_1$.

It should be noted that this calculation assumes that the image of the bottom marker ($V_2$) remains essentially stationary with respect to the film. This may not always be true; for example, if the cassette or film holder is not in contact with the bottom surface of the test object, or if larger source shifts are used.In that instance, the location of the flaw may be computed by the following formula:

$$X = h\Delta F \qquad \text{(Eq.15-5)}$$

$$D + \Delta F$$

where
- $X$ = distance of flaw above film
- $h$ = focus-to-film distance
- $\Delta F$ = change in position of flaw image
- $D$ = distance source has shifted from $L_1$ to $L_2$ [see Figure 15.16(G)]

**15.4.4 Interpretation of Radiographs.** Since accurate interpretation of radiographs allows work to be judged on its merits according to applicable standards, the welding inspector should strive to become proficient in reading radiographs.

The essential steps in evaluating a radiograph of a weldment are these:

(1) Check the identification of the radiograph against accompanying records for accuracy.

(2) Determine the weldment design and welding procedure used to construct the joint.

(3) Determine the radiographic setup procedure used and the correctness of technique attributes.

(4) Review film under adequate film viewing conditions.

(5) Identify the presence of any film artifacts and request a re-radiograph if necessary.

(6) Identify any surface marks or irregularities not associated with internal soundness and verify their type and presence.

(7) Evaluate and propose disposition of discontinuities revealed in the radiograph.

(8) Prepare a complete radiographic report.

**15.4.4.1 Film Viewing Conditions.** To properly interpret a radiograph, it should be examined under conditions of best legibility and maximum comfort for the observer. The viewing equipment should be located in a well-ventilated room with background lighting subdued to reduce glare. The illuminator should provide a cold light or should have forced ventilation so that the films placed against it for viewing do not curl due to heat.

Fluorescent lamps provide satisfactory cold light sources, and ventilated high-intensity incandescent lamps with rheostat or variac controls are commercially available. For viewing radiographs of butt joints in which the background film density does not vary significantly, a single-intensity viewer will usually suffice. However, variable-intensity viewers are more versatile and provide advantages when viewing high-density negatives.

The viewing equipment should mask off the extraneous area beyond the film. The radiograph should be placed at eye level so that the interpreter may sit erect comfortably.

**15.4.4.2 Film Artifacts.** Certain indications that appear on radiographic films and are irrelevant to the weld being inspected are referred to by the general term *artifacts.* These may be caused during the exposure or by improper handling or processing of the film. Some of the principal causes are as follows:

(1) Screens that are dirty, scratched, mutilated, or have foreign material between them and the film will have these imperfections reproduced as part of the image.

(2) Electrostatic discharge during film handling will expose the film to light and cause an easily-recognized pattern of sharp black lines on the developed film.

(3) Localized pressure on or bending of pre-processed film results in typical "pressure marks" or "crimp marks" when the film is processed.

(4) Processing defects of various kinds may occur; such as colored stains or blisters that result from improper stop-bath application between developing and fixing solutions. Streaks could be the result of improper agitation during development. Fogging could be caused by overexposure of the film to a safelight lamp before fixing, or by using old film. Stains can be caused by improperly mixed or exhausted solutions, and water marks can result from handling partially dried film. Fingerprints are obviously caused by handling the film. Scratches result from rough handling, especially during processing (when the emulsion is soft). Chemical fog may be caused by overdeveloping.

Properly used automatic processing equipment, in large measure, tends to eliminate many of these deficiencies; but it too can give rise to certain others. These may include marks from the rollers in the equipment if they become scored, contaminated with chemical residue, or do not function properly. Further data on film processing may be obtained from literature published by film and processor manufacturers.

It is the duty of the inspector to learn to recognize and evaluate film artifacts, with regard to their influence on film interpretation, and to require re-radiography when warranted.

**15.4.4.3 "Pitfalls" in Interpretation.** As a general rule radiographs fall into one of three evaluation categories: (1) unquestionably acceptable, (2) clearly rejectable, and (3) borderline. There will be many borderline cases in radiographic interpretation. This category arises from honest differences of opinion, and from cases without clear-cut evidence. For example, although most standards permit slag inclusions in varying degree, some reject any incomplete fusion; yet incomplete fusion may be similar in appearance to an inclusion in nature and in appearance on the radiograph. Generally, the two are indistinguishable with total certainty. The inspector should decide whether the radiograph indicates a rejectable lack of fusion or an acceptable inclusion.

The inspector may be called upon to judge repair welds in castings or assembly welds of cast items. Here, the inspector may be faced with inequalities between casting standards and welding standards (the latter are, on the whole, more restrictive): if an indication could be construed as a casting discontinuity, it may be acceptable; yet, if interpreted as a weld discontinuity, it may be rejectable.

The conscientious inspector should always attempt to render judgment equitably, in accordance with the applicable standards, bearing in mind that the prime consideration is a safe and serviceable component.

**15.4.4.4 Radiographic Acceptance Standards in Specification, Codes, and Other Standards.** Most industrial radiography is accomplished in accordance with some specified set of rules or mutually agreed upon conditions.These rules and conditions may pertain to such aspects as radiographic technique conditions, coverage requirements, acceptance criteria, and radiographic procedure approvals. Controlling criteria are usually contained in a manufacturing specification, code, or standard for fabricating components of a particular nature. Some of the organizations that have adopted such criteria for weldments include:

(1) The Armed Forces (military standards)
(2) American Welding Society
(3) American Society of Mechanical Engineers
(4) American Society for Testing and Materials
(5) American Petroleum Institute
(6) Ship Structure Committee

**15.4.4.5 Technique Conditions.** Most specifications and codes will, as a minimum, specify requirements for controlling radiographic image quality. These controls will normally consist of penetrameter sizes, film density requirements, source-to-film focal distances, radiation energy range, and exposure technique arrangement requirements. They may also specify certain techniques for ensuring weld coverage, such as the positioning of spot or location markers on the test object. Some specification and codes will sometimes refer to an alternate standard or practice and will adopt such criteria as requirements for complying with their own requirements.

**15.4.4.6 Coverage Requirements.** Specifications and codes will specify what sections or components of an assembly will require radiographic examination. In addition, they will usually state conditions for which partial radiography will be allowed or whether 100 percent coverage will be required. The required terms of samplings for initial radiography are usually stated, as well as those for follow-up examination after a defect has been located. Some specifications and codes provide options for using a different NDE method instead of or in conjunction with radiography. In many instances, coverage requirements are finally governed by the designer or engineer who works closely with the specification or code or customer. In this case, coverage requirements may be specified on fabrication shop or field drawings.

**15.4.4.7 Acceptance Criteria.** An essential of most specifications or codes is the specifying of the acceptance criteria to be used for film evaluation. Acceptance standards may be indicated as written rules, formulae, pictorials, charts, graphs, or reference radiographs. In some cases, it will be a matter of convenience as to which method will be used. It is beyond the scope of this section to discuss acceptance criteria in detail, as there are many different applications and rules; however, the welding inspector should be familiar with the specification or code being used and be able to evaluate workmanship in accordance with the applicable acceptance criteria.

**15.4.4.8 Procedure Approvals.** Some specifications and codes require qualification of radiographic techniques and procedures. Usually, the major emphasis is on the ability of the procedure to detect discontinuities that are of concern to the product service. Such a qualification for radiography may involve radiographing a test object with known defects, using the technique essentials contained in the basic specification or code. If these qualification radiographs are judged capable of rendering a meaningful examination of the test object, the technique is said to be qualified or to have a "demonstrated proficiency." Qualification of radiographic techniques is an added assurance feature of the capabilities of radiographic technique.

**15.4.5 Radiographs of Weld Discontinuities.** Generally, defects in welds consist either of a void in the weld metal or an inclusion that differs in density from surrounding weld metal, a valuable reference on discontinuities is section 2 of Reference 15.2. Radiographs may show internal discontinuities as well as surface discontinuities (see Chapter 9). Figure 15.17 provides photographs of some typical weldments and related radiographic images of discontinuities.

### 15.4.6 Advantages and Limitations of Radiography

**15.4.6.1 Advantages.** Since radiography operates on the principle of radiation absorption, it is noteworthy that some of the physical dilemmas that affect other NDE methods pose little or no significant problems for radiography. Radiography is not restricted to ferrous materials—or any other one type of material. Since radiation is penetrating, radiography is good for surface as well as subsurface discontinuities. Although there are requirements for exposure geometry, radiography does not require precisely parallel sides as a prerequisite for inspection. Multiple film radiography provides a tremendous thickness range over which a single exposure may yield valid indications. Another advantage is that a permanent record is available for both the customer and manufacturer to review for positive quality assurance, and a picture type of image is permanently available. Although conventional radiography is more of an art than a science, it does not require extensive developmental studies to adapt it to variations in technique.

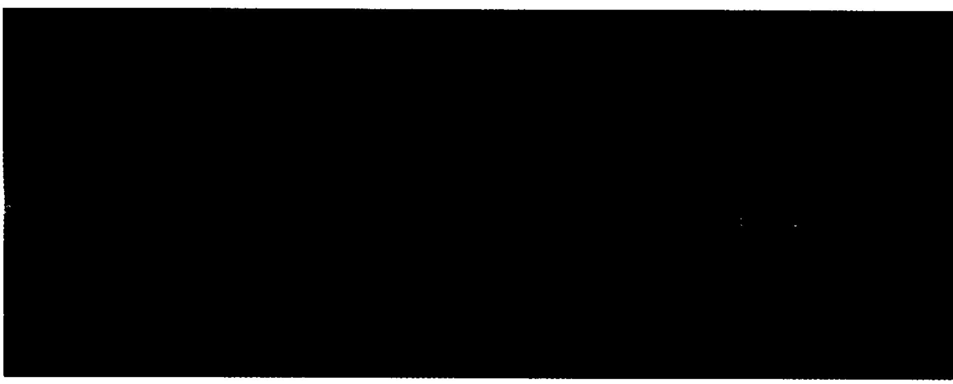
**15.4.6.2 Limitations.** Certainly, a major limitation is the hazard of radiation exposure to the radiographer and nearby personnel. In certain industries, radiographic examination can be disruptive. Radiography usually requires special facilities or areas where radiation may be used in a controlled manner without endangering personnel.

Radiography can detect cracks that are aligned parallel with the radiation beam; such cracks are usually normal to the plate surfaces. However, radiography usually cannot detect laminations in plate. Other NDE methods are capable of detecting such conditions and, with the proper choice of technique, can usually be relied upon to detect cracks normal to the plate surfaces. Discontinuity orientation, then, is a major consideration when specifying radiography as an examination method.

Additional limitations include the high cost of x-ray machines, isotopes and their related licensing, safety programs, exposure dosimetry control, and film processing equipment. Permanent exposure facilities, such as radiographic booths constructed of heavy concrete, are expensive and not portable.

The lengthy time cycle of film radiographic examination is another limitation. A typical

**(A) Radiographic Image of Elongated Slag Inclusions**



**(B) Radiographic Image of Incomplete Joint Penetration**

**(C) Radiographic Image of Tungsten Inclusions**

**Figure 15.17—Typical Radiographs of Weld Discontinuities**

cycle involves (1) the exposure process, (2) the film processing and related handling, and (3) the film interpretation process. Due to the degree of specialization frequently encountered, the exposed radiograph usually changes hands several times before the examination is complete and disposition is rendered. Many other NDE methods render more "on-the-spot" results, without such time delays. This limitation may sometimes be overcome by the application of various "real time" radiographic techniques.

Other limitations include the need for accessibility to opposite sides of the test object or clearance of several feet on several sides of the test object for placement of radiographic apparatus. The radiographic process, as a whole, requires operators with broad and diversified skills.

More information is available in the literature on industrial radiography, some of which are listed in the references and suggested reading material at the end of this chapter.

## 15.5 Ultrasonic Examination of Welds and Weld Related Materials

**15.5.1 General Principle.** Ultrasonic examination is a nondestructive method of detecting, locating, and evaluating internal discontinuities in metals and other materials. The basic principle involves directing a high-frequency sound wave into the test material on a predictable path, which, upon reflecting back from an interruption in material continuity (interface), produces a signal that is amplified and usually displayed as a vertical displacement on a cathode ray tube (CRT).

The detection, location, and evaluation of discontinuities becomes possible because (1) the velocity of sound through a given material is nearly constant, making distance measurement possible, and (2) the relative amplitude of a reflected pulse is more or less proportional to the size of the reflector.

**15.5.2 Equipment.** Equipment operating in the A scan mode of the pulse-echo method with video presentation is most commonly used for hand scanning of welds and materials (see Figure 15.18). The pulse-echo equipment produces repeated pulses of high-frequency sound with a rest-time interval between pulses to allow for the detection of return signals from sound reflectors. The time rate between pulses, called the *pulse rate*, usually occurs at about 500 pulses per second, depending upon the equipment in use.

In the video presentation, the time base line is located horizontally along the bottom of the CRT screen, with a vertical initial-pulse indication at the left end of the base line. The A scan indicates that the time lapse between pulses is represented by the horizontal direction; and the relative amplitude of signal is represented by the degree of vertical deflection on the CRT screen. The screen is usually graduated in the horizontal and vertical directions to facilitate measurement of pulse displays.

The horizontal time interval (sweep-length) is adjustable with a material and velocity control knob, making it possible to translate the time interval into material distance. The horizontal location of the initial pulse with a sweep delay adjustment allows the whole presentation to be properly positioned on the CRT screen.

In order that a sound wave might be directed into material, a search unit should be used. The search unit consists of some kind of holder and a transducer. The transducer element is a piezoelectric crystalline or ceramic substance. When excited with high-frequency electrical energy produced by the power supply, the transducer produces a mechanical vibration at a natural frequency of the transducer element. A transducer also has the ability to receive vibrations and transform them into low-energy electrical impulses. In the pulse-echo mode, the ultrasonic unit senses the return impulses, amplifies them, and presents them as vertical deflections (pips) on the CRT screen. The horizontal location of a reflector pip on the screen is proportional to the distance the sound has traveled in the test piece, making it possible to determine loca-

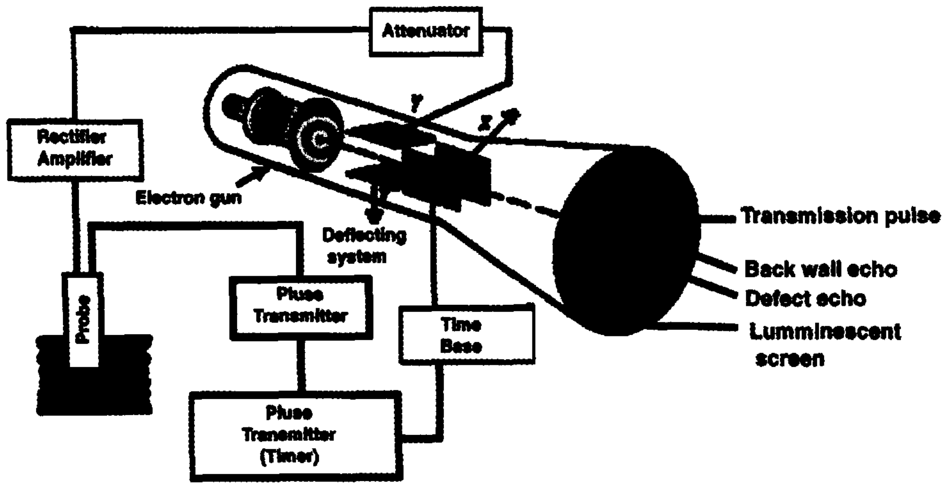



**Figure 15.18—Block Diagram, Pulse-Echo Flaw Detector**

tion of reflectors by using horizontal screen graduations as a distance measuring ruler.

The vertical display is adjustable with a pulse energy-level gain or attenuation control that makes it possible to show relative height of reflector indications.

**15.5.3 Sound Behavior.** The behavior of high-frequency sound resembles that of visible light in the following ways:

(1) The sound wave divergence can be controlled by focusing.

(2) The sound wave will reflect predictably from surfaces of different densities.

(3) The sound wave will refract at an interface between materials of different density.

When a search unit is applied to the surface of a uniform thickness test piece, only a small portion of the reflected sound energy is absorbed by the transducer, while the remainder will reflect from that surface back into the test piece interface, reverberating between the parallel test piece surfaces and causing an additional indication on the CRT screen upon each return of the sound wave to the initial surface.

Unlike audible sound, high-frequency sound is easily attenuated by air, but travels freely in homogeneous solids or liquids. Therefore, it is necessary to eliminate any air gap that might occur between the search unit and the test material surface, using a fluid couplant.

**15.5.4 Interpretation.** There are two basic methods of evaluating reflector amplitudes. The one offering greater range and affording greater evaluation accuracy uses a calibrated decibel gain or attenuation control. The other employs percentile CRT screen height ratios.

The percentile method often requires that sound attenuation patterns be drawn or overlayed on the CRT screen to compensate for sound attenuation with distance. With units so equipped, compensation for these losses can be made with a calibrated decibel gain or attenuation control. The decibel is a unit measuring the relative amplitudes of two acoustic or electric signals. In order to use the decibel system for flaw evaluation, each indication to be evaluated is adjusted to a reference level on the CRT with use of the calibrated gain or attenuator control; decibel ratings are made mathematically.

Some ultrasonic units are also equipped with distance amplitude correction (DAC) features that compensate electronically for amplitude losses, but the linearity of the vertical scale, especially when used in conjunction with decibel amplitude readings.

**15.5.5 Equipment Qualification.** AWS D1.1, *Structural Welding Code—Steel*, is probably the most restrictive code for ultrasonic inspection in that the tolerable decibel error is plus or minus one decibel over a sixty decibel range.

The decibel, as related to ultrasonics, is a function of voltage ratios. Usually, the percentile and voltage graduations on the CRT screen are linear, making the decibel ratios logarithmic in nature. The following equation can be applied for converting voltage changes to decibel differences:

$$D_N = 20 \text{ Log}_{10} V_1 \qquad \text{(Eq. 15-6)}$$

$$V_2$$

where

$D_N$ = decibel difference

$V_1$ = voltage one

$V_1$ = voltage two.

Screen percentages can be substituted for voltages in the equation. The nomograph shown on Figure 15.19 is a graphical solution to the equation.

**15.5.6 Ultrasonic Attenuation and Wave Form.** Ultrasonic attenuation is a combination of sound loss due to the divergence of the sound and the losses due to dispersion of the sound wave when encountering an interface.

High-frequency sound does not always pass through a material in the same manner. There are three basic modes of sound-wave propagation that can usually be associated with weld or weld-related materials. The simplest mode is the longitudinal (straight or compressional) wave mode that results when high-frequency sound is introduced into the test medium in a direction normal to the interface between the search unit and test material. In this mode, the principal direction of material particle vibration is parallel to the direction of sound-wave propagation through the material.

Another mode is the shear (angle or transverse) mode in which the principal direction of material particle vibration is perpendicular to the direction of sound wave propagation.

The third mode is the surface (Rayleigh) wave, transverse in nature, that follows along material surfaces. Shear and surface waves cannot propagate in liquid media.

When a longitudinal ultrasonic beam is directed from one medium into another of different acoustic properties at an angle other than normal to the interface between the two media, a wave-mode transformation occurs. The resultant transformation is dependent upon the incident angle in the first medium and on the velocity of sound in the first and second media.

In each transformation, there is an equal angle of reflection back into the first medium, along with at least one shear wave form of refracted angle in the second medium only if the incident wave is less than the first critical angle.

**15.5.7 Geometry.** Snell's law can be used to calculate angle transformations based on the sound-path angles and the sound velocities of the two media [see Figure 15.20(A)]. For example, the sine of incident angle *a* is to the sine of *d* (longitudinal) or *e* (shear) refracted angle as the sound velocity of the incident Medium 1 is to the sound velocity of the refracted Medium 2. This same equation can be used for determining refracted reflected angles that occur in wave-mode conversions within the same medium, using the sound velocities of different wave modes in the equation [see Figure 15.20(B)].

For example, in views (A) and (B) of Figure 15.20, the sine of incident angle a is to the sine of refracted reflected angle *c* as the sound

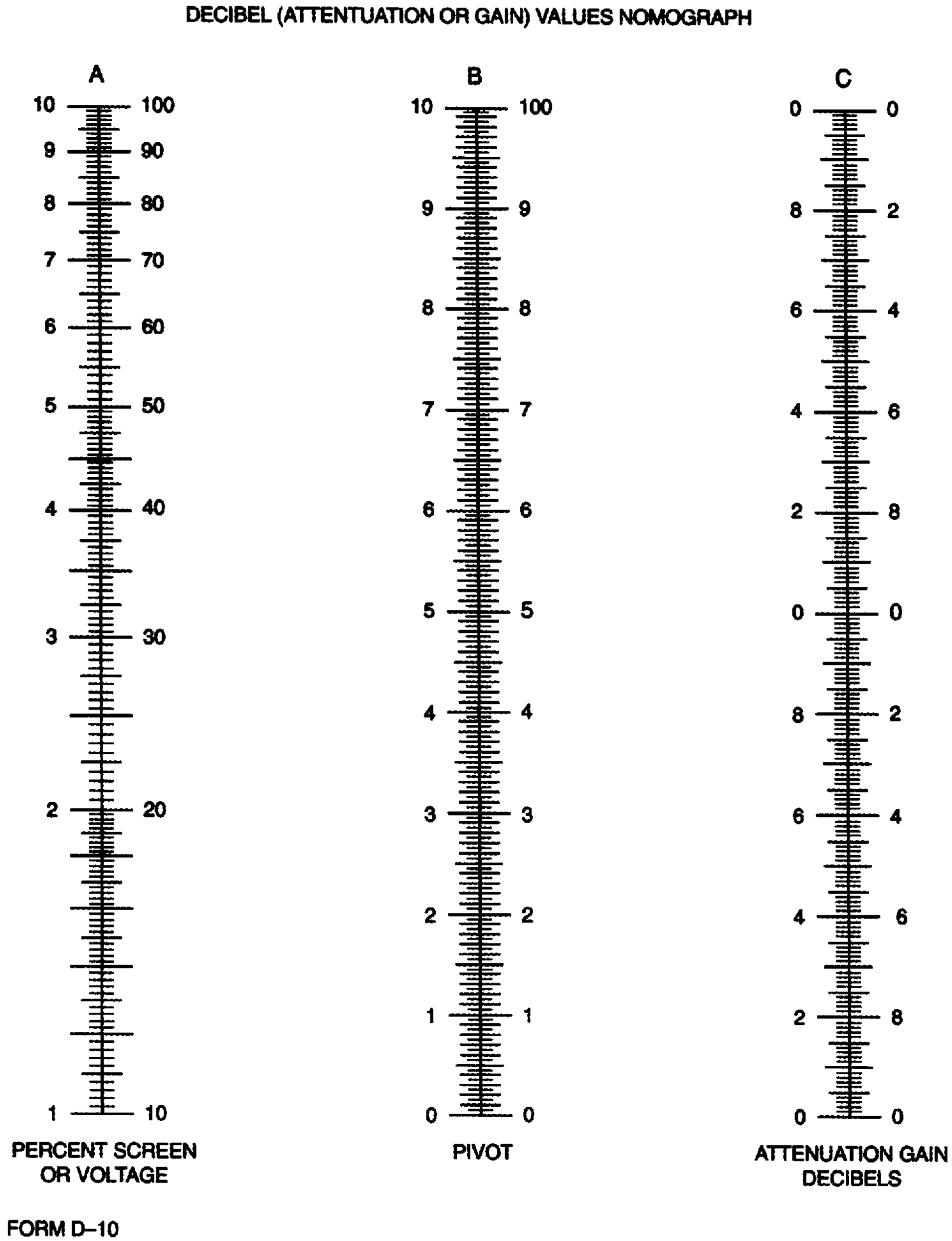



**Figure 15.19—Decibel-To-Screen Height or Voltage Nomograph**

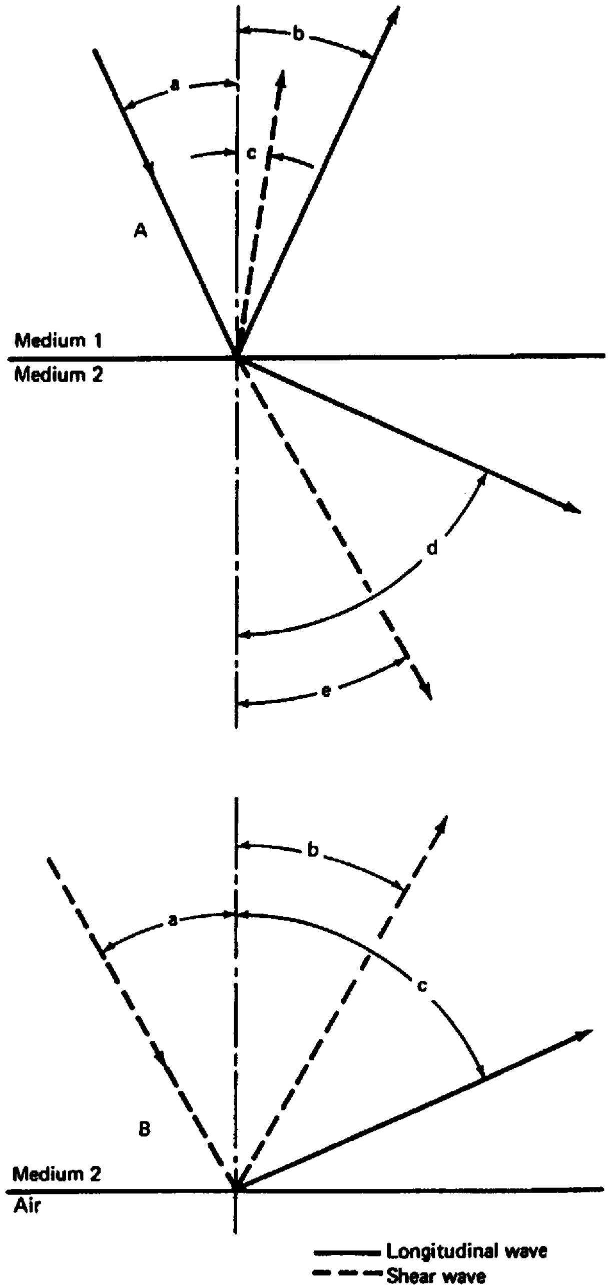



**Figure 15.20—Snell's Law of Reflection and Refraction**

velocity of incident angle sound beam is to the sound velocity of the *c* angle sound beam.

These equations can be written as follows:

View A:

$$\frac{\sin a}{\sin d} = \frac{\text{velocity (Medium 1, long.)}}{\text{velocity (Medium 2, long.)}}, \quad \text{(Eq. 15-7)}$$

$$\frac{\sin a}{\sin e} = \frac{\text{velocity (Medium 1, long.)}}{\text{velocity (Medium 2, shear)}}$$

or

$$\frac{\sin a\ \text{(long.)}}{\sin c\ \text{(shear)}} = \frac{\text{velocity (Medium 1, long.)}}{\text{velocity (Medium 2, shear)}} \quad \text{(Eq. 15-8)}$$

View B:

$$\frac{\sin a\ \text{(long.)}}{\sin c\ \text{(shear)}} = \frac{\text{velocity (Medium 1, short)}}{\text{velocity (Medium 2, long.)}} \quad \text{(Eq. 15-9)}$$

As the incident angle *a* is increased from the normal, which results in only longitudinal wave form, the resultant longitudinal angle *d* also increases until it becomes 90°, at which time there is no longer any longitudinal wave entering the second medium. This angle of medium one is called the *first critical angle.*

As the incident angle a is further increased, the shear angle *e* also increases until it becomes 90°, at which point the total shear wave in the second medium has been transformed into a surface wave. This angle in the incident medium is known as the *second critical angle.*

These calculations are based on simple geometry, using the centerline of sound beam for input. However, actual application is much more complex in that the sound beam has breadth, divergence, and also higher amplitudes at its centerline that gradually diminish to its outside extremities.

Figures have been developed to show effects of angle changes on amplitude responses; but, because of critical variables, these can be used only for tendencies and not for relative amplitude calculations.

**15.5.8 Calibration.** Since both the horizontal (time) and the vertical (amplitude) dimensions on the CRT screen are related to distance and size, respectively, but are not relative to any zero starting point, it is necessary to calibrate an ultrasonic unit to some basic standard before examination can commence.

Various types of reflectors can be machined in blocks of material similar in acoustic qualities to those of the material to be examined. Such reflectors can be used as calibration media for standardizing equipment settings of distance and amplitude.

Acceptable longitudinal distance calibration can usually be made with flat blocks having parallel surfaces. As a sound beam is transmitted into the block from one of the parallel surfaces, most of the sound energy reverberates back and forth between the parallel surfaces. This reverberation will result in multiple back wall indications on the cathode ray tube screen, which can be used for distance calibration.

Flat-bottom holes of various sizes and depths can be drilled into this block to provide sound amplitude standardization and acceptability standard levels (see Figure 15.21).

When a shear-wave ultrasonic beam is introduced into material at an angle other than normal to its parallel surfaces, the sound is propagated away from the sound entry point, with none being reflected back to the search unit (see Figure 15.22). For this reason, certain types of reflectors should be introduced into material to provide reflectors for calibration purposes.

In addition to providing distance calibration, a calibration block usually should provide amplitude standardization for flaw size evaluation. Figure 15.23 illustrates most of the types of reflectors used for this purpose. Holes drilled normal to the test surface of (A), parallel to the test surface (B), or flat-bottom holes at an angle making the flat bottom normal to the sound beam (C) can be used for

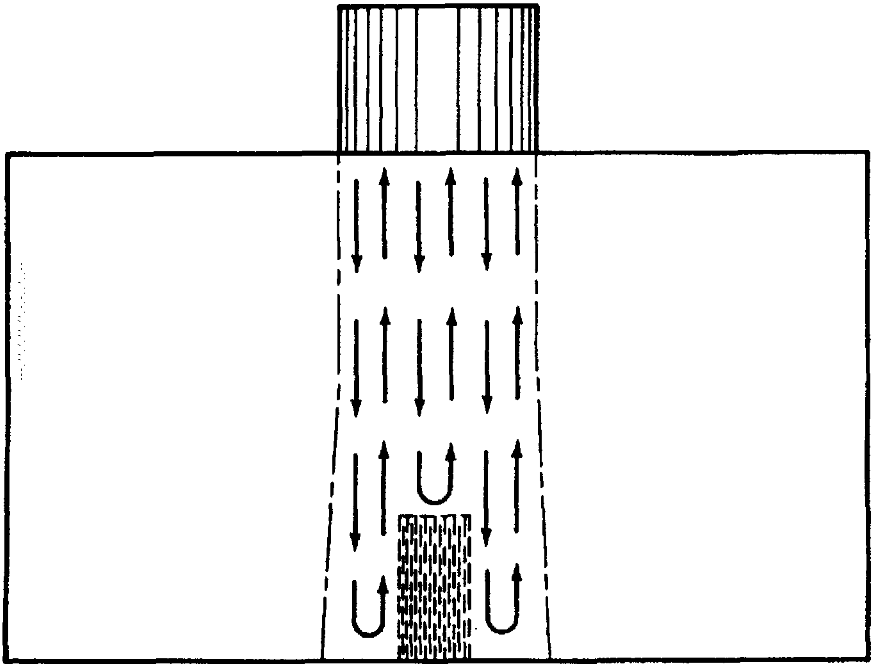


**Figure 15.21—Amplitude Calibration Using Flat Bottom Holes**

**Figure 15.22—Shear Wave Ultrasonic Beam**

this purpose. Other types of reference reflectors can be in the form of square corners (D), square or beveled grooves cut normal to the sound beam (E) and (F), or radial grooves (G). Combinations of different types or sizes of indicators can be put into single blocks if necessary.

The cost of producing reference test plates dictates a simplicity of construction. However, the initial cost may be quite insignificant when compared to their usefulness in attaining repeatable standardization.

The transducer element height-to-width ratio is an important factor in considering the type of reference reflector for use in attaining desired results. The wider element will produce higher amplitude response from the reflectors shown in Figure 15.23(B), (E), and (F), while an element of greater height will respond at higher amplitude to those shown in views (A) and (G). Hence, the square or nearly square transducer element are usually more desirable for indication evaluation on a sound amplitude basis.

Reflectors (A), (D), and (E) depend upon corner incidence for amplitude response, which makes surface and corner conditions around the intersection of the hole-to-plate surface critical in attaining repeatability from various reference blocks. Significant probe angle differences also create a variable that should be compensated for when using the corner incidence method of calibration, due to ultrasonic wave mode conversion.

The cylindrical hole drilled parallel to the test surface (B) is a widely used type of reference reflector. The general tendency is to relate the diameter of this type of hole to a weld discontinuity size, which will not usually be true since its reflectance amplitude is based on its being a one-one reflector with nearly equal amplitude reflectance regardless of hole diameter, especially as the sound-path distance is increased.

Corner incidence effects can also occur on calibration reflectors as shown in Figure 15.23 (B), (D), (E), and (F) when the sound beam is directed slightly toward the intersection between the reference reflector and the side of the reference plate, which will create higher amplitude responses, making this type of reflector difficult to use in attaining repeatability if the length of reflector is not considerably greater than the ultrasonic sound-beam width, and the sound beam is not directed toward the center of the reflector.

The size evaluation of the lamellar type of reflector (root of groove, E) that lies in a plane parallel to the plate test surface is rather difficult with shear wave, due to the acute angle of 1 sound-beam-to-reflector surface. This type of evaluation is usually limited to straight-beam (longitudinal) examination.

The flat-bottom hole (C) reference reflector seems almost ideal at first glance, but unless the inclination angle of the flat bottom of the hole exactly matches that of the sound beam, a great deal of variation of sound amplitude responses will occur. Most tolerance of probe angles is at least plus or minus 2 degrees.

The radial groove (G) reflector has all the advantages of all the other types of reflectors in that it responds equally with any angle of probe at a constant sound path distance and does not create corner incidence effects. However, the intricate machining of this type of groove is costly and the choice of a square or nearly square transducer element is important in attaining desirable results.

**15.5.9 Determinate Variables.** The sound velocity through a given material is the distance that sound energy will propagate in that material in a given amount of time and is a function of material density, acoustic impedance, and temperature.

Since these sound velocities are relatively high, the most common means of expression are in meters or feet per second. The sound velocity of a shear wave in a given material is usually about half that of a longitudinal and about 1.1 times that of a surface wave. For calculations of angle transformation, specific velocities should be used and are usually available from technical data or can be determined with instrumentation.

Effects of temperature on sound velocity are not usually very significant in most metals but should be considered when calculating angles in plastics for use as wedge material for shear wave-search units.

The frequency of the sound used for testing welds and weld-related materials is usually between 1 and 6 megahertz (MHz = million cycles per second), with the most commonly used frequency being about 2.25 MHz.

A transducer element will resonate at its natural frequency when excited electrically or mechanically. This frequency is not a single frequency, but a relatively narrow band of frequencies, with one or more specific frequencies responding at the highest amplitude. The

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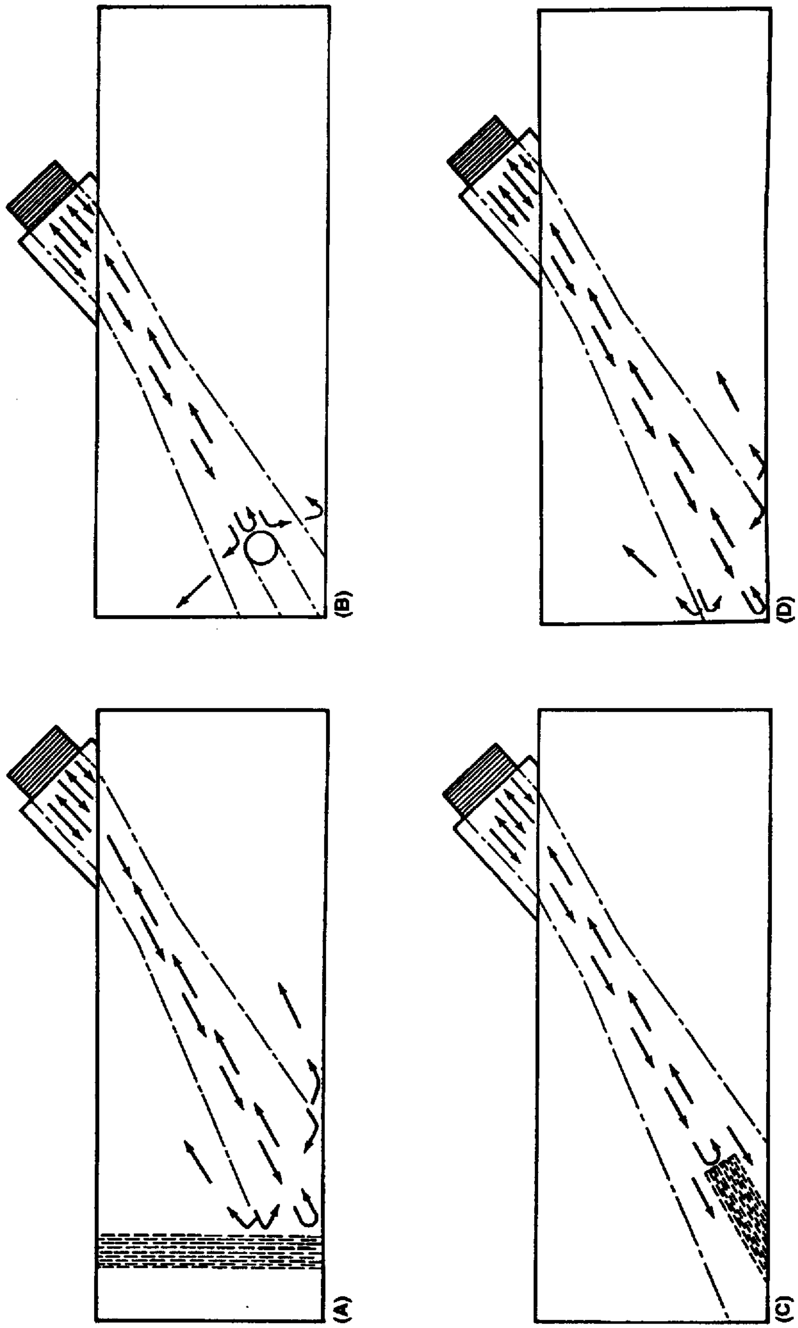



Figure 15.23—Amplitude Calibration

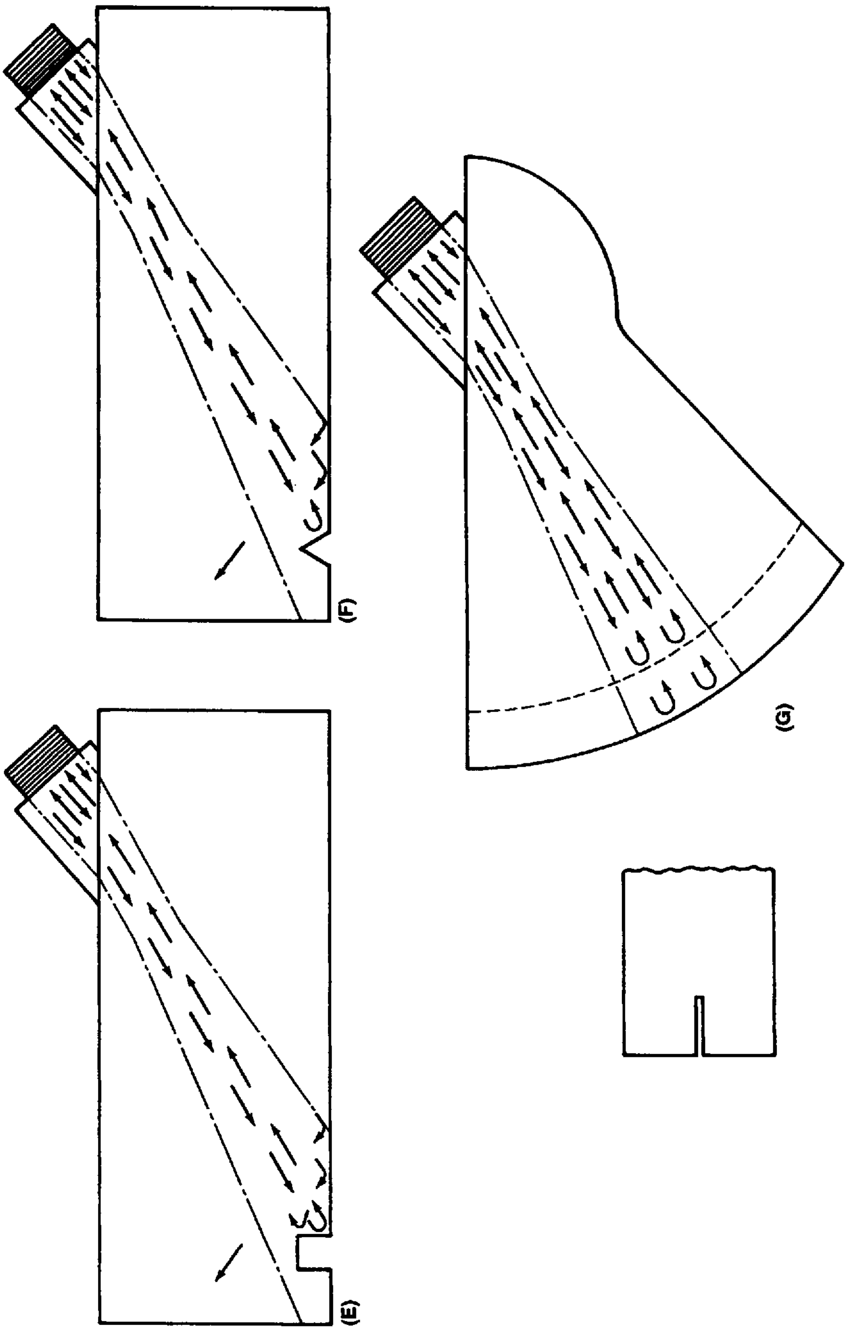



Figure 15.23 (Continued)—Amplitude Calibration

frequency is related to the transducer-element thickness, increasing as its thickness is reduced. The electrical pulse that excites the transducer element should be of a frequency in resonance with the natural frequency of the element in order to attain maximum sound-amplitude response, although broad band pulse generation is usually quite effective and is usually used with portable test equipment.

Wave length, usually symbolized by the Greek letter "lambda," is a function of velocity divided by the frequency. The expected minimum size of reflector detectable with high-frequency sound is about one-half wave length as measured in a direction perpendicular to the direction of sound propagation.

**15.5.10 Equipment Selection.** A longitudinal ultrasonic wave is generally limited in use to detecting inclusions and lamellar-type discontinuities in base material. Shear waves are most valuable in the detection of weld discontinuities because of their ability to furnish three-dimensional coordinates for discontinuity locations, orientations, and characteristics. The sensitivity of shear waves is also about double that of longitudinal waves for the same frequency and search unit size.

Shear-wave angles are measured in the test material from a line perpendicular to the test surface. The three most commonly used angles are 70°, 60°, and 45°. Search unit angle selection is usually based on expected flaw orientation or as stated in AWS D1.1, possible orientation in a direction most detrimental to the integrity of the weld joint (which would be normal to the material surface).

It is advisable to pretest the material area through which the shear-wave should travel in testing a weld with longitudinal wave for assurance that the base material does not contain discontinuities that would interfere with the shear wave evaluation of the weld.

**15.5.11 Coupling.** It is not usually necessary to remove weld reinforcement to obtain satisfactory results in testing a weld, as the sound beam is directed under the weld bead at an angle from the base material. If a weld is to be ground flush to satisfy contractual requirements, final testing should be done after grinding is completed.

The material surface to which the search unit is applied should be smooth and flat enough to maintain intimate coupling. It is usually not necessary to remove tight mill scale or thin layers of smooth paint; however, for many reasons, it is advisable to test welds prior to painting.

Grinding, unless very closely controlled, will usually result in an inferior work surface as compared to the unground surface. Weld spatter in the scanning area should be removed for complete weld coverage; this can often be accomplished with a hand scraper. In the event that sand, granulated weld flux, or dirt blows onto a test area to which couplant has been applied, the only solution is to wipe the surface clean and apply new couplant.

Couplant materials used for testing should be hydraulic in nature and have enough body to maintain coverage of the test surface during testing. Some common couplant materials are water, oil, grease, glycerine, and cellulose gum powder mixed with water. Sometimes it is necessary to add a wetting agent to a couplant to promote wetting of the test surface and thus allow sound to be introduced into the test material. Some qualities that should be considered in the selection of a couplant material are viscosity, safety (slipping hazard), ease of removal, and effects of residue on future part operations, such as hydrocarbon pick-up during weld repair. Some significant advantages of cellulose gum powder mixed with water as a couplant are low cost, variable viscosity, residue does not create slipping hazard, residue will not contaminate weld repairs, and weldment will not usually require solvent cleaning prior to painting. A number of proprietary couplants are available that combine desirable features of the couplant materials mentioned above.

**15.5.12 Flaw Location and Interpretation.** One of the most useful characteristics of ultrasonic testing is its ability to determine the position of flaws in a weld or weld-related materials. In order to attain the necessary accuracy of cross-sectional location with a shear wave, it is important to translate sound-path-distance displays to surface and depth measurements. This can be very easily accomplished with the use of ultrasonic rulers, an example of which is shown in Figure 15.24.

There is a ruler for each of the common testing angles. Each ruler contains three scales. The B scale is a common inch ruler and represents the actual dimension of the sound path. For each inch of sound path, there is an A scale inch of surface measurement and a C scale inch of depth. These surface and depth dimensions can be translated to common inch distances by using the B scale.

It is not usually necessary to translate surface dimensions, as the ruler can be placed directly on the test material and measured with the A scale set to the search unit index point. The example shown in Figure 15.24 relates a 4 in. (??? mm) sound path to a 3-3/4 in. (94 mm) surface measurement and a 1-3/8 in. (35 mm) depth.

The measurements used by AWS D1.1 for the X, Y, and Z directional location of flaws are shown in Figure 15.25.

**15.5.13 Procedures.** Most weld testing is done with a transducer frequency of about 2.25 MHz. This frequency is usually adequate for weld testing in both longitudinal and shear-wave modes. With the use of miniature search units (less than 1/2 in. × 1/2 in. [13 × 13 mm]), it is usually necessary to use higher frequency transducers in order to reduce sound beam divergence which is increased by the smaller size of the element.

Most ultrasonic testing of welds is done following a specific code or procedure. Some requirements are much more straight-forward and specific than others. An example of such a procedure is that contained in AWS D1.1 for testing groove welds in a thickness range of 5/16 in. (8 mm) to 8 in. (200 mm) in structural types of steels.

The following are several basic rules applied in the use of this procedure:

(1) The sound path distance is basically limited to 10 in. (see Figure 15.26).

(2) Three basic search unit angles are used for weld testing: 70°, 60°, and 45°, as measured in test material from a line normal to the test surface of the material.

(3) The weld throat thickness is divided into three zones described as the top quarter, middle half, and bottom quarter of throat thickness.

(4) It is assumed that any weld flaw might be oriented in a plane normal to the test material surface and parallel to the weld axis. This flaw orientation would be the most serious direction for flaws in most welds.

(5) The 70° search unit would provide highest amplitude response from the type of flaw described in rule 4, with second highest response from the 60°, and lowest response from the 45° unit. Hence, the order of preference is the same.

(6) It is assumed that the relative amplitude response from a weld flaw is in direct proportion to its effect on the integrity of the weld. The generally accepted diminishing order of flaw severity in welds is as follows:

(a) Cracks

(b) Incomplete fusion

(c) Incomplete penetration (except near material surface; in which case, high amplitude response can be expected)

(d) Slag

(e) Porosity

(7) Ultrasonic indications are evaluated on a decibel amplitude basis. Each indication to be evaluated is adjusted with the calibrated dB gain or attenuation control to a reference level height on the CRT, and the decibel setting number is recorded as indication level *a*.

(8) Reference level *b* is attained from a reflector in an approved calibration block. The reflector indication is maximized with search unit movement and then adjusted with the gain or attenuation control to produce a reference level height indication. This decibel reading is the reference level.

(9) Decibel attenuation factor *c* used for structural steel weldment testing is at the rate of two decibels per inch of sound path after

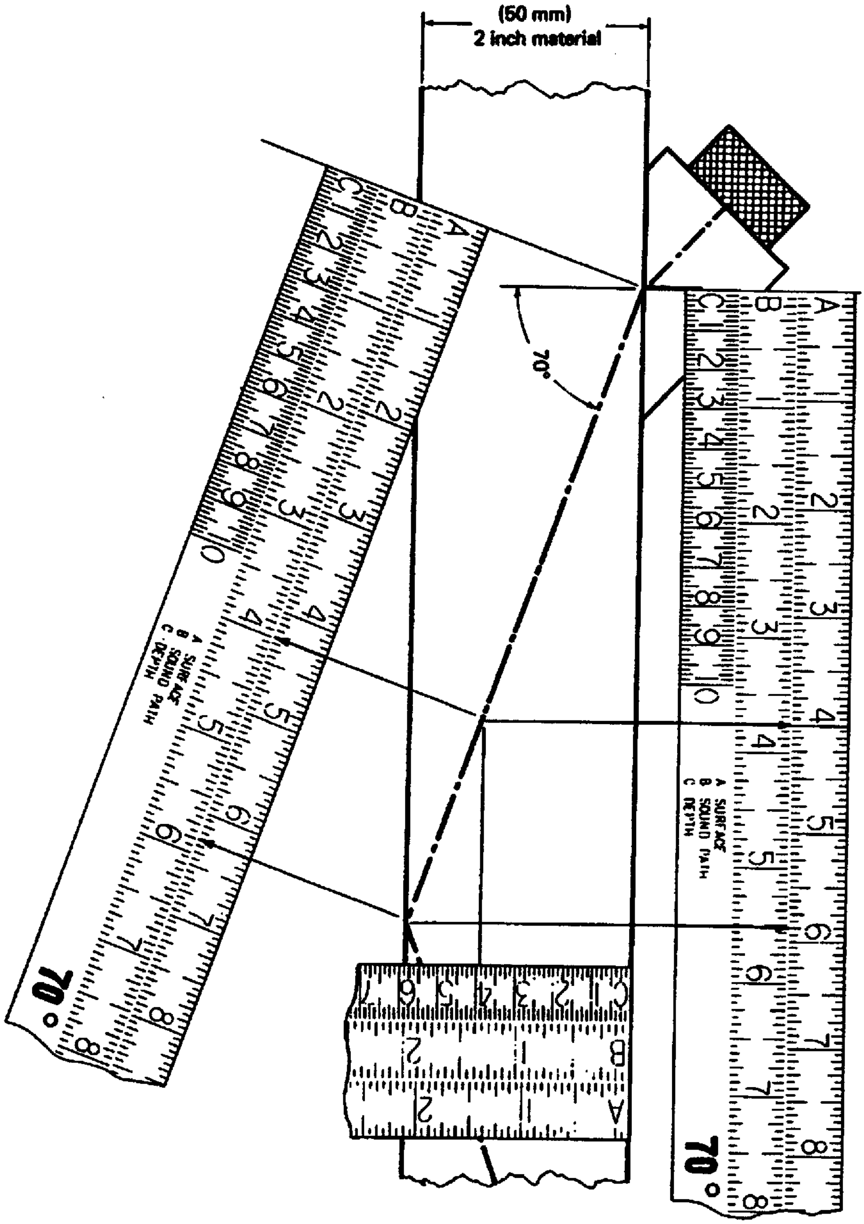



**Figure 15.24—Ultrasonic Ruler Application**

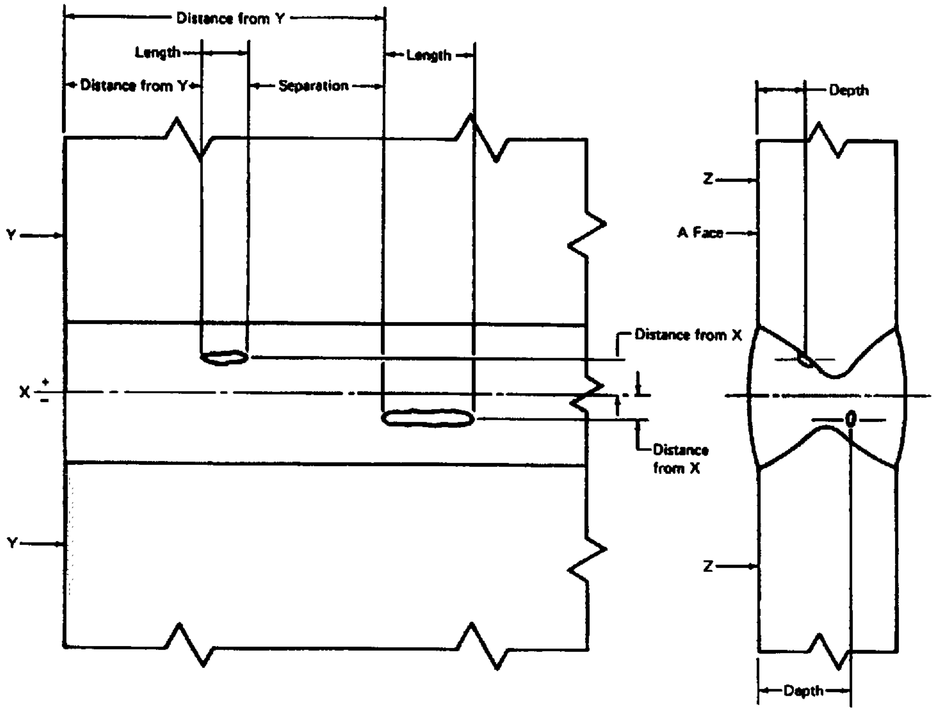



**Figure 15.25—Flaw Orientation**

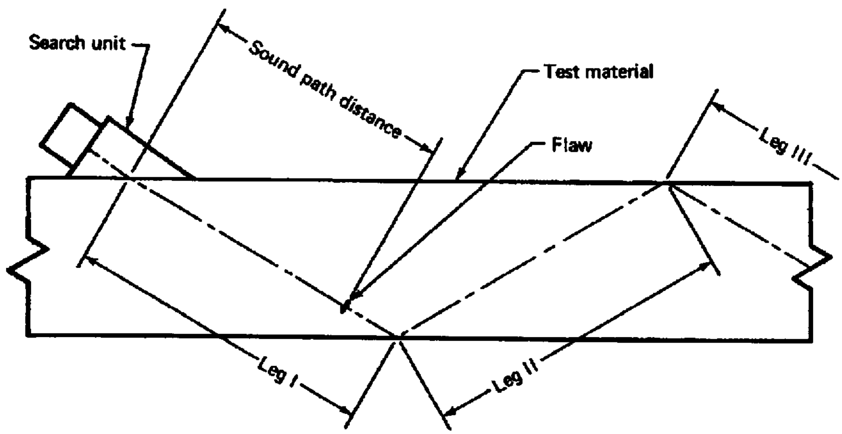



**Figure 15.26—Sound Beam Propagation Showing Sound Path Distance**

the first inch. Example: a 5-in. sound path would produce an attenuation factor of (5–1) × 2 = 8.

(10) Decibel rating *d* for flaw evaluation in accordance with the code for equipment with gain control is attained by applying the equation a – b – c = d; and for equipment with attenuation control, b – a – c = d (letters taken from rule numbers 7, 8, 9, and 10).

(11) There are no direct provisions in the code for testing fillet welds, some unusual geometries, or certain material thicknesses. These omissions are based not on the inability of ultrasonics to detect flaws, but on the need for specialized applications for evaluation.

By following the general format in the preceding rules, special procedures can be established providing satisfactory results in the testing of other materials that have significant acoustic differences, such as sound velocity and sound attenuation. AWS D1.1 contains provisions for establishing special ultrasonic procedures upon agreement between owner and producer for testing techniques not covered by the code.

Other codes and specifications for ultrasonic testing of welds leave many factors to the discretion of the operator, such as the selection of search unit angle and frequency. Some codes depend on the operator to identify the type and size of flaw, evaluating it to the approximate equivalent of a radiographic standard, using the relative percentile screen height of indication as a reject or disregard criterion. Others require records of all data so that an indication can be plotted as to location, position in a weld or adjacent material, vertical dimension, and length.

**15.5.14 Reporting.** In the past, a major objection to the use of ultrasonics in determining the quality of welds was its inability to produce permanent records. Careful tabulation of information on a report form similar to that in AWS D1.1 will usually satisfy these objections. The welding inspector should be familiar with the kinds of data that should be recorded and evaluated so that a complete and satisfactory determination of acceptability can be obtained in accordance with a code or specification requirement for the particular project or weld being examined.

## 15.6 Magnetic-Particle Examination

Magnetic-particle inspection is a nondestructive method of detecting discontinuities in ferromagnetic materials. This method will detect surface discontinuities including those that are too fine to be seen with the unaided eye. It will also detect those discontinuities that lie slightly below the surface, although sensitivity is reduced and the method should not be relied on to detect these discontinuities.

Not all discontinuities in metal detract from satisfactory performance in service. It is necessary, therefore, for the inspector to be able to interpret the indications given by the magnetic-particles to determine which discontinuities are to be regarded as detrimental. Since variation in the evaluation of results is to be expected, the following points should be agreed upon when examination is being discussed:

(1) What weldments or sections of weldments are to be inspected

(2) What techniques will be used (specified in detail)

(3) What types and extent of discontinuities will be rejected or accepted

(4) Definition of rework and subsequent examination

A great deal of information regarding the soundness of weldments can be obtained from proper application of magnetic particle examination. This method may be used to inspect welds and plate edges prior to welding and for the examination of welded repairs. Among the defects that can be detected are surface cracks of all kinds, both in the weld and in the adjacent base metal; laminations or other defects on the prepared edge of the base metal; incomplete fusion and undercut; subsurface cracks; and inadequate joint penetration.

This technique is not a substitute for radiography or ultrasonics in locating subsurface discontinuities, but may present advantages in locating tight cracks and surface defects. It may often be employed to advantage in cases where the application of radiography or ultrasonics is neither available nor practical because of the shape of the weldment or location of the weld.

The magnetic particle method of examination is applicable only to ferromagnetic materials in which the deposited weld metal is also ferromagnetic. It cannot be used to inspect nonferrous materials or austenitic steel, and difficulties may arise in inspecting weldments where the magnetic characteristics of the deposited metal are appreciably different from those of the base metal. Joints between metals of dissimilar magnetic characteristics create magnetic discontinuities that may produce irrelevant indications even though the joints themselves are sound.

The degree of sensitivity in this method depends upon certain factors. Sensitivity decreases with a decrease in size of the discontinuity, and also with an increase in depth below the surface. A decrease in sensitivity is evident when discontinuities are rounded or spherical, rather than linear, or cracklike. Maximum sensitivity is obtained when defects are essentially perpendicular to the direction of the magnetic flux.

A discontinuity should sufficiently interrupt or distort the magnetic field to cause an external magnetic flux leakage. Fine, elongated discontinuities, such as seams, inclusions, or fine cracks, will not interrupt a magnetic field that is parallel to the direction of the discontinuity. In this case no indication of the discontinuity will be apparent. Such discontinuities can, however, be detected by using a magnetic field that is not parallel to the discontinuity.

If the general direction of possible defects is unknown, it is necessary to perform magnetic-particle inspection by magnetizing from mutually perpendicular directions.

The surface conditions also influence the sensitivity of the inspection process. The surface should be clean, dry, and free from oil, water, excessive slag, or other accumulations that would interfere with efficient inspection. Wire brushing, sandblasting, or other comparable cleaning methods are usually satisfactory for most welds. Surface roughness decreases the sensitivity and tends to distort the magnetic field and may cause nonrelevant indications. It also interferes mechanically with the formation of powder patterns and may result in false indications.

**15.6.1 Principles of Magnetic-Particle Examination.** The basic principle of magnetic particle examination is that when a magnetic field is established in a piece of ferromagnetic material containing one or more discontinuities in the path of the magnetic flux, minute poles are set up at the discontinuities. The magnetic field lines of force (flux lines) are distorted by the presence of the discontinuity, and if at or near the surface, the magnetic field is forced from the part resulting in a flux leakage or leakage field at the site of the discontinuity. Applied magnetic particles will be attracted to the poles established on opposite sides of the discontinuity, thereby creating a magnetic-particle indication that outlines the shape and orientation of the discontinuity.

The piece to be inspected is magnetized by introducing electric current into it, or by putting the piece in a current-carrying coil or in contact with the poles of a strong magnet. The magnetic field in the part is interrupted by discontinuities and a leakage field is produced on the surface. The areas to be inspected are covered by finely divided magnetic particles that react to the magnetic leakage field produced by the discontinuity. These magnetic particles form a pattern or indication on the surface that assumes the approximate shape of the discontinuity. The two types of magnetization generally employed in magnetic-particle testing are longitudinal magnetization and circular magnetization.

An example of longitudinal magnetization is the magnetic field associated with a permanent bar magnet having a north and south pole at opposite ends. These poles produce a flow of imaginary lines of force between them to create a magnetic field in the surrounding medium (see Figure 15.27).

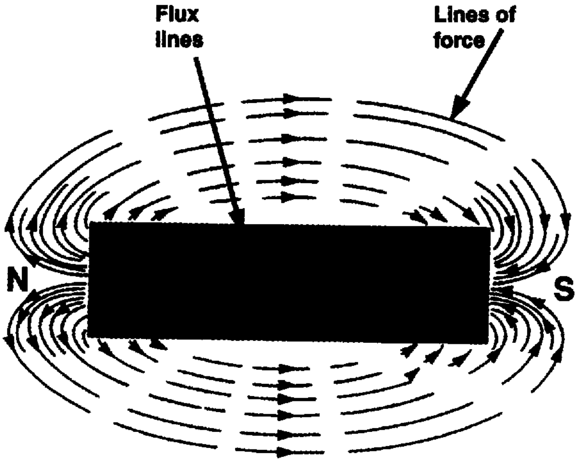



**Figure 15.27—Magnetic Field in a Bar Magnet**

The most apparent characteristic of a magnet is its ability to attract any magnetic materials placed within its field. This property is attributed to the tendency of the lines of force to pass through these magnetic materials, since they offer a path of lower reluctance than a path through the surrounding atmosphere; hence, the lines of force tend to crowd into the magnetic material.

If the bar magnet is cut in half, each half becomes an individual magnet with two poles, and the opposite faces of the cut assume opposite polarity (see Figure 15.28).

If, instead of cutting the magnet, a notch is made in it, the flux distribution or the flow of the lines of force will be markedly changed only in the area surrounding the notch, and the distortion diminishes as the distance from the notch increases (see Figure 15.29).

Each face of the notch assumes opposite polarity and produces a flow of leakage flux across the air gap. It is this leakage flux that permits the detection of defects by the magnetic particle method.

The other type of magnetization commonly employed in magnetic-particle examination, is circular magnetization, obtained with an electric current. In general practice, it is not practical to use a permanent magnet, so the electromagnetic field produced by a high amperage, low-voltage current flowing through a conductor is used.

A different condition of flux flow is produced in which the density and direction of the lines of force may be controlled.

A current flowing through a conductor creates a magnetic field, and the lines of force thus produced flow in concentric circles at right angles to the conductor, with their centers at the center of the conductor as shown in Figure 15.30. The intensity of the field is proportional to the amount of current.

The flux flows within the conductor as well as around it, and when the conductor is a ferromagnetic material (as it is when used in magnetic-particle examination), the field is almost entirely confined to the conductor itself (see Figure 15.31). The field will be zero at the center of the conductor and increase to its maximum value at the surface of the conductor.

Thus, if a current is made to flow through a steel section, the magnetic field produced will be uniform if the section is uniform. If, how-

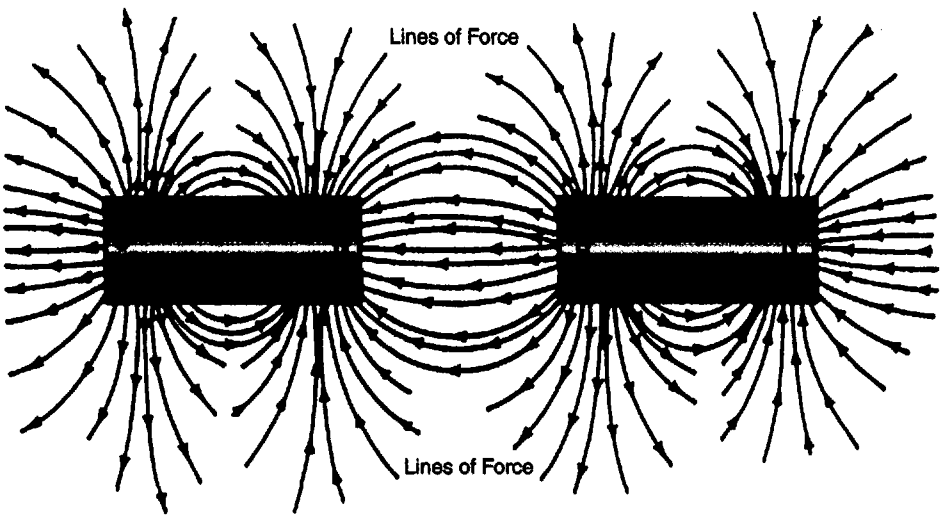



**Figure 15.28—Magnetic Field in a Bar Magnet That Has Been Cut in Half**

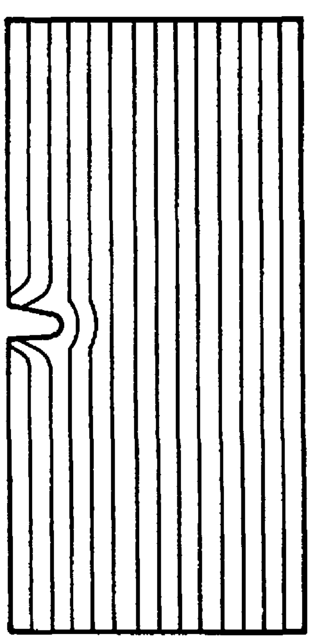


**Figure 15.29—Magnetism Around a Notch Cut in a Bar Magnet**

ever, there is a flaw or sharp change of section, the same effect is produced as if there were a notch in a bar magnet: local poles form and a leakage flux flows across the defect encountered. If a finely divided magnetic material is dusted on the surface while the current is flowing, the particles near the defect will be attracted to the local poles, and tend to build up across the gap and thereby reduce the reluctance of the path of leakage flux (see Figure 15.32). If any surplus magnetic powder is then removed, the outlines of the defect, with regard to dimensions and directions, are rather well defined by the powder that remains.

Circular magnetization is used to detect lengthwise cracks. The part to be examined is "set up" in the inspection unit and current is passed through the part or through an electrical conductor within the part. The circular magnetic field cutting across the crack attracts and holds iron powder, to indicate the invisible defects. Electricity is passed through the part parallel to the defects to be found. This is commonly referred to as a *head shot.*

Figure 15.30—Magnetic Field Around a Conductor Carrying Current

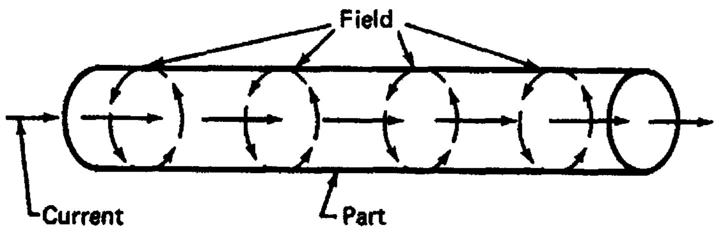
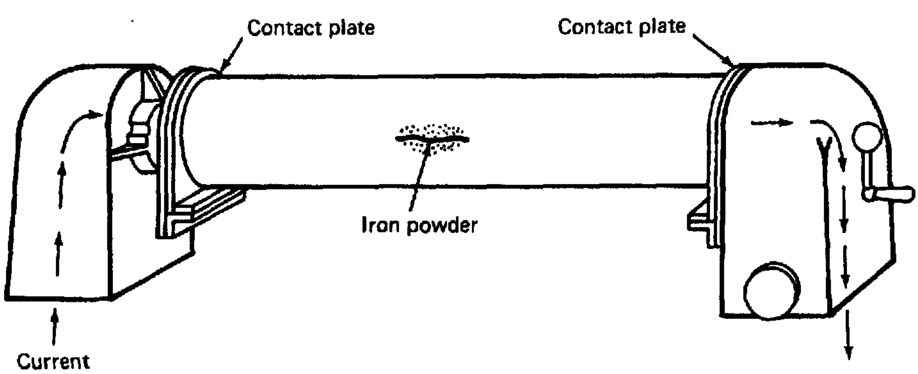



Figure 15.31—Field of Ferromagnetic Conductor is Confined Almost Entirely to the Conductor Itself




Circular magnetization is used to detect lengthwise cracks. Part to be inspected is "set up" in the inspection unit and current is passed through the part or through an electrical conductor within the part. The circular magnetic field cutting across the crack attracts and holds iron powder, to indicate the invisible defects. Electricity is passed through the part parallel to the defects to be found.

Figure 15.32—Magnetic Particles Near a Defect are Attracted to the Local Poles

providing the defect is perpendicular to the flux path. If, however, the flux path is parallel to the defect, it is probable that no pattern (or, in the case of the larger defect, only a weak or indefinite pattern) will appear.

On large parts, such as large weldments, strong magnetic fields may be produced by passing a high current through local areas by means of contact prods (prod magnetization—see Figure 15.33), which also produces circular magnetization.

**15.6.2 Orientation of Magnetic Field.** The magnetic field should be in a favorable direction to produce indications. When parallel to a discontinuity, the indication may be weak or lacking. The best results are obtained when the magnetic field is at right angles to the discontinuity. Thus, when applying current directly to the part, the best discontinuity indications are produced when the current is flowing parallel to the discontinuity, because the magnetic field is always at right angles to the flow of current.

**15.6.2.1 Longitudinal Magnetization.** The part to be inspected can be made the core of an electromagnet by placing it within a solenoid (see Figure 15.34). This produces a field that runs through the part in a direction parallel to the axis of the coil and produces two or more poles, usually at the ends of the part. This is referred to as *longitudinal* or *bipolar magnetization*. Similar effects can be obtained by making the workpiece a link in a magnetic circuit or by placing it in a magnetic field created by a strong permanent magnet or electromagnet. Shafts, drums, girders, and the like may be magnetized by means of a flexible electric cable coiled around the part. When a current is passed through the cable, the part is longitudinally magnetized.

**15.6.2.2 Overall Circular Magnetization.** Circular magnetization is normally obtained by passing high current through the piece itself (see Figure 15.32). This is known as the *direct method of magnetization*. The magnetic field produced is usually circular in

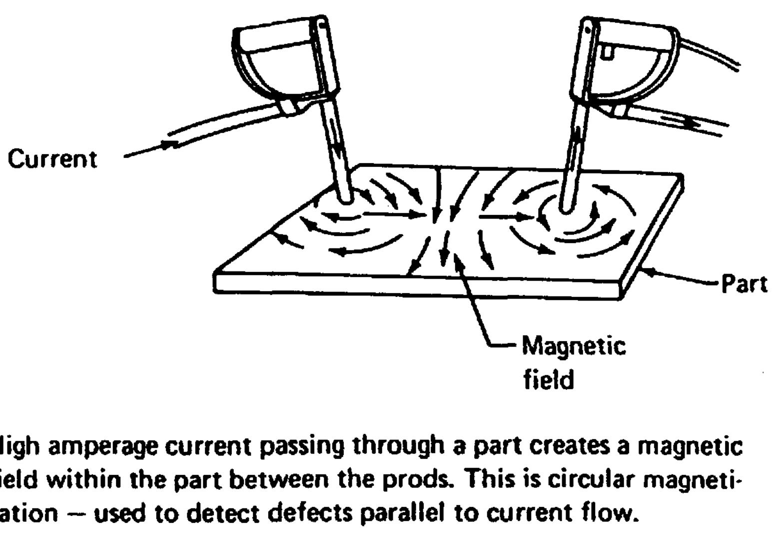



**Figure 15.33—In Large Parts, Local Areas Can Be Magnetized; Arrows Indicate Field**

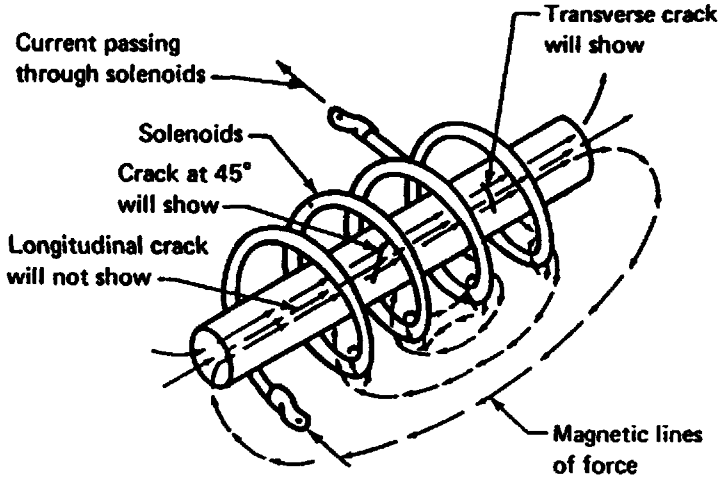



**Figure 15.34—Part to be Inspected Can Be Magnetized by Making it the Core of a Solenoid**

form and is at right angles to the direction of current flow. It can be used to detect discontinuities that lie approximately in the direction of current flow.

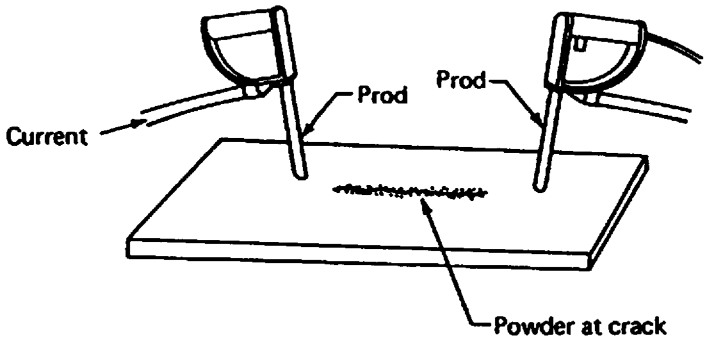
Circular magnetization may also be obtained on hollow parts (such as cylinders) by passing magnetizing current through a conductor or bar placed through a central opening in the part. When the current is passed through the bar, the inner surface as well as the outer surface of the cylinder is magnetized. This is known as the *indirect method of magnetization*. The surface of the bore of a hollow part is not magnetized when current is passed through the part.

When the direct method of circular magnetization is used, the field is normally contained within the contours of the part. This provides maximum field strength and, therefore, maximum sensitivity to subsurface discontinuities.

**15.6.2.3 Prod Magnetization.** It is generally impractical to attempt to magnetize large parts as a whole. They may be magnetized locally by passing current through areas or sections by means of contacts or prods (see Figure 15.35). This produces a local circular field in the area between the contact points. The technique is generally used in the inspection of large weldments where only the weld and adjacent metal are to be inspected. The prods are applied to the surface to be tested and held firmly in position while the current is passed through the area to be examined.

The contact prods and the areas to be examined should be sufficiently clean to permit passage of high current without arcing or burning. A low open-circuit voltage (2 to 16 v) is advisable for this reason and also to prevent arc flash. The usual procedure is to position the contact prods parallel to the axis of the weld and to perform a second inspection with the prods transverse to the axis of the weld.

It is necessary to have some convenient method for turning the magnetizing current on and off to prevent arcing. This may be accomplished by a switch connected in the




Circular magnetization is used to detect cracks in welds or local areas of large surfaces, heavy castings, forgings, etc.

High amperage current is passed through the part or an area of the part between the prods or clamps held firmly to the surface. Any crack which cuts across the magnetic field attracts the magnetic particles to form an indication and indicate defects.

High amperage current is passed through the part parallel to the defects to be found.

**Figure 15.35—Crack in Large Plate is Indicated by Alignment of Particles Between Prods**

circuit of the generator or in the primary circuit of the stepdown transformer. The switch is usually located on the handle of one of the contact prods.

**15.6.3 Amount of Magnetizing Current.** The current should be of sufficient strength to indicate all discontinuities that might affect the performance of the weldment in service. Excessive magnetizing current should be avoided because it may produce irrelevant patterns. Magnetizing current should be determined by specifications, standards, or purchase orders. If these documents are unavailable, current requirements may be determined by experience or actual experiment. Voltage has no effect on the magnetic field and should be kept low to prevent arcing and overheating.

**15.6.4 Type of Magnetizing Current.** Alternating current, direct current, and rectified current all may be used for magnetizing the parts to be examined. High amperage, low-voltage current is usually employed.

Portable equipment that makes use of electromagnets and permanent magnets is occasionally used. These are generally satisfactory for the detection of surface cracks only.

**15.6.4.1 Alternating Current.** Alternating current produces a field primarily on the surface. The use of alternating current increases particle mobility. The method is effective for locating discontinuities that extend to the surface, such as fatigue or service cracks. It may be used to examine welds where subsurface evaluation is not required. Surface cracks will be indicated, but deeper lying discontinuities will not.

**15.6.4.2 Direct Current.** Direct current produces a field that penetrates deeper within the part and is, therefore, more sensitive than alternating current for the detection of subsurface discontinuities. Full-wave, three-phase rectified current produces results essentially comparable to direct current obtained from batteries.

Half-wave rectified single-phase current provides maximum sensitivity. The pulsating field increases particle mobility and enables the particles to line up more readily in weak leakage fields. The pulse peaks also produce a higher magnetizing force.

**15.6.5 Sequence of Operations.** The sequence of operations of magnetization and application of the inspection medium has an important bearing on the sensitivity of the method. The two primary methods are detailed below.

**15.6.5.1 Continuous Method.** The magnetic particles are applied to the surface of the work while the magnetizing current is flowing. This method offers maximum sensitivity, since the magnetic field is at its maximum while the magnetic particles are being applied. The magnetizing current continues to flow during the entire time the particles are applied and the excess removed. Should the current be turned off before the excess particles are removed, the only indications remaining will be those held by the residual field.

ASTM Specification E-109 recommends that the air stream used to remove excess dry particles be so controlled that it does not disturb or remove lightly held powder patterns.

When using a wet suspension with the continuous method, it is usual to flow the material over the area being inspected and immediately apply the magnetizing current for approximately one-half second. The inspection medium should not be reapplied after the current has ceased to flow, since this would tend to wash away lightly held indications.

**15.6.5.2 Residual Method.** This method relies on the residual magnetic field that remains after the magnetizing current has been switched off, since the inspection medium is applied at this time. Thus, since the accuracy and sensitivity depend upon the strength of the residual field, this method can be used only on materials of relatively high magnetic retentivity (which should be determined by actual experiment). Many codes and other standards prohibit the application of this method.

**15.6.6 Inspection Media.** Various forms and colors of magnetic particles are available. The type of surface and the type of defect suspected will determine the material to be selected.

**15.6.6.1 Dry Method.** Additional information on the dry method is provided in ASTM E709, *Practice for the Magnetic Particle Examination Method*. Finely divided ferromagnetic particles in dry powder form, coated to afford greater particle mobility, are dusted uniformly over the work by means of a dusting bulb, shaker atomizer, or spray gun. The magnetic particles are available in various colors. The dry method is easier to use on rough surfaces and has maximum portability. The powder should be applied in a low-velocity cloud with just enough motive force to direct the particles to the desired location. This permits particles to line up in indicating patterns as they near the surface of the magnetized part. Excess powder should be removed with a stream of air just strong enough to carry away the excess powder without disturbing lightly held powder patterns. Figure 15.36 shows the dry powder method in use.

When examining with dry powder, best results are obtained by blowing excess powder from around the indications and by having a surface reasonably free from oil, moisture, and dirt.

**Figure 15.36—Dry Powder Magnetic-Particle Inspection of Welds with Portable Equipment**

**15.6.6.2 Wet Method.** The indicating particles for the wet method are smaller than those used in the dry method and are suspended in a liquid bath of light petroleum distillate or water. Because of the small particle size, the wet method is more sensitive to fine surface defects (see Figure 15.37), but it is not as sensitive as the dry method for the detection of subsurface discontinuities.

The magnetic particles for liquid suspension are available either in a paste or in dry concentrate form. The formulations are usually prepared for use either with oil or with a water bath and are not necessarily interchangeable. The proportion to be used in the bath should be in accordance with the manufacturer's recommendations. Prepared baths in pressurized spray cans are also available.

The bath should be continuously agitated to prevent indicating materials from settling out. The use of a water suspension has several advantages: its sensitivity is equal to or better than that of oil, and the fire hazard due to arcing is eliminated. There is also an economic advantage. However, when using water, other additives such as rust inhibitors, wetting agents, and anti-foaming agents may be necessary. Also, whenever water is used in close proximity to electrical circuits, a potential hazard may exist. Precautions should be taken to protect workers from such hazards.

The bath is either flowed onto or sprayed over the surface to be inspected, or the part can be immersed in the suspension. The smaller particle size increases the sensitivity, and exceedingly fine defects are located

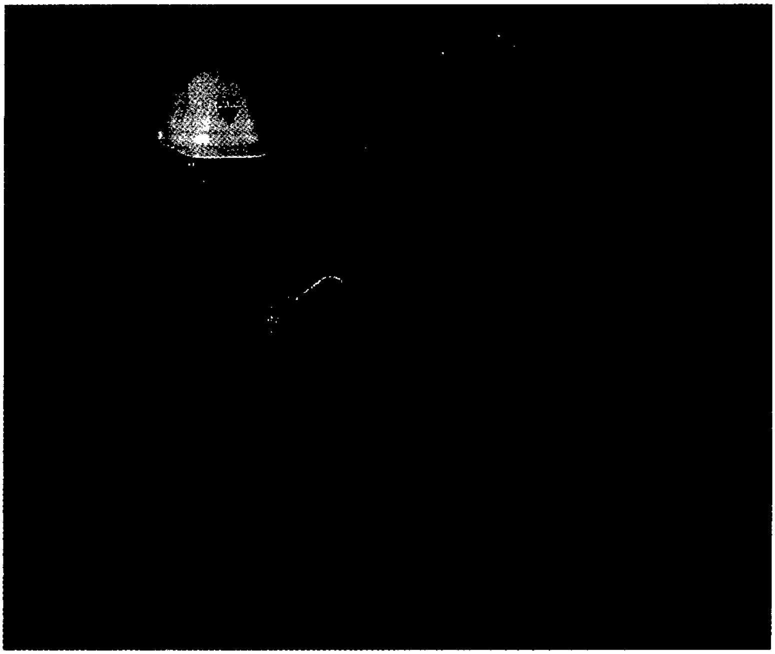


**Figure 15.37—Wet Fluorescent Magnetic-Particle Inspection to Show Fine Surface Defects**

without difficulty. Visible particles may be used in the bath and are commonly available in colors such as black, grey, or red. As with dry powders, the color selection should be based on that which will provide best color contrast with the surface being examined.

When the particles are coated with a dye that fluoresces brilliantly under ultraviolet (black) light, the sensitivity of the method is increased. Fluorescent inspection material indicates very small or fine discontinuities and permits rapid inspection of irregular or dark surfaces. The inspection should be performed in a darkened area.

The fluorescent magnetic-particle method is particularly valuable in locating discontinuities in corners, keyways, splines, deep holes, and similar locations. Nonrelevant indications can generally be eliminated by reducing the current below the points where these indications form.

The fluorescent magnetic-particle method is applicable only to magnetic materials and should not be confused with fluorescent penetrant inspection, which is described elsewhere.

Additional information on the wet method is provided in ASTM E709, *Practice for the Magnetic Particle Examination Method.*

**15.6.7 Demagnetization.** Demagnetization is usually necessary for engine and machine parts that have been strongly magnetized. These parts are exposed to filings, grindings, and chips (resulting from operational wear) that would be attracted by the magnetized parts. In aircraft construction, all steel parts in close proximity to the compass should be demagnetized to eliminate any effect upon the compass.

Most weldments do not require demagnetization after magnetic particle inspection. A residual magnetic field in a part has no appreciable effect on its mechanical characteristics. Demagnetization is unnecessary unless the residual field interferes with subsequent machining, arc-welding operations, or with structures (such as aircraft) where sensitive electrical instruments might be affected.

Demagnetization may be accomplished by inserting the part in the field of an alternating current coil and gradually withdrawing it from the field. Larger parts may be demagnetized by subjecting them to an alternating current field that is gradually reduced in intensity by means of a current controller. If circular residual fields remain in cylindrical parts, they should be converted to longitudinal fields prior to demagnetization.

When large masses of iron or steel are involved, alternating current has insufficient penetration to demagnetize such pieces thoroughly; direct current should be used and gradually reduced to zero while undergoing cyclic reversals. Hammering or rotating in the field will sometimes assist demagnetization. Heat treating or stress relief will demagnetize weldments, and total demagnetization is always accomplished when the workpiece is heated above the curie temperature of the metal (1414°F [768°C] for carbon steel).

**15.6.8 Equipment.** The basic equipment for magnetic-particle inspection is relatively simple. It includes facilities for setting up fields of proper strengths and in correct directions. Means are provided for adjusting the current, and an ammeter, plainly visible to the inspector, should be provided in the magnetizing circuit so that the inspector will know that the 56-correct magnetizing force has been created for each inspection. Many instruments allow for application of either ac or dc current.

**15.6.9 Recording the Indications.** It is frequently desirable to record not only the appearance of the indications on a part, but also their locations on a part. One way of accomplishing this is by lifting the magnetic particles from the part by carefully pressing transparent pressure-sensitive tape over the indication; the indication adheres to the tape when it is removed. This may be placed on white paper or directly on a sketch or report to form a permanent record. In this procedure, the tape should be cut long enough not only to cover the indication, but also to extend to a corner hole, keyway, or other change of section that may be used as a reference. When used with the wet method, the oil should then be removed from around the indication to prevent smearing and distortion when tape is applied. This is most easily accomplished by permitting the part to dry in the air for 4 to 5 hours or drying the part with warm air or careful application of a volatile solvent. A drawing or simple sketch may also be used to indicate the location at which the transfer was made.

A permanent record may also be made by photographs. Other special techniques such as magnetic rubber solutions are also available.

### 15.6.10 Common Applications

**15.6.10.1 Inspection of Large Weldments.** Magnetic particle inspection may be applied to all types of large weldments as long as the materials are magnetic. It is usually used to inspect the finished welds. On heavy, multiple-pass welds, however, it is sometimes used to inspect intermediate weld passes during welding. It is also used to inspect roots of joints that have been backchipped in order to be certain that the weld metal has been removed to sound metal and that no cracks are present.

Where the weldment is to be stress relieved, it is usual to make a final inspection after stress relieving. It is possible to obtain greater sensitivity for detection of subsurface defects after stress relief.

The dry continuous method, using some type of direct current and employing local circular magnetization (prod technique), is usually recommended for heavy weldments. Half-wave rectified current is preferable for location of subsurface discontinuities. Alternating current may be used if inspection is to be limited to detection of cracks that extend to the surface. The weld is magnetized with a prods by passing about 600 to 1000 A along the length of the weld, using a prod spacing of from 4 to 8 in. (100 to 200 mm). Prods are positioned both parallel and transverse to the axis of the weld. The prod positions should be overlapped slightly on consecutive shots.

**15.6.10.2 Inspection of Light Weldments (Aircraft Type).** Many steel weldments used in aircraft are inspected by the magnetic-particle method. These parts in service are subjected to conditions that cause fatigue failure, which means that location and elimination of all surface cracks are particularly important. Also, since the weldments are relatively thin, magnetic-particle inspection may provide sufficient sensitivity to detect any subsurface discontinuities that might be detrimental.

Light, aircraft-type weldments are usually inspected by the wet continuous method. Direct current is usually used, although alternating current has been found satisfactory on thin materials. The continuous method is usually recommended despite the high retentivity of many of the alloys commonly used in aircraft structures.

Small weldments that can conveniently be given overall examination at a standard stationary-type examination setup are given two examinations that use both longitudinal and circular fields. Larger weldments are examined by local circular magnetization. This is accomplished by making contact with the structure using clamps or other suitable contacts. A longitudinal field may be used on large structures by wrapping several turns of cable around the weld area.

**15.6.10.3 Plate Inspection.** Magnetic-particle examination is frequently used to inspect plate edges prior to welding. The purpose of this examination is to detect cracks, laminations, inclusions, and segregations. It will reveal only those discontinuities that are near or extend to the edge being examined.

Not all discontinuities found on plate edges are objectionable; however, it is necessary to eliminate those that would affect either the weldability of the plate or the ability of the material to assume design loads under service conditions.

The dry continuous method, using the prod technique with either alternating or direct current, is suitable for plate edge examination. When alternating current is used, the examination is limited to discontinuities that extend to the edge being examined.

**15.6.10.4 Repair or Rework Examination.** Magnetic-particle examination can be applied with good effect in conjunction with repair work or rework procedures, both on new parts and on parts that may have developed cracks in service. This applies not only to repair of weldments, but also to rework done by welding in the repair or salvage of castings and forgings.

Many objectionable discontinuities that have been detected by magnetic particle, radiographic, visual, or other examination methods may be removed by chipping, gouging, or grinding, and the repair made by welding. In this type of work, it is useful to examine the cavity after the defect has been removed to make certain that the discontinuity has been reduced to acceptable limits before proceeding with the repair weld. It is also advisable to check the completed repair weld.

In general, the same examination procedures should be used in connection with repair or rework procedures as would be used on the original parts.

**15.6.11 Interpretation of Patterns.** The shape, sharpness of outline, width, and height to which the particles have built up are the principal features by which discontinuities can be identified and distinguished from one another.

**15.6.11.1 Surface Cracks.** Powder patterns are sharply defined, tight held, and usually built up heavily with powder. The deeper the crack, the heavier the buildup of the indication (see Figure 15.38).

**15.6.11.2 Subsurface Discontinuity Indications.** Powder patterns have a fuzzy appearance, less sharply defined and less tightly held (see Figure 15.39).

**15.6.11.3 Crater Cracks.** These cracks are recognized by their patterns, which are small and occur at the terminal point of a weld. They may be a single line in almost any direction, or possibly multiple, or star-shaped.

**15.6.11.4 Incomplete Fusion.** Accumulation of powder will generally be pronounced, and the edge of the weld will be seen. The pattern will be sharper the closer the discontinuity is to the surface.

**15.6.11.5 Undercut.** A pattern that is held less strongly than the indications obtained by incomplete fusion is produced at the weld edge. Undercut is usually detected by visual examination.

**15.6.11.6 Inadequate Joint Penetration or Gap Between Plates at the Weld Root.** The powder pattern may resemble that produced by a subsurface crack. The requirements for the particular weld will determine whether such inadequate penetration constitutes a defect.

**15.6.11.7 Subsurface Porosity.** In this case, the powder patterns are not clearly defined. They are neither strong nor pronounced, yet are readily distinguished from

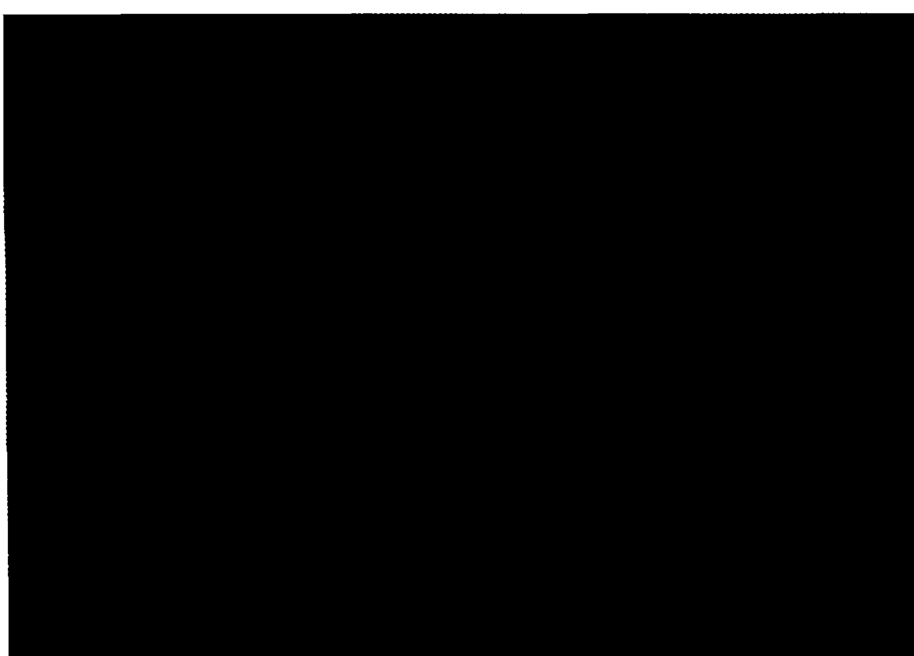


**Figure 15.38—Typical Indication of Surface Crack in a Weld**

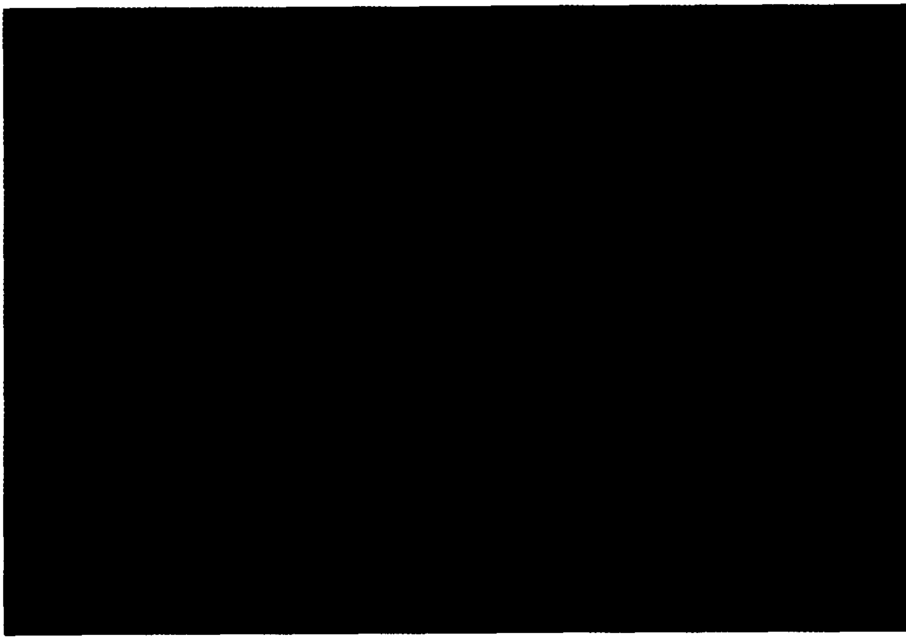


**Figure 15.39—Indication of a Subsurface Crack in a Weld (The Dry Magnetic Particles Assume a Less Defined Pattern)**

indications of surface conditions. Small rounded porosity cannot be detected.

**15.6.11.8 Slag Inclusions.** A pattern similar to subsurface porosity appears when a strong magnetizing field strength is used and slag inclusions are present.

**15.6.11.9 Seams.** The indications are straight, sharp, fine, and often intermittent. Buildup of magnetic particles is slight.

**15.6.11.10 Irrelevant Indications.** Irrelevant or false indications that do not indicate the presence of cracks or other discontinuities, which have no significance concerning the soundness of the welds, are frequently produced. They occur when some examination factor causes the magnetic field to change direction suddenly. This causes flux leakage, which irrelevant or false indications on the surface.

*Irrelevant* indications are real indications caused by a leakage field or change in material permeability. They are real but nonrelevant because they are to be expected. An Example would be small radii, root of thread, press-fit parts. Also changes in permeability where "hard" and "soft" metals are joined can cause irrelevant indications.

*False* indications are not caused by actual leakage fields but are caused by mechanical entrapment of magnetic particles such as in weld ripples, scratches, etc.

**15.6.11.10.1 Physical Contour.** A thin area, a change in section, an oil vent, or a hole drilled in the part all will tend to produce indications that have no significance with respect to joint performance. The magnetic particle patterns are usually readily identified by their location and the shape of the part.

**15.6.11.10.2 Change in Magnetic Characteristics.** Abrupt changes in magnetic properties may occur at the edge of the HAZ. The pattern will be diffused and fuzzy and will run along the base metal in a line parallel and usually quite close to the edge of the weld. This pattern resembles closely that caused by undercutting, but is very loosely held. Postweld thermal treatment may restore the magnetic characteristics, in which case, the indications will not reappear.

**15.6.11.10.3 Magnetic-to-Nonmagnetic Metal.** A similar pattern may occur when a magnetic (ferritic) base metal is welded with nonmagnetic (austenitic) filler metal. Magnetic-particle examination is not applicable to the inspection of welds of this type.

**15.6.11.10.4 Materials with Differing Magnetic Properties.** When two materials with widely differing magnetic properties are joined, an indication develops at the junction. This indication is very difficult to distinguish from a crack. It occurs, for example, when low-alloy steel or carbon steel is welded or bonded to high-carbon steel.

When a magnetized steel part is struck by another part or dragged over it, leakages may occur at the places that have been cold worked. Consequently, indications that are not caused by discontinuities will appear. These conditions are liable to occur during examination or transportation and are called magnetic writing.

**15.6.12 Evaluation.** The examination will determine the existence, if any, of discontinuities. The weld will be judged acceptable, or rejectable according to evaluation of the discontinuities disclosed by examination. The decision will be governed by applicable specifications, standards, or purchase orders.

Indications of subsurface discontinuities, unless clearly understood, should be investigated by radiographic examination or other suitable nondestructive methods, sectioning, or chipping. It should also be determined whether or not subsequent processing or machining operations would expose or remove the defective area. All crack-like discontinuities, particularly those that occur at the surface, can be regarded as potential stress raisers. Fatigue or other service cracks may develop from these discontinuities, or they may become starting points for corrosion.

**15.6.13 Standards.** Many standards have been developed in which the service conditions alone dictate the acceptance criteria for a part. When indications are found on a part that has performed satisfactorily in service, the indication is either an irrelevant indication or a discontinuity that has not affected service performance.

It is not only the size of the indication but also its location and orientation that are important. In all cases of doubt, acceptance or rejection should be made with a view toward safety. In areas of high stress, the slightest discontinuity may be unacceptable; in less highly stressed regions, a relatively large discontinuity may be acceptable with a wide margin of safety.

When unusual patterns are produced, it may be necessary to establish identity by correlating the results with other examination methods such as observation under magnification, sectioning, etching, or metallurgical examinations. Once the proper interpretation has been established for a given type of indication, in many cases, this interpretation can readily be applied to similar indications on other parts.

## 15.7 Penetrant Examination

The liquid penetrant examination method is base on the ability of certain types of liquids to enter into voids and crevices by capillary action and to remain there when the surface liquid is removed. Thus, liquid penetrant examination, when done properly, is a reliable and revealing method for detecting discontinuities open to the surface. Very small and tight imperfections usually can be shown. The several variations of the method each have their advantages and disadvantages.

**15.7.1 Technique.** The penetrant liquids and, therefore, the penetrant examination techniques are divided into two basic categories: fluorescent dye and visible dye.

The fluorescent methods offer exceptionally good resolution of indications; the visible method is almost as good in this respect.

Water washable methods may be preferable for certain classes of work in which the object can be transported to a routine examination area, whereas non-water-washable methods can be performed on location or where water is not available or should not be used.

Examination using fluorescent penetrants involves use of a liquid that will fluoresce under ultraviolet or "black" light. This is near ultraviolet light, 330 to 390 nm wavelength. A wavelength of about 365 nm is considered optimum. Lamps emitting such light are necessary to this technique and are marketed as standard equipment by nondestructive examination equipment suppliers. To be effective, the examination should be performed under subdued or darkened lighting conditions.

Examination using the visible dye technique is based on use of a penetrant containing a vivid red dye that contrasts sharply with the background of white developer.

The importance of following an approved procedure in liquid penetrant examination cannot be overstated. The simplicity of the test may mislead the user: there are many variables that influence the examination results. For example, inadequate cleaning may not permit the penetrant to enter the discontinuity, and the examination results will be meaningless.

Regardless of the type test selected, the procedure can be described in seven basic steps, as follows:

(1) Clean the surface to be examined.

(2) Apply penetrant.

(3) Allow sufficient penetrant dwell time.

(4) Remove excess penetrant.

(5) Apply developer to indicate retained penetrant.

(6) Examine part.

(7) Clean, if required.

**15.7.1.1 Fluorescent Penetrant Method.** Fluorescent penetrants can be either water washable for removal of excess penetrant, or made water washable by application of an emulsifier to the surface of the penetrant. The directly water washable type has additives that give the penetrant this property; however, these additives may somewhat reduce its penetration efficiency.

Developers may be dry powder type, water suspension type, or nonaqueous suspension type. The effect of each is to draw out the penetrant from a discontinuity so that it becomes visible under excitation of black light. Steps to be followed in a fluorescent penetrant examination are as follows:

**15.7.1.1.1 Precleaning.** All extraneous material such as scale, slag, grease, oil, paint, water, and the like should be removed. Cleaning with chlorinated hydrocarbons, volatile petroleum distillates, or acetone is effective. It should be remembered that the chlorinated hydrocarbons are toxic if inhaled, and the petroleum distillates are highly flammable. Proper precautions should be observed. Vapor degreasing is likewise effective, if applicable. Suitable cleaners are marketed by producers of the inspection materials. A short time should be allowed for the evaporation of the volatile cleaner from discontinuities before the penetrant is applied.

**15.7.1.1.2 Application of Penetrant.** The penetrant should be applied to the dry part over the areas to be examined. This may be done by dipping, brushing, or spraying.

**15.7.1.1.3 Sufficient Dwell Time.** Sufficient dwell time for the penetrant to enter discontinuities should be allowed. The dwell time may vary depending upon conditions, materials, and temperatures. Approved procedures should be followed.

**15.7.1.1 Excess Penetrant Removal.** If the directly water washable type penetrant has been used, the excess penetrant is rinsed from the part with a spray nozzle. Special nozzles are marketed by equipment producers for this purpose. Since hot water may tend to wash out penetrant from some discontinuities, an upper limit of 110°F (43°C) for rinse water should be maintained. Water sprays should be directly at an angle of less than 90% to the surface and the pressure controlled to some maximum (e.g., 40 psi). The part or area should be checked by observation under black light to assure complete removal of excess penetrant.

If a post-emulsifiable type penetrant has been used, an emulsifier should be applied to render the excess penetrant water-removable. The emulsifier may be applied by dipping, flowing on, or spraying. The length of time necessary for the emulsifier to work is important, and recommendations of the producer should be followed. Following emulsification, the part is water washed as detailed above.

**15.7.1.1.5 Application of Developer.** Wet developer, made by a water suspension of dry powder, may be applied to the part immediately after rinsing away the excess penetrant. It should then be dried by circulating warm air over the part being examined. Pools of excess developer should be avoided because they might flow the penetrant out of discontinuities.

Nonaqueous wet developers are also available. These are suspensions in volatile, nonaqueous liquids. These are always applied by spraying. Pressurized cans of developer are marketed for spraying. The part should be dry prior to application, as with dry powder developers.

Suspension-type wet developers may be applied by brushing or by spraying from pressurized equipment. Spraying is considered preferable, since it gives a smooth, even coating of developer. If brushing is employed, care should be taken to avoid a thick coating. It is necessary to keep the suspension well agitated in spray equipment, and coagulation of the solid particles should be avoided. Pools of developer should be avoided as they dry to a thick coating that could mask fine indications.

**15.7.1.1.6 Examination.** Sufficient time should be allowed after the developer has been applied to permit it to draw or blot out the penetrant from any discontinuities. Roughly, this developing time should be about half the penetrant dwell time and is usually determined by code or standard. Recommendations of the producer should be followed. The part should be examined under black light in a darkened area or enclosure. Indications of discontinuities glow brilliantly when excited by the black light and contrast sharply with the darker background.

**15.7.1.1.7 Final Cleaning.** If required, the part or area may be cleaned with solvents following completion of the examination.

**15.7.1.2 Visible Dye Penetrant Methods, Type B.** As with fluorescent penetrants, the visible dye penetrants may be directly water washable as applied; may be water washable after the addition of an emulsifier; or may not be water washable, but removable by certain solvents. The directly water washable type leads to a less sensitive examination because the water rinse may remove penetrant from discontinuities.

Developers may be dry powder, aqueous suspensions, or nonaqueous wet developer, the latter being the one most often used. Steps to be followed in a dye penetrant examination are as follows:

**15.7.1.2.1 Precleaning.** Cleaning as stated for precleaning for fluorescent methods.

**15.7.1.2.2 Application of Penetrant.** The penetrant may be applied by spraying, brushing, or immersion. Immersion would be desirable for multiple small parts. While spraying is often used, the dye has a certain nuisance factor because of staining, so some consider brushing more controllable and prefer this method.

**15.7.1.2.3 Sufficient Dwell Time.** The dwell time may vary depending on conditions, materials, and temperatures. Approved procedures should be followed. The part and the penetrant should be between 60°F and

125°F (15 and 52°C) for best results. The penetrant should not be permitted to dry on the surface during the dwell time. (While this should not normally happen, if it does, the part should be re-cleaned and the process repeated.)

**15.7.1.2.4 Excess Penetrant Removal.** If directly water-washable penetrant has been used, the excess penetrant is rinsed off with a water spray. If a post-emulsifiable penetrant has been used, the emulsifier should be applied over the penetrant, after which the excess penetrant is rinsed off as a water-washable emulsion.

Methods of removing the solvent-removable excess penetrant vary. For highest examination accuracy, and as required by most specifications, as much of the excess as possible is first wiped off with a clean lint-free cloth or absorbent paper, followed by wiping with a clean cloth or paper lightly dampened with solvent. This process should be repeated until the dampened wiping cloth or paper shows essentially no red stain. The surface should not be overcleaned once all excess dye is shown to be removed.

In all instances, flushing of the surface with solvent cleaner should be prohibited. Producers of the examination material market cleaners for their penetrant products, and their use is recommended.

**15.7.1.2.5 Application of Developer.** If water rinsing has been employed, the part should be dried before application of developer, except when an aqueous suspension developer is used. In this case, drying is accomplished after the application of the developer. If dry powder is used, it is dusted on the part. As stated previously, the nonaqueous developer is the one most often employed. The directions for the application of suspension-type wet developers are applicable here. Developers should be sprayed lightly. Heavy application can give incorrect interpretation or mask indications.

**15.7.1.2.6 Examination.** After the developer has dried, a short time is allowed for the dry developer to blot or draw the red dye from a discontinuity. The waiting time will vary and will depend on the size and type of discontinuity; however, even the smallest and tightest may be expected to give an indication in from five to seven minutes. Discontinuities are bright red indications against the white background of the developer.

**15.7.1.2.7 Final Cleaning.** The part or area may be cleaned with solvents or other means following completion of examination.

**15.7.2 Applications.** As-welded surfaces are normally suitable for penetrant examination methods if the surface contour does not contain sharp depressions between beads or weld ripples that could interfere with complete cleaning and complete excess-penetrant removal. Any one of these could result in false or irrelevant indications. Such weld surfaces should be ground smooth prior to examination.

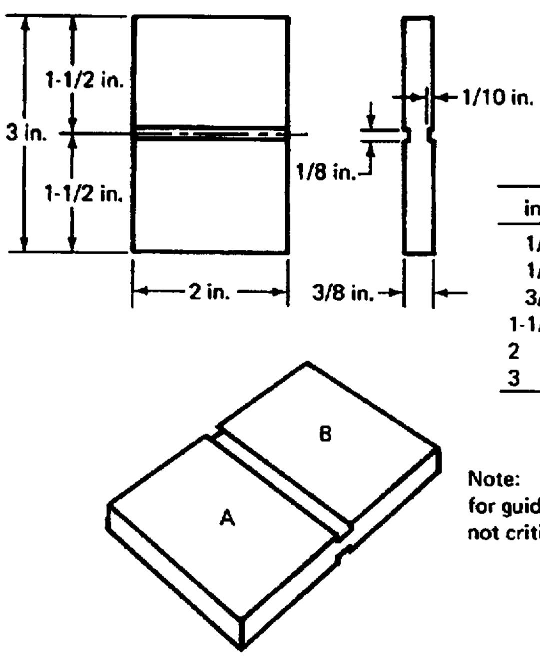
In setting acceptance or rejection standards for dye penetrant examination, the severity of service of the piece should be considered. In most weld standards, cracks are considered unacceptable. Cracks are shown by liquid penetrant examination as a solid linear indication or, for very tight cracks, as a series of small, aligned, adjacent indications that may join up upon longer development time. For deeper cracks, the indication may first show as a thin line and widen with longer development time as more penetrant is drawn out of the defect. (This is true for indications in general: the deeper ones will continue to bleed out penetrant and enlarge the indication as development time lengthens).

When examining welds in conjunction with cast materials, it should be recognized that a certain amount of casting imperfections are to be expected in some cast metals. Because of the effectiveness of liquid penetrant examination, these will all show on casting surfaces. This aspect should be taken into consideration when judging such weld assemblies.

Some specifications call for liquid penetrant examination of nonmagnetic materials, and magnetic-particle examination for ferromagnetic materials. Except that magnetic-particle examination may show some subsurface defects, it should be realized that liquid penetrant inspection is just as effective as magnetic particle for discontinuities open to the surface.

**15.7.3 Liquid Penetrant Comparator.** When it is not practical to make a liquid penetrant examination within the temperature range of 60 to 125F (16 to 52°C), the examination procedure at the proposed temperature requires qualification. This may be accomplished by producing quench cracks in an aluminum block, which for this purpose is designated as a *liquid penetrant comparator.* One section of the block can then be examined at the proposed temperature and the other section at a temperature in the range of 60 to 125°F.

The liquid penetrant comparator shown in Figure 15.40 is made of aluminum, SB-211, Type 2024, 3/8 in. (10 mm) thick, with approximate face dimensions of 2 by 3 in. (50 by 75 mm). At the center of each face, an area approximately 1 in. (25 mm) in diameter is marked with a 950°F (510 °C) temperature indicating crayon or paint. The marked area is then heated with a blow torch, a Bunsen burner, or similar device to a temperature between 950 and 975°F (510 and 525°C) and the specimen is then quenched in cold water to produce a network of fine cracks on each face. The block is then dried by heating to approximately 300°F (150°C). A groove may be machined across the center of each face approximately 1/16 in. (1.6 mm) deep and 3/64 in. (1.2 mm) wide, or some other means provided to permit side-by-side comparison




| in. | mm |
|---|---|
| 1/10 | 2.5 |
| 1/8 | 3.2 |
| 3/8 | 9.7 |
| 1-1/2 | 38 |
| 2 | 50 |
| 3 | 75 |

Note: Dimensions given are for guidance only and are not critical.

**Figure 15.40—Liquid Penetrant Comparator**

without interfering cross-contamination between the two sides. One half of the specimen may be designated "A" and the other "B" for identification in subsequent procedures. Figure 15.40 illustrates the comparator after the grooves, have been cut.

**15.7.3.1 Comparator Application.** If it is desired to qualify a liquid penetrant examination procedure at a temperature less than 60°F (16°C), the proposed procedure may be applied to area "B" after the block and all materials have been cooled to the proposed examination temperature. The block is then allowed to warm up to a temperature between 60 and 125°F (16 and 52°C), and area "A" examined in a manner that has previously been demonstrated as suitable for use in this temperature range. The indication of cracks is compared between areas "A" and "B." If the indications obtained under the proposed conditions are essentially the same as obtained under examination at 60 to 125°F, the proposed procedure is considered qualified for use.

If the proposed temperature for the examination is above 125°F, then the block is held at this temperature throughout the examination of the "B" section (the penetrant and developer are not preheated). The block is then allowed to cool to a temperature between 60 and 125°F and area "A" is examined and compared as described in the previous paragraph.

**15.7.3.2 Evaluation of Indications.** All indications are examined in terms of the acceptance standards of the referencing code.

Discontinuities at the surface will be indicated by the bleeding out of the penetrant; however, localized surface irregularities, such as from machining marks or other surface conditions, may produce nonrelevant indications.

Broad areas of fluorescence or pigmentation that could mask indications of discontinuities are unacceptable, and such areas should be cleaned and re-examined.

For further details of liquid penetrant inspection methods, reference may be made to the latest issue of ASTM specification E165, Liquid Penetrant Inspection, and to literature published by the various producers of liquid penetrant examination materials.

## 15.8 Eddy Current (Electromagnetic) Examination

This section describes the electromagnetic examination (ET) of both ferromagnetic and nonferromagnetic metals. ET was formerly called eddy current testing. This method uses an alternating magnetic filed applied to a metal, and the field induces an electric current (eddy current). These eddy currents induce another magnetic field that will be distorted, at discontinuities, and at locations where the physical or metallurgical properties change.

**15.8.1 General.** Eddy current (electromagnetic) testing is a nondestructive examination based on the principle that an electric current will flow in any conductor subjected to a changing magnetic field. It is used to check welds in magnetic and nonmagnetic materials and is particularly useful in testing bars, billets, welded pipe, and tubes. Test frequencies vary from 50 Hz to 1 MHz, depending on the type and thickness of material and the application. Frequency ranges for some applications are shown in Figure 15.41.

**15.8.2 History.** While the investigation of electromagnetic wave examination methods preceded the development of practically every other modern technique of nondestructive examination, the method was slow to develop commercially. Until recently, the electromagnetic method had only limited applications, because the process could not discriminate between responses to discontinuities, heat treatment variations, internal stresses due to forming operations, and small vibrations of the part or of examination coils. Thus, electromagnetic examinations were limited in usefulness.

**15.8.3 Theory.** Nondestructive examination by electromagnetic methods involves inducing electric currents (eddy or foucault currents) in a test piece and measuring the

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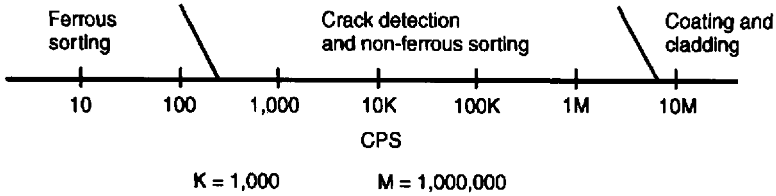



**Figure 15.41—Frequencies Used for Various Test Problems**

changes caused in those currents by discontinuities or other physical differences in the test piece. Thus, such examinations can be used not only to detect discontinuities but also to measure variations in test piece dimensions and resistivity. Since resistivity is dependent upon such properties as chemical composition (purity and alloying), crystal orientation, heat treatment, and hardness, these properties can also be determined indirectly. Electromagnetic methods are classified as magnetoinductive and eddy current methods. The former pertains to examinations where the magnetic permeability of a material is the factor affecting the examination results and the latter to examinations where electrical conductivity is the factor involved.

One method of producing eddy currents in a test specimen is to make the specimen the core of an alternating current (ac) induction coil as shown in Figure 15.42. There are two ways of measuring changes that occur in the magnitude and distribution of these currents. The first is to measure the resistive component of impedance of the exciting coil (or of a secondary test coil), and the second is to measure the inductive component of impedance of the exciting (or of a secondary) coil. Electronic equipment is available to measure either the resistive or inductive impedance components singly or both simultaneously.

**15.8.4 Electric and Magnetic Properties of Metals.** Electronic test equipment measures such properties as hardness, crack depth, coating thickness, etc., indirectly through their relationship to properties that can be measured electronically, such as conductivity and permeability. Two such characteristics of a metal that are measured directly and are of importance to electromagnetic examination are electrical conductivity and magnetic induction.

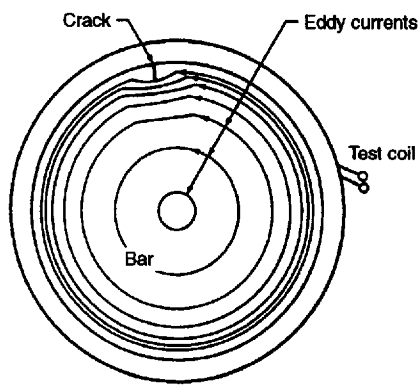



**Figure 15.42—Cross-Sectional View of a Bar With a Small Crack, Surrounded by an Exciting Coil and a Pickup Coil, Showing Eddy Current Distribution**

**15.8.5 Electrical Conductivity.** Conductivity can be expressed mathematically as the reciprocal of the electrical resistivity of the metal.

$$C = \frac{L}{R \times A} = \frac{1}{p} \qquad \text{(Eq.15-10)}$$

where

$C$ = Conductivity (ohm/unit length)
$p$ = Resistivity (ohm unit length)
$L$ = Length
$R$ = Resistance (ohm)
$A$ = Cross-sectional area

The conductivity of various metals and alloys is shown in Figure 15.43. A convenient means of categorizing metals is to refer to them as either "conductors" or "nonconductors." The conductivity and resistivity of metals and alloys is a material property (See Table 15.4).

The addition of impurities to a pure metal will normally reduce its conductivity sometimes markedly. For example, copper containing 0.005 percent phosphorus exhibits a conductivity of only four percent of that of pure copper. The effect of other alloying elements in copper on the conductivity of copper alloys is shown in Figure 15.44. Most other additions to pure copper also affect the conductivity, although not as severely as phosphorus.

The current distribution within a test piece may also be changed by the presence of inho-

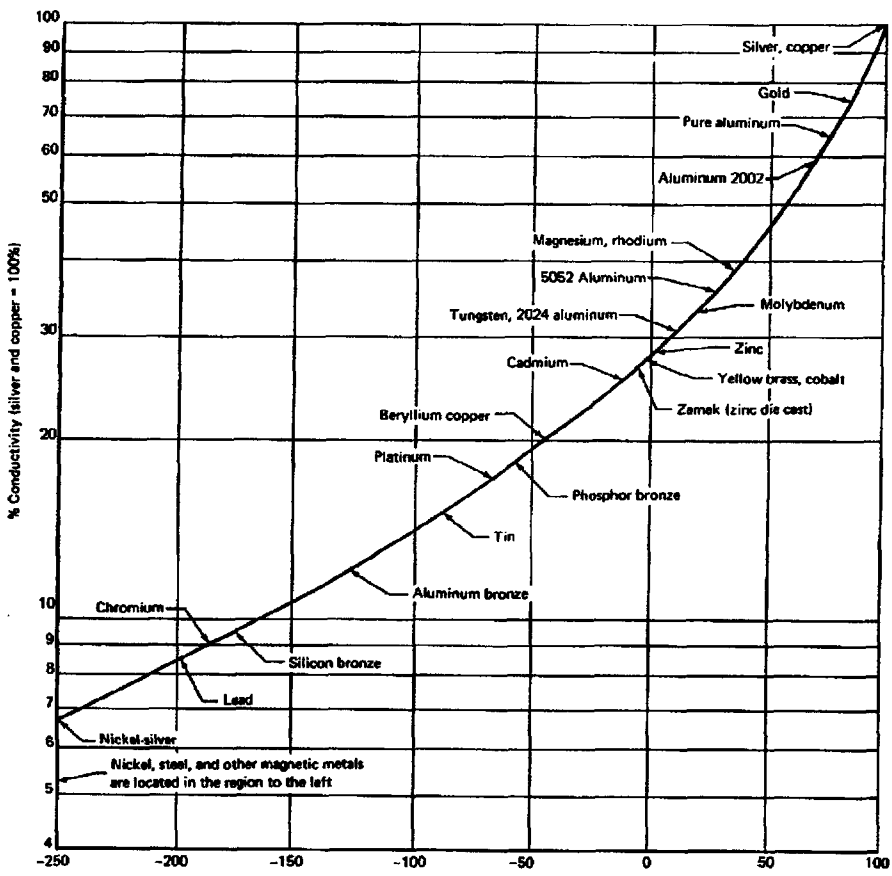



**Figure 15.43—Relative Conductivity of Metals and Alloys Related to Eddy Current Meter Readings**

**Table 15.4**
**Resistivity and Conductivity of Some Metals and Alloys**

| Metal | Resistivity p (ohm-m) × $10^{-8}$ | Conductivity o (ohm/m)× $10^{7}$ | Temperature | |
|---|---|---|---|---|
| | | | °F | °C |
| Silver | 1.629 | 6.14 | 64 | 18 |
| Copper | 1.692 | 5.91 | 68 | 20 |
| Aluminum | 2.63 | 3.8 | 32 | 0 |
| Zinc | 5.75 | 1.74 | 32 | 0 |
| Iron (99.98%) | 10 | 1 | 68 | 20 |
| Platinum | 10 | 1 | 68 | 20 |
| Aluminum Bronze | 12–13 | 0.83–0.77 | 32 | 0 |
| Lead | 22 | 0.455 | 68 | 20 |
| Titanium | 43.1 | 0.232 | 72 | 22 |
| Steel (4% Si) | 62 | 0.161 | 68 | 20 |
| Bismuth | 119 | 0.084 | 64 | 18 |
| Steel (5% V. 1.1% C) | 121 | 0.083 | 68 | 20 |

mogeneities. If a sample is perfectly homogeneous, free from discontinuities, and has a regular spaced lattice, the mean-free path of an electron passing through it will have the maximum length. That is, the conductivity will be maximum. A crack, slip plane, inclusion, high- or low-density regions, chemical inhomogeneity, cavity or void, or other conditions in an otherwise homogeneous material will cause a back scattering of the electron and thereby shorten its mean-free path, and reduce the conductivity. When a device detects a change in conductivity in a workpiece, it is detecting the presence of an inhomogeneity or a discontinuity.

If an electric wave is considered instead of electrons, the same factors impeding the flow of a single electron will impede the passage of a wave front, causing it to be totally or partially reflected, or absorbed, or both. The various relationships between conductivity and such factors as impurities, cracks, grain size, hardness, strength, etc., have been investigated and reported in detail.

**15.8.4.1 Magnetic Induction.** When a magnetic material is placed within an applied field (*H*), there is induced into that material a flux density (*B*) that may be stronger than the original applied field. As *H* is increased from zero, *B* also increases. The typical curve shown in Figure 15.45 can provide considerable information on the magnetic properties of materials. Notice that the virgin curve does not retrace itself. The envelope curve is referred to as the *hysteresis loop.*

**15.8.5 Electromagnetic Properties of Coils.** When a coil is energized, a magnetic field is produced around the coil as indicated in Figure 15.46. If a conductor is present in the induced field, then the field induces eddy currents into the conductor which set up a magnetic field that acts in opposition to the magnetic field induced by the coil. The impedance (*Z*) of the exciting coil, or, for that matter, any coil in close proximity to the conductor is affected by the presence of the induced eddy currents in the specimen. The path of the eddy currents in the specimen is

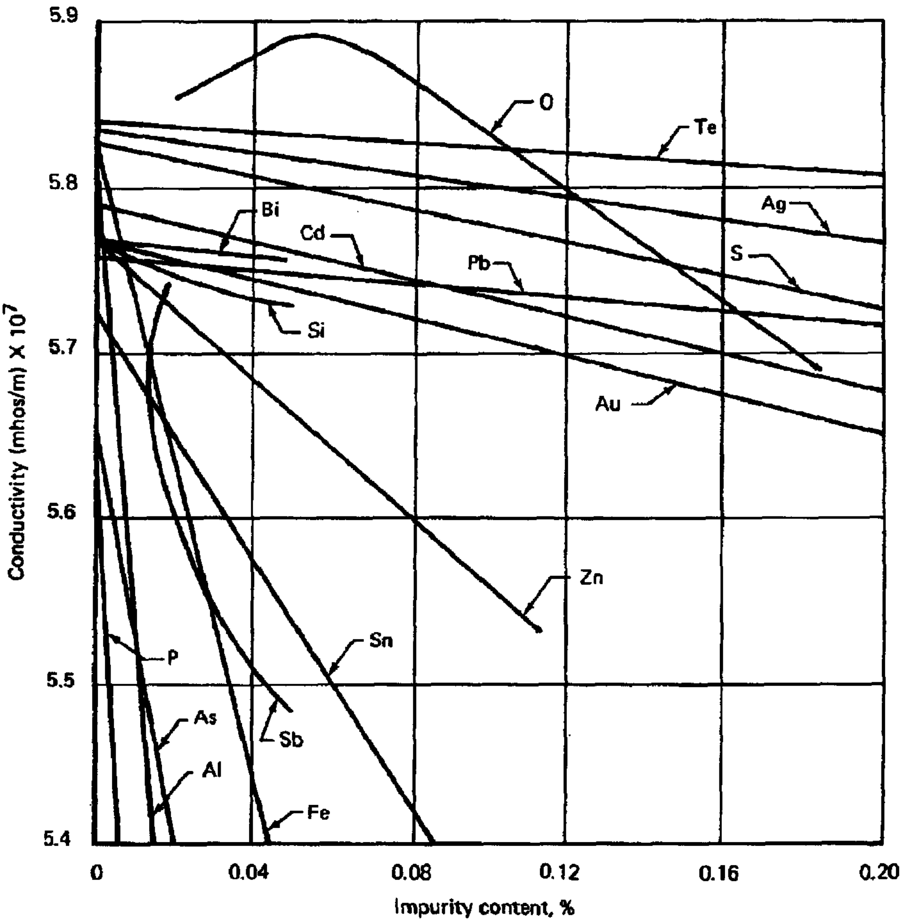



**Figure 15.44—Influence of Impurities on the Conductivity of Pure Copper**

distorted by the presence of discontinuities or other inhomogeneities. The apparent impedance of the coil is also altered by the presence of discontinuities in the specimen. This change in impedance indicates that discontinuities or differences in physical, chemical, and metallurgical structure are present in the conductor. Instrumentation and circuitry readout of the coil impedance are shown in Figure 15.47.

In electromagnetic examination, the applied magnetic field strength (H) is of great importance in determining the validity of an examination procedure. The field strength of a system is determined by the current in the primary coil. In magnetoinductive examination, the field strength and its selection are of prime importance. Magnetoinductive examination is electromagnetic examination where eddy currents are present but are of no significance in the procedure; magnetic properties, such as permeability and related variables, are the prime factors.

**15.8.5.1 Properties of Eddy Currents.** Eddy currents are induced into the conducting

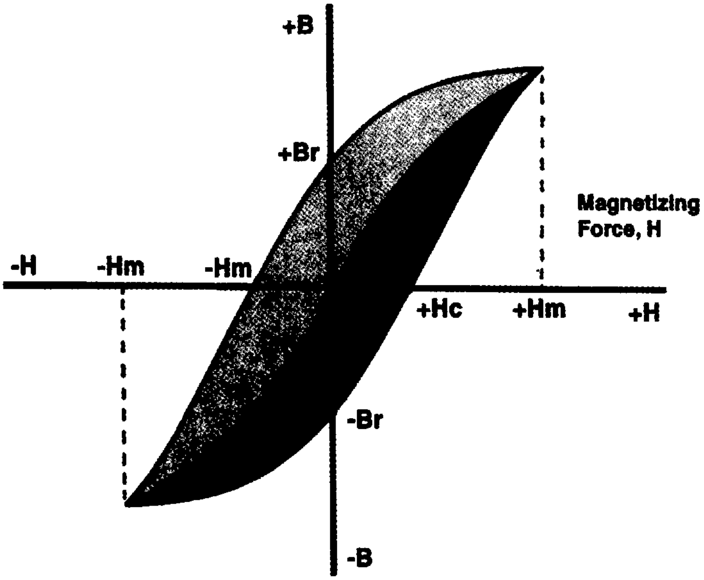



Figure 15.45—Typical B/H (Hysteresis) Curve

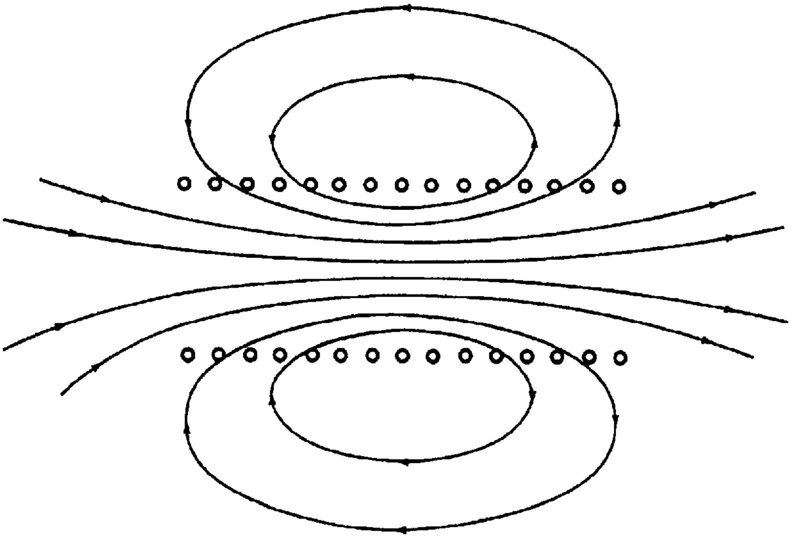


Figure 15.46—Lines of Magnetic Flux Surrounding a Solenoid

**Figure 15.47(A)—Instrumentation Readout for Electromagnetic Testing**


**Figure 15.47(B)—Typical Eddy Current Readout from Strip Chart Illustrating Good and Bad Weld Areas**

test specimen by alternating electromagnetic induction or transformer action (see Figure 15.48). Eddy currents are electrical in nature and have all the properties associated with electric currents. In generating eddy currents, the test piece, which should be a conductor, is brought into the field of a coil carrying alternating current as shown in Figure 15.49. The coil (a) may encircle the part, (b) may be in the form of a probe, or (c) in the case of tubular shapes, may be wound to fit inside a tube or pipe. Typical coils are illustrated in Figure 15.50. As stated, an eddy current in the metal specimen also sets up its own magnetic field which opposes the original magnetic field. The impedance of the exciting coil, or of a

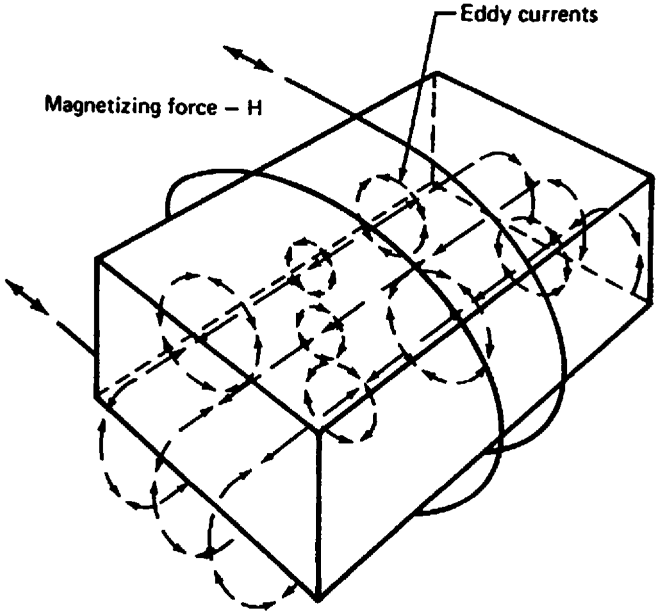



**Figure 15.48—Production of Eddy Currents by an Alternating Field**

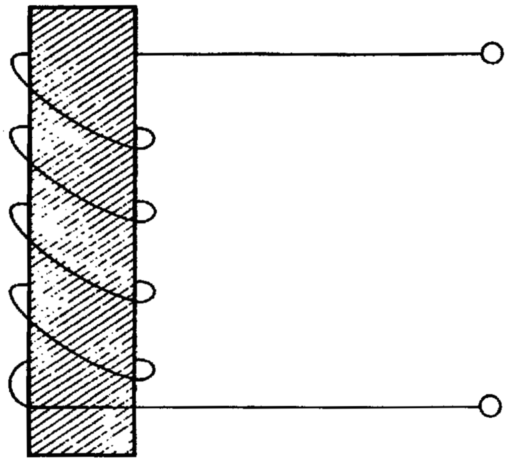
second coil magnetically coupled to the first, in close proximity to the specimen, is affected by the presence of the induced eddy currents. This second coil is often used as a convenience and is called a *test, sensing*, or *pickup coil*. The path of the eddy current is distorted by the presence of a discontinuity or other inhomogeneity.

Subsurface discontinuities may also be detected, but the current declines with depth as shown in Figure 15.51. Figure 15.52 shows how a crack both diverts and crowds eddy currents. In this manner, the apparent impedance of the coil is changed by the presence of the discontinuity. This change can be measured and is used to give an indication of discontinuities or differences in physical, chemical, and metallurgical structure.

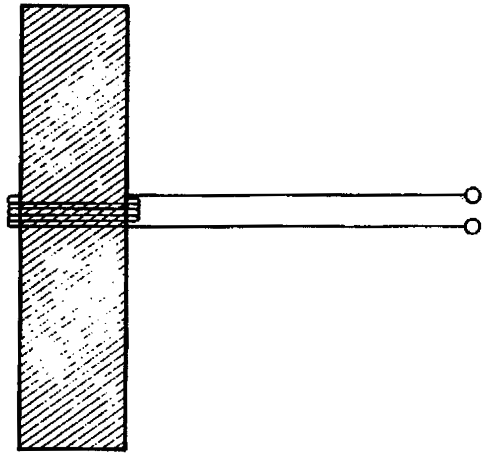
**15.8.6 Alternating Current Saturation.** A high alternating current magnetizing force may be used to simultaneously saturate (magnetically) a test piece and create an eddy current signal. This enhances certain disturbing magnetic variables.

All ferromagnetic materials that have been magnetically saturated will retain a certain amount of magnetization, called the residual field, when the external magnetizing force has been removed. The magnitude of the residual field depends on the magnetizing force applied.

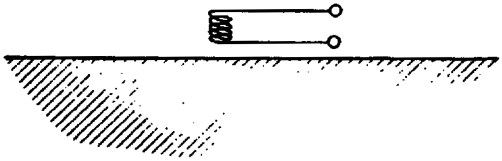
Demagnetization is necessary whenever the residual field (1) affects the operation or accuracy of instruments when placed in service, (2) interferes with inspection of the part at low field strengths or with the proper functioning of the part, and (3) might cause particles to be attracted and held to the surface of moving parts, particularly parts running in oil, thereby causing undue wear. There are many ways to demagnetize an object, the most common being to pass current directly through the



Wide encircling coils for conductivity determinations



Narrow encircling coils for detection of small flaws and local diameter variations



Small probe coil for best sensitivity to small flaws; also for testing plates and irregularly formed parts

**Figure 15.49—Testing Coils Carrying Alternating Current**


**Figure 15.50—Examples of Electromagnetic Probe Coils**
**(A–B) Custom made probes for testing inside of a hole**
**(C) Custom shielded probe for testing inside a hole in aluminum work**
**(D) Surface probe (note set screw for sliding coil up and down to obtain a given lift-off)**

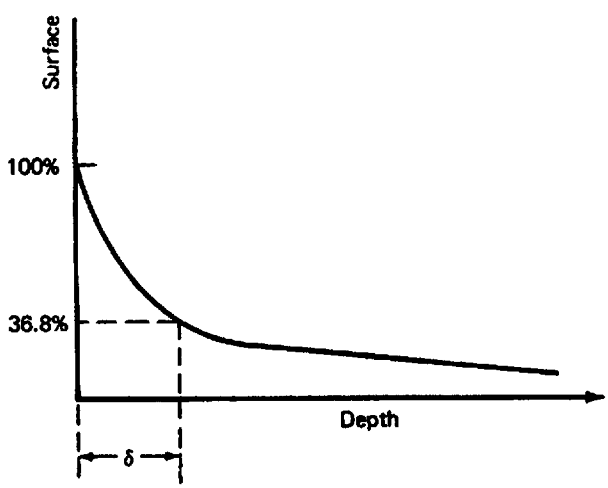
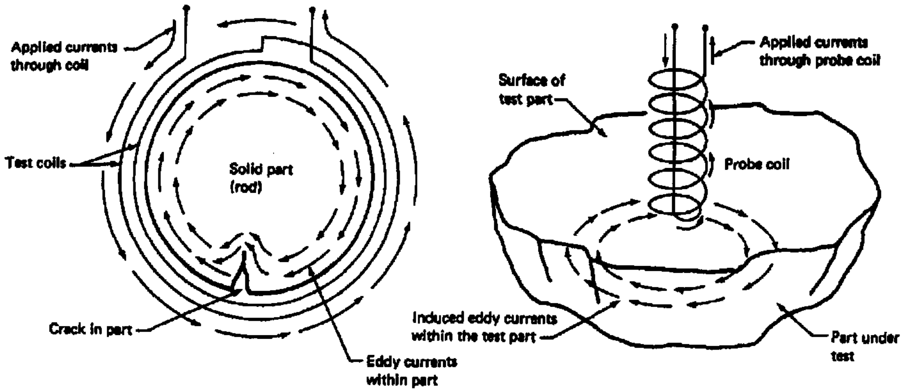



**Figure 15.51—Eddy Current Strength Drops Off With Distance From Surface**




A part is passed through a test coil. The applied current in the coil induces eddy currents within the part. These are affected by a crack or other change in the part.

Electric currents in the probe coil induce eddy currents within the test part. These react back on the applied current for "read out."

**Figure 15.52—Eddy Current Flaw Detection Equipment**

test piece. The selected method should give the required degree of removal of the residual field.

**15.8.7 Electromagnetic Examination.** Electromagnetic testing consists of observing the interaction between electromagnetic fields and metals. The following are three things required for an electromagnetic examination:

(1) A coil or coils carrying an alternating current

(2) A means of measuring the electrical properties of the coil or coils

(3) A metal part to be tested

As specialized sensing elements, the test coils are in some ways analogous to lenses in an optical system, and their design is a fundamental consideration depending upon the nature of the examination. Probe coils that are brought up against the surface to be examined are used in examining a variety of metallic shapes for physical properties, flaws or defects, and plating or coating thicknesses. Annular coils encircle the part and are used especially for examining tubing, rods, bars, wires, and small parts.

Electromagnetic examination involves (1) interaction between applied and induced electromagnetic fields, and (2) imparting of energy into the test part much like the transmission of x-rays, heat, or ultrasound. Upon entering the test piece, a portion of the electromagnetic energy produced by the examination coil is absorbed and converted into heat through the action of resistivity and, if the conductor is magnetic, hysteresis. The rest of the energy is stored in the electromagnetic field. As a result, the electrical properties of the examination coil are altered by the properties of the part under test. Hence, the current flowing in the coil carries information about the part: its dimensions, its mechanical, metallurgical, and chemical properties, and the presence of discontinuities.

The character of the interaction between the applied and induced electromagnetic fields is determined by two basically distinct phenomena within the test part:

(1) The induction of the eddy currents in the metal by the applied field

(2) The action of the applied field upon the magnetic domains, if any, of the part

Obviously, only the first phenomenon can act in the case of nonferromagnetic metals. In the case of ferromagnetic metals, both phenomena are present; however, the second usually has the stronger influence. This accounts for the basic difference in principle between the examination of ferromagnetic and nonferromagnetic metals.

Among the physical and metallurgical variables that affect electromagnetic examination in metals are the following:

(1) Physical shape, external dimensions, and thickness of the part

(2) Distance between the part and the electromagnetic coil

(3) Plating or coating thickness

(4) Chemical composition

(5) Distribution of alloying or impurity atoms (influenced by heat treatment of the part and, hence, may be a clue to hardness, strength, phase, gain size, etc.)

(6) Lattice dislocations caused by heavy working or radioactive bombardment

(7) Temperature

(8) Discontinuities and inhomogeneities

(9) In ferromagnetic metals, residual and applied stresses

In practice, many, and sometimes all, of the above factors may vary simultaneously. It is difficult under such conditions to obtain a meaningful response from the magnetic flux set-up within the test piece since several variables may have affected the examination signal. The resulting voltage, which is the variable usually sensed by electromagnetic examination devices, should be very carefully analyzed to isolate the sought-after effects from the extraneous effects.

Associated with any electromagnetic examination signal are three important attributes: amplitude, phase, and frequency. The examination signal may contain either a single frequency (that selected for the examination), or a multitude of frequencies (harmonics of the examination signal frequency). In the latter case, the test-signal frequency is referred to as the *fundamental frequency*. In addition, there are amplitude and phase factors associated with each harmonic frequency. The engineer has available a number of techniques that make use of all this information, thereby permitting the discrimination between examination variables. The important techniques used are amplitude discrimination, phase discrimination, harmonic analysis, coil design, choice of examination frequency, and magnetic saturation.

Because each examination involves straightforward scanning of the test-part surface by an examination coil or coils, either manually or by mechanical methods, the following section will emphasize the results of selected standard specimens or examples.

**15.8.8 Equipment Calibration and Quality Assurance Standards.** In using electromagnetic examination methods for the examination of metals, it is essential that adequate standards be available (1) to make sure the equipment is functioning properly and is picking up imperfections or discontinuities, and (2) to ascertain whether the are cause for rejection of the sample (defects). The discontinuities are inhomogeneities, deviations in physical, mechanical, or geometrical properties, or heat treatment effects. A *discontinuity* is any imperfection in a metal, which may or may not be harmful. A *defect* is a discontinuity in a metal that is unacceptable. A defect is always a discontinuity, but a discontinuity is not necessarily a defect.

It is not the discontinuity that is detected by the test equipment, but rather, the effect that the discontinuity has on the electromagnetic properties of the metal being examined. It is necessary, therefore, that it be possible to correlate the change in electromagnetic properties with the cause of the change. For this reason, calibration standards containing natural or artificial discontinuities should be used. The calibration standards should produce similar changes in the electromagnetic response as production product containing similar discontinuities. Such standards are usually considered equipment calibration standards; that is, they demonstrate that the equipment is, in fact, detecting the discontinuities for which the metal is being examined.

These standards are not only used to facilitate the initial adjustment or calibration of the examination instrument, but also used to periodically check on the reproducibility of the measurements.

It is not enough just to be able to locate discontinuities in a test piece; the inspector should determine if the discontinuity is unacceptable. For this purpose, quality assurance standards are required against which the examination instrument can be calibrated to show the limits of acceptability or rejectability for any type of discontinuity. Once acceptance criteria are established, quality assurance standards may be selected from actual production items or from prepared samples containing indications representing the limits of acceptability.

A quality assurance standard performs a function altogether different from that of an equipment calibration standard. While the equipment calibration standard shows what the instrument can do under a certain adjustment, the quality assurance standard seeks to keep this level of performance, whatever it is, identical and reproducible at all times and under all conditions of time and temperature.

**15.8.9 Application.** Research activities of scientists and engineers, together with the constant expansion of the knowledge of electronics, have stimulated the selection and use of electromagnetic examination techniques to a greater extent than ever before. Although comparatively little use was made of electromagnetic examination techniques prior to 1950, in more recent years, industry has found electromagnetic examination most useful and particularly adaptable to rapid, 100 percent automatic examination of production items and materials. The urgent need of industry to examine bars and welded tubing has led to the development of a number of commercial instruments and equipment capable of handling many of the problems involved in defect detection. This has been particularly true in the application of electromagnetic methods to the critical examination of items having high-quality requirements.

**15.8.10 Advantages.** There are two significant advantages of electromagnetic examination.

(1) It can, in many cases, be completely automated; thus, it provides automatic inspection at high speed and at relatively low cost.

(2) Under certain circumstances, the indications produced are proportional to the actual size of the defect; thus, the examination results can be useful for grading and classifying.

*EXAMPLE:* Tubing now can be electromagnetically examined for minute cracks and other discontinuities at speeds of more than 300 ft/min (1.5 m/s), while a comparable visual examination would usually proceed at much less than a tenth of this speed and would fail to detect flaws that were not on the surface.

## 15.9 Acoustic Emission Examination

Acoustic emission examination (AET) methods are currently considered supplementary to other nondestructive examination methods. They have been applied, however, during proof testing, during recurrent inspections, during service, and during fabrication.

AET consists of the detection of acoustic signals produced by plastic deformation or crack formation during loading. These signals are present in a wide frequency spectrum along with ambient noise from many other sources. Transducers, strategically placed on a structure, are activated by arriving signals. By suitable filtering methods, ambient noise in the composite signal is significantly reduced, and any source of significant signals is plotted by triangulation based on the arrival times of these signals at the different transducers.

AET methods have successfully been applied to welded pressure vessels and other welded structures during proof testing, such as pressurization. A sound vessel stops emitting signals when the load is reduced, and does not emit further bursts until the previous load has been exceeded. A growing crack emits an increasing number of signals as it is loaded. Location of suspect areas in such structures is a very well established AET technique. Locating systems have been developed, some providing sophisticated analysis of the signal data collected. The information obtainable on the nature and significance of the recorded "events" obtained by AET methods is currently considered to be limited. Efforts are being made by many organizations to develop and improve techniques for such evaluation.

AET applied during recurrent inspections has not been fully developed due to insufficient experience. These applications of AET may be considered an extension of proof testing, requiring pressurization in order to compare a prior AET examination with a later one.

AET surveillance of structures during operation offers many potential advantages. Transducers, constructed for long-term resistance to thermal and nuclear environments, have been developed, and wave guides may be used to remove the active elements from the most hostile regions, thus allowing either continuous or triggered-mode operation. AET offers advantages of reduced exposure to personnel, early warnings of problem areas, and reduction of access problems.

Standards and code-writing organizations are active in preparing standards for AET so that a data base can be obtained and credence established for routine, regular use. The American Society of Mechanical Engineers (ASME) has published a proposed *Standard for AE Examination During Application of Pressure*. The American Society for Testing and Materials (ASTM) Committee E-7 on NDT is standardizing AE terminology, transducers, methods of application, acoustic waveguides, etc., and is developing a recommended practice for calibrating frequency responses. The Committee also deals with AE instrumentation, such as recommended practices for performance of event-counting and locating systems, and applications of AET. It is clear that great effort is being expended to reduce AET technology to established, routine practice.

AET monitoring of some structures during the welding operations is possible, the object of which is to detect defects as they arise during fabrication. Such conditions as delayed cracking should be detectable.

### 15.9.1 Summary

(1) AET equipment development has proceeded for several years and has reached a high state of refinement.

(2) Locating of AET sources during proof testing is an established method, has been applied to welded steel structures, and an experience base has been achieved.

(3) Evaluation of sources of AET signals needs further development and standardization.

(4) AET during proof testing may be of present value to fabricators and user and offers promise of wider application for this purpose.

(5) Standardization efforts are beginning to produce tangible results toward providing industry with a common basis for evaluation and comparisons of AET results.

(6) AET monitoring can improve production control of welding during fabrication.

Acoustic emission is considered to be in its early stages of use by industry. Additional and more extensive use is to be anticipated in the future. For more information on the subject of AE, see "References and Suggested Reading Material" at the end of this chapter and the more than 35 papers on the subject that have been published in "Materials Evaluation," the journal of the American Society for Nondestructive Testing (ASNT).

## 15.10 Leak Examination

*Leak testing* is a term used to describe several methods of nondestructive examination. Common to all these methods is the fact that leak testing is used to discover discontinuities that extend from the inside to the outside of a vessel.

This nondestructive examination can be used on any material as long as a pressure differential can be created across the material. The American Society for Nondestructive

Testing recognizes four methods of leaking testing and the ASM *Metals Handbook* Vol. II, 8th edition describes at least eight techniques of leak testing.

**15.10.1 Techniques.** The most commonly used leak testing method is visual examination. A vessel is pressurized using a fluid that will be visible to the human eye. After pressurization, the vessel is visually examined for leaks.

Other techniques of leak testing include acoustic methods, bubble testing, flow detection, and gas detection.

**15.10.1.1 Acoustic Methods.** When a gas is forced through a small opening, sound is produced at both sonic and supersonic frequencies. When sound is produced at sonic frequencies it is possible to detect it with the ear. Electronic instruments are needed to detect sound at supersonic frequencies. Ultrasonic detectors can detect air leaking through a 0.010 in. diameter hole at 5 psi pressure from a distance of 50 feet.

**15.10.1.2 Bubble Testing.** One of the most simple techniques is this method, small vessels are pressurized and submerged in a liquid, where any leaks will show as bubbles in the liquid. Bubble testing can also be applied by flowing a bubble-forming solution over the surface of the item to be tested. Care should be taken that the bubbles are not formed by the process itself.

**15.10.1.3 Flow Detection.** In this technique, a pressurized vessel is placed inside a larger vessel and connected by a duct. A leak in the pressurized vessel will cause a flow of gas from the pressurized vessel to the enclosing vessel. An instrument designed to measure flow is attached to the connecting duct and measures the flow rate.

**15.10.1.4 Gas Specific Detectors.** A variety of instruments are available that will detect the leakage of a specific gas. The human nose is the most common of these devices. Other instruments use chemical-reaction to detect gases or positive ion flow that increases with an increase in the amount of gas detected. Thermal conductivity is also used by some instruments to detect specific gases. Each gas has a specific ability to cool a heated electrical filament, thereby controlling the temperature of the filament which in turn determines the filament's electrical resistivity.

In most cases, when using leak testing, it is advisable to first use a method that is capable of detecting gross leaks. Those methods that are sensitive to small leaks cannot be used in the presence of gross leaks. After determining the presence, or lack thereof of gross leaks, then proceed to use more sensitive methods. Leak testing should be done in at least two steps, gross leakage detection, and small leakage detection.

The reader should realize that hydro-testing is not leak testing. Usually, measurement of the leak rate is not accomplished during hydro testing. Hydro testing is a proof test, or testing for leaks.

## 15.11 Ferrite Content Examination

**15.11.1 Effects of Ferrite Content.** Fully austenitic stainless steel weld deposits have a tendency to develop small fissures even under conditions of minimal restraint. These small fissures tend to be located transverse to the weld fusion line in weld passes (and base metal) that were reheated to near the melting point of the material by subsequent weld passes. Cracks are clearly injurious defects and usually cannot be tolerated. On the other hand, the effect of fissures on weldment performance is less clear, since these micro-fissures are quickly blunted by the very tough austenitic matrix. Countless tons of fissured weld deposits have performed satisfactorily under very severe conditions. However, a tendency to form fissures generally goes hand-in-hand with a tendency for larger cracking, so that it is often desirable to avoid fissure-sensitive weld metals.

Since the 1940s, at least, it has been recognized that the presence of a small fraction of the magnetic delta ferrite phase in an otherwise austenitic (nonmagnetic) weld deposit has a pronounced influence in the prevention of both centerline cracking and fissuring. The amount of delta ferrite in as-welded material is largely, but not completely, controlled by a balance in the weld metal composition between the ferrite-promoting elements (chromium, silicon, molybdenum, and columbium are the most common) and the austenite-promoting elements (nickel, manganese, carbon, and nitrogen are the most common).

Excessive delta ferrite, however, can have adverse effects on weld metal properties. The greater the amount of delta ferrite, the lower will be the weld-metal ductility and toughness. Delta ferrite is also preferentially attacked in a few corrosive environments (such as urea). And in extended exposure to temperatures in the range of 900 to 2700°F (480 to 930°C) ferrite tends to transform in part to a brittle intermetallic compound (sigma phase) that severely embrittles the weldment.

**15.11.2 Delta Ferrite Verification and Measurement.** For the reasons previously mentioned, control over ferrite content in austenitic stainless weld metal is often required. This, in turn, requires a method of measurement. In the past, estimation of ferrite content by metallographic examination of prepared specimens has been used to determine the volume percent ferrite present. However, nonuniform ferrite distribution in weld metal, the sensitivity of the volume percent ferrite measurement to the sample preparation procedure, and the difficulty in preparing and examining the sample have led to this method being largely discarded. Estimation of ferrite content by chemical composition through a constitution diagram (the Schaeffler and the DeLong diagrams are the most popular) has been more common, but it is subject to analytical errors and uncertainties concerning alloying influences. Since ferrite is magnetic and austenite is not, ferrite content can also be measured by magnetic responses of the material, and this is currently the most common method of ferrite measurement, reproducible from laboratory to laboratory with properly calibrated instruments. Most instruments convert the force holding a standard magnet to the surface into a ferrite measurement.

Because agreement between laboratories as to the absolute percent ferrite in an austenitic stainless steel weld metal has thus far proven impossible to achieve, an arbitrary ferrite number (FN) scale has been established and is presented in AWS A4.2, *Standard Procedure for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal.* The FN scale, though arbitrary, is believed to approximate the true volume percent ferrite at least up to 10 FN.

The ferrite content recommended in weld filler metal is usually between 3 and 20 percent. A minimum of 3 percent ferrite is desirable to avoid microfissuring in welds. Up to 20 percent ferrite is permitted when needed to offset dilution losses. Delta ferrite verification can be made by tests on undiluted weld deposits using magnetic measuring devices. AWS A5.4, *Specification for Corrosion-Resisting Chromium and Chromium-Nickel Steel Covered Electrodes*, describes a procedure for test-pad preparation and ferrite measurement. The magnetic measuring devices used for examination of the weld pad for delta ferrite should be calibrated prior to use, following the procedure given in AWS A4.2.

**15.11.3 Austenitic Stainless Steels.** Austenitic chromium-nickel stainless steel types are the most widely used stainless steels. The variations in composition among the standard austenitic types are important, both in the performance of the steel in service and in its behavior in welding. As examples, Types 302, 304, and 304L, represent the so-called "18-8" stainless steels. They differ chiefly in carbon content. Types 316, 316L, and 317 contain an addition of molybdenum for improved corrosion resistance. Types 321, 347, and 348 are "stabilized" with titanium, columbium, and some tantalum to avoid intergranular chromium carbide during welding.

**15.11.4 Behavior in Welding.** An important part in the successful welding of austenitic stainless steels is the control of compositions and microstructures through proper selection of electrode type, welding procedure, and postweld treatment. Base-metal compositions, fully austenitic in wrought form, will often show the presence of small islands of delta ferrite in an austenite matrix in the cast or weld metal form. Figure 15.53 shows the microstructure of a typical austenitic weld specimen containing some delta ferrite. Fully austenitic weld deposits are occasionally susceptible to hot-short cracking.

Weld-metal cracking in austenitic stainless steels can be separated into four types: (1) crater cracks, (2) star cracks, (3) hot cracks or microfissures, and (4) root cracks. All four types of cracking are believed to be manifestations of the same basic kind of cracking: namely, "hot cracking" or, when present in its earliest, least severe stage, "microfissuring." Hot cracks or microfissures occur intergranularly. The segregation of low-melting compounds to the grain boundaries appears to promote fissuring susceptibility. Microfissures can develop in the as-deposited weld metal shortly after solidification.

Microfissures can also occur in the heat-affected zones (HAZ) of previously deposited sound beads of weld metal.

The presence of ferrite usually inhibits this tendency to crack. Many manufacturers design austenitic stainless steel electrodes to deposit a weld metal containing sufficient ferrite to reduce the susceptibility toward hot cracking. Thus, the weld metal for many of the standard austenitic grades may contain ferrite, although the same grade base metal does not contain any. Postweld heat treatments may decrease or even eliminate the ferrite in a weld deposit.

The presence or absence of ferrite in a weld-metal structure will depend principally upon composition. Since many of the corrosion-resistant stainless steels have

**Figure 15.53—Microstructure of Austenitic Weld Specimen**

borderline phase distribution, a single type of weld metal may be fully austenitic or partially ferritic, depending upon the composition balance. The constitution of a weld metal deposit is indicated in Figure 15.54. This figure is called a *Schaeffler diagram*, named for its originator. A subsequent variation of this diagram is the *W. T. DeLong diagram* shown in Figure 15.55. The DeLong diagram provides more accuracy and accounts for the contribution of nitrogen content.

**15.11.5 Ferrite Values and Testing.** Ferrite content has traditionally been expressed as the volume percent ferrite in the weld bead until the recent application of the term *ferrite number* (FN). Key factors in the recommended procedure for testing ferrite are the following:

(1) Use of the term *ferrite number (FN)* instead of percent ferrite

(2) Use of National Institute of Standards and Technology (NIST) coating thickness specimens as reference and calibration standards, and ferrite numbers assigned by Welding Research Council (WRC) for calibrating ferrite gauges

(3) Provisions for calibration of all other magnetic instruments through weld metal standards that have been rated for ferrite number (FN)

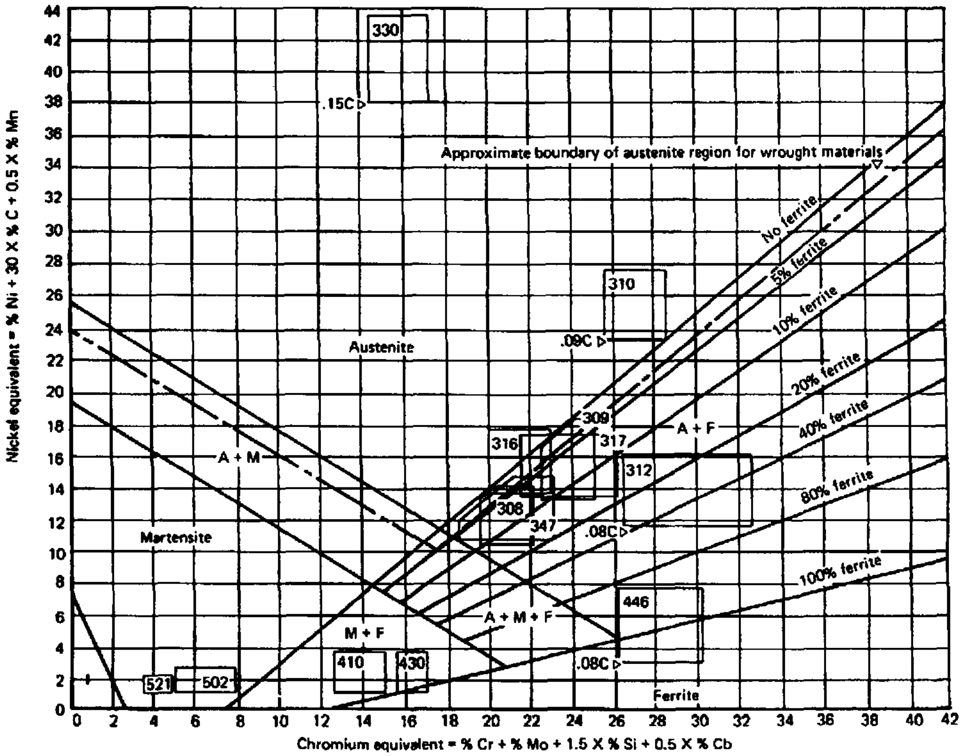



**Figure 15.54—Schaeffler Diagram for Stainless Steel Weld Metal**

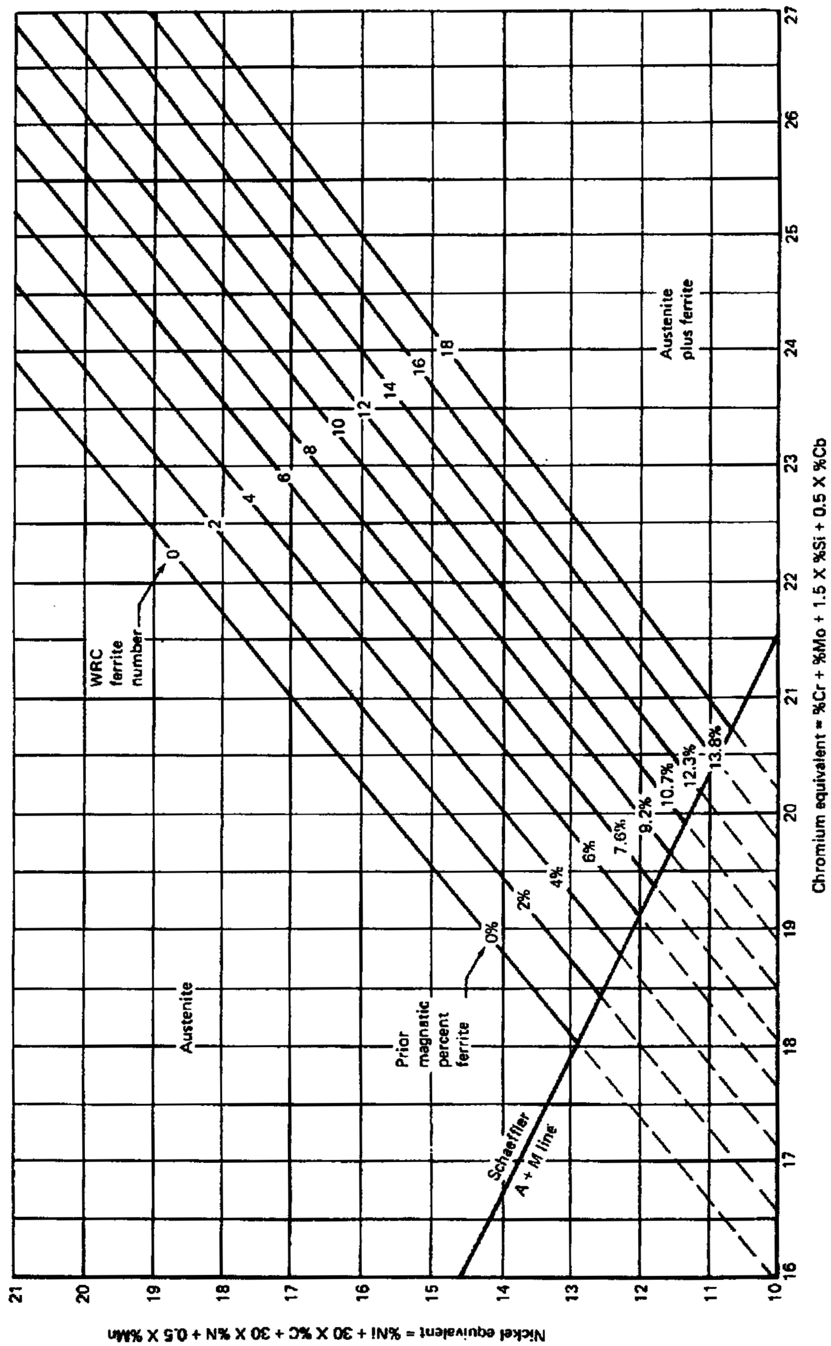



**Figure 15.55—DeLong Diagram for Stainless Steel Weld Metal**

The magnetic ferrite phase is most commonly measured using a portable instrument, such as the Ferritescope by Twin City Testing Corp., the Ferrite Content Meter by Institut Dr. Forster, and the Severn gauge by Severn Engineering Co. The WRC procedure is based on a sensitive instrument, the Magne-Gauge Tester by American Instrument Co., well known for its laboratory applications.

Portable ferrite indicators are designed for on-site use. Ferrite content of the weld deposit may be indicated in percent ferrite or FN numbers and may be bracketed between two values. This provides sufficient control in most applications where minimum ferrite content or a ferrite range is specified.

## 15.12 Nondestructive Examination Procedures

The previous sections of this chapter have been devoted to fundamental concepts of individual NDE methods. In applying these NDE methods to weld inspections, the welding inspector will discover that each particular NDE method has numerous variables that may be traded off to optimize (1) economics, (2) adaptability of the technique to a particular weld type; and (3) technical results desired. In addition, the welding inspector will discover that acceptance criteria vary depending upon the job and its specification requirements. Many contractors are working multiple jobs that require different technique and acceptance requirements. In order to provide the desired assurance of quality in the customer's product, specific NDE procedures are commonly employed to ensure uniformity and continuity in the inspection process. Preplanned NDE procedures provide the following advantages:

(1) Consolidate all of the customer's basic inspection criteria into a single document

(2) Promote efficient integration of manufacturing and inspecting operations

(3) Provide interpretation by experienced, knowledgeable, and responsible personnel

To give the welding inspector some background in the usefulness of NDE procedures, the following text expands upon some of the typical sources of requirements.

**15.12.1 Engineering a Procedure.** There are several approaches to engineering nondestructive examination procedures. The approach that will prove most effective will depend upon a particular contractor's policies governing the engineering, manufacturing, technical, and administrative factors involved. Each factor should receive due consideration if the nondestructive examination operation is to function successfully. The flow diagram (see Figure 15.56) shows how requirements invoked in the contract may be transformed into a written operational procedure.

**15.12.2 Specifications, Codes, and Other Standards.** The requirements for the technical content of a typical NDE procedure usually begin with the contractual "package" of detailed specifications for building or manufacturing the product. As may be seen in our flow diagram, a contractor specifies the basic fabrication standard or code to be used in conjunction with internal requirements or particular needs. This fabrication standard becomes the "backbone" for the job package, which establishes engineering conditions for construction and allied processes, i.e., inspections. The fabrication standard usually further refines building requirements by invoking a standard or practice especially tailored to provide specific, detailed inspection requirements. These detailed inspection requirements may be modified at almost any stage depending upon the customer's requirements. It is not uncommon to discover that specifications and associated documents employ extensive cross-referencing to related various details. Some networks of cross-referencing can generate a complicated situation for selection of applicable inspection conditions. In addition, such specifications and documents are characteristically comprehensive and require careful interpretation by experienced, knowledgeable, and responsible personnel. Most contractual requirements will generally address the following inspection related variables:

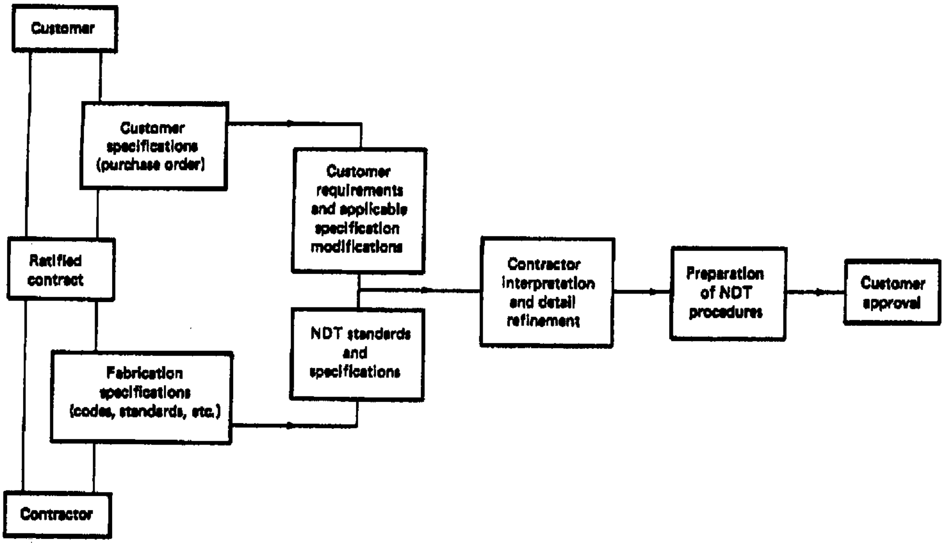



**Figure 15.56—Typical Flow Diagram from Contract to Approved Operations Procedures**

(1) Extent of examination coverage (what is required?)

(2) Examination method required

(3) NDT techniques for the method

(4) Qualification of examination technique methods

(5) Acceptance criteria for the welds using that method

(6) Personnel qualification and certifications

(7) Safety practices and miscellaneous

In addition, the contractual requirements will usually stipulate when the examination should be performed and what examination methods are to be used for weld repairs, should any be necessary. If any of these important conditions are not fully understood by the contractor, further discussion should ensue until a finalized agreement is reached on the complete requirements for examination of the welds. At this point, an NDE procedure may be beneficial to both customer and contractor in that an approved system may be agreed upon and uniformly followed throughout the manufacturing process.

**15.12.3 NDE Procedures.** Nondestructive examination Procedures generally fall into two basic categories: (1) company procedures, and (2) general standard operating procedures (S.O.P.s). Company procedures normally consolidate requirements and finalize interpretations concerning a particular NDE method into a single package (i.e., customer requirements, specification requirements, necessary modifications, etc.). The company procedure therefore represents an agreed upon consolidation and interpretation of contractual requirements. Standard operating procedures (S.O.P.s) are generally intended to serve as "recipe" or step-by-step procedures or methods to carry out the examination or portions of it. Examples of S.O.P.s could typically include equipment calibrations, job lay-out procedures, equipment maintenance, personnel qualifications, etc.

S.O.P.s can provide an efficient method of administering procedures in that they tend toward minimizing redundant or repetitive mention in the specific operating procedures, especially where examination areas overlap or where multiple procedures are used extensively.

Fundamental rules for developing the procedural text can apply to both categories since their basic differences are determined by their scope and their functional objective. A company procedure may reference a series of standard operating procedures for performance of specific functions (e.g., personnel qualification, equipment calibration and standardization, etc.) but the standard operating procedure generally represents the "end of the line" for respective written requirements.

**15.12.3.1 Procedure Mechanics.** An effectively written procedure sustains the primary objective of providing nondestructive examination personnel with simplified instructions. This objective should always be kept in mind when phrasing the respective requirements for incorporation into the procedure. A verbatim transfer of the applicable requirements from the involving document as the procedure text may defeat the objective of the procedure and may not suffice. Although this method may succeed in achieving technical compliance, it may not complement the overall procedure program. The respective requirements should be interpreted by an experienced person and refined as necessary to provide a precise but simplified account of acceptable practices and policies.

The mechanics associated with procedure preparation may vary with different situations, but certain fundamental rules will apply. The procedure will generally be evaluated on the basis of organization, content, and ability to communicate and function effectively. The respective requirements should be arranged in logical sequence. Commonly, a basic outline structure is used. The format or an index should provide a convenient means for locating and identifying any particular requirement. Generally, procedure wording is brief and to the point, producing a text that is accurate and concise without undue sacrificing of necessary details. Redundancies and repetition should be avoided unless they are considered necessary for emphasizing or clarifying a certain point. Tables, charts, and sketches usually prove effective in describing certain conditions and depicting various situations.

The distribution of nondestructive examination procedures is generally controlled as to the number of copies and the locations of each. This control assures that the procedures are distributed to only those parties requiring their use. The distribution control system should also encompass procedure changes and revisions that may be required as a result of changing policies and practices. The control system ensures that each procedure holder receives a copy of the respective change. An effectively maintained procedural distribution system will provide assurance that all related examination is being performed in accordance with up-to-date requirements.

## 15.13 References and Suggested Reading Material


1. American Society for Metals (ASM). "Nondestructive inspection and quality control." *ASM Metals Handbook*, Vol. II, 105-156. Materials Park, OH: ASM.

2. American Society for Nondestructive Testing (ASNT). *Personnel Qualification and Certification in Nondestructive Testing*. ASNT No. SNT-TC-1A, Columbus, Ohio: The American Society for Nondestructive Testing.

3. American Welding Society (AWS). A3.0, *Standard Welding Terms and Definitions*. Miami, FL: American Welding Society.

4. American Welding Society (AWS). B1.10, *Guide for the Nondestructive Examination of Welds*. Miami, FL: American Welding Society.

# Chapter 16
# Qualification of Nondestructive Examination Personnel

Nondestructive examination (NDE) personnel must be properly qualified in order to effectively do their jobs. The process of qualification gives some assurance that the NDE operator is knowledgeable in the theory and application of the method being used, as well as its advantages, disadvantages, and limitations. Experience, training, and ethical conduct are important elements that all NDE personnel should possess. The most widely used document for NDE personnel qualifications in the U.S. is *Recommended Practice No. SNT-TC-1A*, written and published by The American Society for Nondestructive Testing, Inc. While this document is a recommended practice, various codes, other standards, or specifications require its use, thus making it a minimum requirement. The welding inspector is cautioned that SNT-TC-1A is an ever changing document and the welding inspector should confirm that the applicable edition is being used. The welding inspector should review the manufacturer's written practice for NDE personnel qualifications to assure that it is in compliance with job requirements.

In today's NDE industry there are three levels of qualification. Recommended Practice No. SNT-TC-1A defines the capabilities of each level as follows:

## 16.1 Level I

A Level I individual should be qualified to properly perform specific calibrations, specific tests, and specific evaluations for acceptance or rejection determinations according to written instructions and to record results.

The Level I shall receive the necessary instruction or supervision from a certified Level II or III individual.

## 16.2 Level II

A Level II individual should be qualified to set up and calibrate equipment and to interpret and evaluate results with respect to applicable codes, other standards, and specifications. The Level II should be thoroughly familiar with the scope and limitations of the methods for which the individual is qualified and should exercise assigned responsibility for on-the-job training and guidance of trainees and Level I personnel. The Level II should be able to prepare written instructions, and to organize and report the results of nondestructive examinations.

## 16.3 Level III

A Level III individual should be capable of establishing techniques and procedures; interpreting codes, other standards, specifications, and procedures; and designating the particular test methods, techniques, and procedures to be used. The Level III should be responsible for the NDE operations for which qualified and to which assigned, and should be capable of interpreting and evaluating results in terms of existing codes, other standards, and specifications. The Level III should have sufficient practical background in applicable materials, fabrication, and product technology to establish techniques and to assist in establishing acceptance criteria where none are otherwise available. The Level III should have general familiarity with other appropriate NDE methods, and should be qualified to train and examine Level I and Level II personnel for certification.

Before being certified, a person working in NDE is considered a *Trainee*. Trainees should not be allowed to perform any NDE function without DIRECT supervision.

In order for the welding inspector to evaluate the performance of an NDE operator, it is necessary to have some familiarity with the method(s) used. This book lists numerous references that can be used to become more familiar with the various methods of nondestructive examination.

# Chapter 17
# Codes and Other Standards

## 17.1 Definitions

This chapter is intended to familiarize the welding inspector with the basic documents that govern or guide welding activities. These documents serve to assure that (1) only safe and reliable welded products will be produced, and (2) those persons associated with welding operations will not be exposed to undue danger or other conditions that would be harmful to their health. Publications relating only to the manufacture of welding materials or welding equipment are not covered in this chapter. However, the publications may be referenced in the basic documents, and their relationship to safety and reliability should not be underestimated.

The American Welding Society uses the general term *standards* to refer to documents that govern and guide welding activities. Standards describe the technical requirements for a material, process, product, system, or service. They also indicate, as appropriate, the procedures, methods, equipment, or tests used to determine that the requirements have been met.

Standards include codes, specifications, recommended practices, classifications, methods, and guides. These documents have many similarities, and the terms are often used interchangeably, but sometimes incorrectly.

*Codes* and *Specifications* are similar types of standards that use the words *shall* and *will* to indicate the mandatory use of certain materials or actions, or both. Both become mandatory when specified by one or more governmental jurisdictions or when they are referenced by contractural or other procurement documents.

*Recommended Practices and Guides* are standards that are offered primarily as aids to the user. They use words such as *should* and *may* because their use is usually optional. However, if these documents are referenced by codes or contractural agreements, their use may become mandatory. If the codes or agreements contain non-mandatory sections or appendices, the use of referenced guides or recommended practices is at the user's discretion.

*Classifications* and *methods* generally provide lists of established practices or categories for processes or products. The most common example is a standard testing method.

The user of a standard should become acquainted with its scope and intended use, both of which are usually included within the *Scope* or *Introduction* section of the standard. It is equally important, but often more difficult, to recognize subjects that are not covered by the document. These omissions may require additional technical consideration. A document may cover the details of the product form without considering special conditions for which it will be used. Examples of special conditions would be corrosive environments, elevated temperatures, or dynamic rather than static loading.

Standards vary in their method of achieving compliance. Some have specific requirements that do not allow for alternative actions. Others permit alternative actions or procedures so long as they result in properties that meet specified criteria. These criteria are often given as minimum requirements.

## 17.2 Sources

Private and governmental organizations develop, issue, and update standards that apply to their particular areas of interest.

Section 17.3.25 lists the organizations of concern to the welding industry and their current addresses. The interests of many of these groups overlap with regard to welding, and some agreements have been made to reduce duplication of effort.

Many standards that address welding, brazing, and allied processes are prepared by the American Welding Society (AWS) because these subjects are of primary interest to AWS members. Standards that apply to a particular product are usually prepared by the group that has overall responsibility. For example, those for railroad freight cars are published by the Association of American Railroads (AAR). However, freight cars are basically structures, and the applicable AAR specification currently refers to AWS for the qualification of welding procedures, welders, and welding operators. In 1986, the American Welding Society published AWS D15.1, *Railroad Welding Specification.* Future revisions to the AAR standards will reference AWS D15.1.

Each organization that prepares consensus standards has committees or task groups to perform this function. Members of these committees or task groups are specialists in their fields. They prepare drafts of standards that are reviewed and approved by a larger group. Each main committee is selected to include persons with diverse interests from producers, users, and government representatives. To avoid control or undue influence by one interest group, consensus should be achieved by a high percentage of all members.

The federal government develops or adopts standards for items and services that are in the public rather than the private sector. The mechanisms for developing federal or military documents are similar to those of private organizations. Standard-writing committees usually exist within a federal department or agency that has responsibility for a particular item or service.

The American National Standards Institute (ANSI) is a private organization responsible for coordinating national standards for use within the United States. ANSI does not actually prepare standards. Instead, it forms national interest review groups to determine whether proposed standards are in the public interest. Each group is composed of persons from various organizations concerned with the scope and provisions of a particular document. If there is consensus regarding the general value of a particular standard, then it may be adopted as an American National Standard. Adoption of a standard by ANSI does not, of itself, give it mandatory status. However, if the standard is cited by a governmental rule or regulation, or imposed by contract requirements, it may then be backed by force of law.

Other industrial countries also develop and issue standards on the subject of welding. The following are examples of other national standards designations and the bodies responsible for them:

BS—British Standard issued by the British Standards Association

CSA—Canadian Standard issued by the Canadian Standards Association

DIN—West German Standard issued by the Deutsches Institute fuer Normung

JIS—Japanese Industrial Standard issued by the Japanese Standards Association

NF—French Standard issued by the Association Française de Normalisation

There is also an International Organization for Standardization (ISO). Its goal is the establishment of uniform standards for use in international trade.

## 17.3 Applications

The minimum requirements of a particular standard may not satisfy the special needs of every user. Therefore, a user may find it necessary to invoke additional requirements to obtain desired quality.

There are various mechanisms by which most standards may be revised. These are used when a standard is found to be in error, unreasonably restrictive, or not applicable with respect to new technological developments. Some standards are updated on a regular basis, while others are revised as needed. The revisions may be in the form of addenda, or they may be incorporated in superseding documents. If there is a question about a particular standard regarding either an interpretation or a possible error, the user should contact the responsible organization.

When the use of a standard is mandatory, whether as a result of a government regulation or a legal contract, it is essential to know the particular edition of the document to be used. It is unfortunate, but not uncommon, to find that an outdated edition of a referenced document has been specified, and should be followed to be in compliance. If there is a question concerning which edition or revision of a document is to be used, it should be resolved before commencement of work.

Organizations responsible for preparing standards that relate to welding are discussed in the following sections. The publications are listed without reference to date of publication, latest revision, or amendment. New publications relating to welding may be issued, and current ones may be withdrawn or revised. The responsible organization should be contacted for current information on the standards it publishes.

**17.3.1 American Association of State Highway and Transportation Officials.** The member agencies of the association known as AASHTO are the U.S. Department of Transportation, and the Departments of Transportation and Highways of the fifty states, Washington DC, and Puerto Rico. AASHTO specifications are prepared by committees made up of employees of the member agencies. These documents are the minimum rules to be followed by all member agencies or others in the design and construction of highway bridges.

**17.3.2 American Bureau of Shipping.** The function of the American Bureau of Shipping (ABS) is to verify the quality of ship, boat, and offshore platform construction. Each year, ABS reissues the *Rules for Building and Classing Steel Vessels.*

ABS also publishes a list of welding consumables, entitled *Approved Welding Electrodes, Wire-Flux, and Wire-Gas Combinations.* These consumables are produced by various manufacturers around the world. They are tested under ABS supervision and approved for use under the ABS rules.

**17.3.3 American Institute of Steel Construction.** The American Institute of Steel Construction (AISC) is a non-profit trade organization for the fabricated structural steel industry in the United States. The Institute's objectives are to improve and advance the use of fabricated structural steel through research and engineering studies, and to develop the most efficient and economical design of structures. The organization also conducts programs to improve and control product quality.

**17.3.4 American National Standards Institute.** The American National Standards Institute (ANSI) is the coordinating organization for the U.S. voluntary standards system; it does not develop standards directly. The Institute provides the means for determining the need for standards, and ensures that organizations competent to fill these needs undertake the development work. The approval procedures of ANSI ensure that all interested persons have an opportunity to participate in the development of a standard or to comment on provisions of the standard prior to publication. ANSI is the U.S. member of nontreaty international standards organizations, such as the International Organization for Standardization (ISO), and the International Electrotechnical Commission (IEC).

**17.3.5 American Petroleum Institute.** The American Petroleum Institute (API) publishes documents in all areas related to petroleum production, storage, and transportation.

**17.3.6 American Railway Engineering Association.** The American Railway Engineering Association (AREA) publishes the *Manual for Railway Engineering.* This manual contains specifications, rules, plans, and instructions that constitute the recommended practices of railway engineering.

**17.3.7 American Society of Mechanical Engineers.** Two standing committees of the

American Society of Mechanical Engineers (ASME) are actively involved in the formulation, revision, and interpretation of standards covering products that may be fabricated by welding. These committees are responsible for preparing the *ASME Boiler and Pressure Vessel Code* and the *Code for Pressure Piping*, which are American National Standards.

**17.3.8 ASTM.** ASTM (formally The American Society for Testing and Materials) develops and publishes specifications for use in the production and testing of materials. The committees that develop the specifications are comprised of producers and users as well as others who have an interest in the subject materials. The specifications cover virtually all materials used in industry and commerce with the exception of welding consumables, which are covered by AWS specifications.

**17.3.9 American Water Works Association.** The American Water Works Association (AWWA) currently has two standards that pertain to the welding of water storage and transmission systems. One of these standards was developed jointly with and adopted by the American Welding Society.

**17.3.10 American Welding Society.** The American Welding Society (AWS) publishes numerous documents covering the use and quality control of welding. These documents include codes, specifications, recommended practices, classifications, methods, and guides. The general subject areas covered are the following:

(1) Definitions and symbols
(2) Filler metals
(3) Qualification and testing
(4) Welding processes
(5) Welding applications
(6) Safety
(7) Standard Welding Procedures

**17.3.11 Association of American Railroads.** The primary source of welding information relating to the construction of new railway equipment is the *Manual of Standards and Recommended Practices* prepared by the Mechanical Division, Association of American Railroads (AAR).

**17.3.12 Canadian Standards Association.** The Canadian Standards Association (CSA) is a voluntary membership organization engaged in standards development and also testing and certification. The CSA is similar to ANSI in the United States, but ANSI does not test and certify products. A CSA Certification Mark assures buyers that a product conforms to acceptable standards.

**17.3.13 Compressed Gas Association.** The Compressed Gas Association (CGA) promotes, develops, represents, and coordinates technical and standardization activities in the compressed gas industries, including end uses of products.

**17.3.14 Federal Government.** Several departments of the Federal Government, including the General Services Administration, are responsible for developing welding standards or adopting existing standards or both. There are in excess of 48 000 standards adopted by the federal government.

**17.3.15 Consensus Standards.** The U.S. Departments of Labor, Transportation, and Energy are primarily concerned with adopting existing national consensus standards, but they also make amendments to these standards or create separate standards, as necessary. For example, the Occupational Safety and Health Administration (OSHA) of the Department of Labor issues regulations covering occupational safety and health protection. The welding portions of standards adopted or established by OSHA are published under the Title 29 of the *United States Code of Federal Regulations*. Part 1910 covers general industry, while Part 1926 covers the construction industry. These regulations were derived primarily from national consensus standards of ANSI and of the National Fire Protection Association (NFPA).

Similarly, the U.S. Department of Transportation is responsible for regulating the transportation of hazardous materials, petroleum, and petroleum products by pipeline in interstate commerce. Its rules are published under Title 49 of the *United States Code of Federal Regulations*, Part 195. Typical of the many national consensus standards incorporated by reference in these regulations are API Standard 1104 and ASME B31.4, which were discussed previously.

The U.S. Department of Transportation is also responsible for regulating merchant ships of American registry. It is empowered to control the design, fabrication, and inspection of these ships by Title 46 of the *United States Code of Federal Regulations.*

The U.S. Coast Guard is responsible for performing the inspections of merchant ships. The *Marine Engineering Regulations* incorporate references to national consensus standards, such as those published by ASME, ANSI, and ASTM. These rules cover repairs and alterations that should be performed with the cognizance of the local Coast Guard Marine Inspection Officer.

The U.S. Department of Energy is responsible for the development and use of standards by government and industry for the design, construction, and operation of safe, reliable, and economic nuclear energy facilities. National consensus standards, such as the ASME *Boiler and Pressure Vessel Code*, Sections III and IX, and AWS D1.1, *Structural Welding Code—Steel* are referred to in full or in part. These standards are supplemented by separate program standards, known as RDT Standards.

**17.3.16 Military and Federal Specifications.** Military specifications are prepared by the Department of Defense. They cover materials, products, or services specifically for military use, and commercial items modified to meet military requirements.

**17.3.17 International Organization for Standardization.** The International Organization for Standardization (ISO) promotes the development of standards to facilitate the international exchange of goods and services. It is comprised of the standards-writing bodies of more than 80 countries, and has adopted or developed over 4000 standards.

The American National Standards Institute is the designated U.S. representative to ISO. ISO standards and publications are available from ANSI.

**17.3.18 National Board of Boiler and Pressure Vessel Inspectors.** The National Board of Boiler and Pressure Vessel Inspectors (NBBPVI), often referred to as the National Board, represents the enforcement agencies empowered to assure adherence to the ASME *Boiler and Pressure Vessel Code.* Its members are the chief inspectors or other jurisdictional authorities who administer the boiler and pressure vessel safety laws in the various jurisdictions of the United States and provinces of Canada.

**17.3.19 National Fire Protection Association.** The mission of the National Fire Protection Association (NFPA) is the safeguarding of people and their environment from destructive fire through the use of scientific and engineering techniques and education. NFPA standards are widely used as the basis of legislation and regulation at all levels of government. Many are referenced in the regulations of the Occupational Safety and Health Administration (OSHA). The standards are also used by insurance authorities for risk evaluation and premium rating.

**17.3.20 Pipe Fabrication Institute.** The Pipe Fabrication Institute (PFI) publishes numerous documents for use by the piping industry. Some of the standards have mandatory status because they are referenced in one or more piping codes. The purpose of PFI standards is to promote uniformity of piping fabrication in areas not specifically covered by codes. Other PFI documents, such as technical bulletins, are not mandatory, but they aid the piping fabricator in meeting the requirements of codes.

**17.3.21 Society of Automotive Engineers.** The Society of Automotive Engineers (SAE) is concerned with the research, development, design, manufacture, and operation of all types of self-propelled machinery. Such machinery includes automobiles, trucks, buses, farm machines, construction equipment, airplanes, helicopters, and space vehicles. Related areas of interest to SAE are fuels, lubricants, and engineering materials.

**17.3.22 Unified Numbering System.** The Unified Numbering System (UNS) provides a method for cross referencing the different numbering systems used to identify metals, alloys, and welding filler metals. With UNS, it is possible to correlate over 3500 metals and alloys used in a variety of specifications, regardless of the identifying number used by a society, trade association, producer, or user.

UNS is produced jointly by SAE and ASTM, and designated SAE HSJ1086/ASTM DS56. It cross references the numbered metal and alloy designations of the following organizations and systems:

(1) AA (Aluminum Association)
(2) ACI (Steel Founders Society of America)
(3) AISI (American Iron and Steel Institute)
(4) ASME (American Society of Mechanical Engineers)
(5) ASTM (Formerly American Society for Testing and Materials)
(6) AWS (American Welding Society)
(7) CDA (Copper Development Association)
(8) Federal Specifications
(9) MIL (Military Specifications)
(10) SAE (Formerly Society of Automotive Engineers)
(11) AMS (SAE Aerospace Materials Specifications)

Over 500 of the listed numbers are for welding and brazing filler metals. Numbers with the prefix *W* are assigned to welding filler metals that are classified by deposited metal composition.

**17.3.23 Underwriter's Laboratories, Inc.** Underwriter's Laboratories, Inc., (UL) is a not-for-profit organization which operates laboratories for the examination and testing of devices, systems, and materials to determine their relation to hazards to life and property. UL Standards for Safety are developed under a procedure which provides for participation and comment from the affected public as well as industry. This procedure takes into consideration a survey of known existing standards, and the needs and opinions of a wide variety of interests concerned with the subject matter of a given standard. These interests include manufacturers, consumers, individuals associated with consumer-oriented organizations, academicians, government officials, industrial and commercial users, inspection authorities, insurance interests, and others.

UL should be contacted if no standard can be found for a particular product. The UL Standards for Safety pertain to more than 11 000 product types in over 500 generic product categories.

**17.3.24 Manufacturers' Associations.** The following organizations publish literature which relates to welding. The committees that write descriptive literature are comprised of representatives of equipment or material manufacturers. They do not generally include users of the products. Although some bias may exist, there is a lot of useful information that can be obtained from this literature. The organization should be contacted for further information.

**Aluminum Association**
900 19th Street, N.W., Suite 300
Washington, DC 20006
(202) 862-5100 Tel.
(202) 862-5164 Fax
www.aluminum.org

**American Association of State Highway and Transportation Officials**
444 North Capitol Street, N.W., Suite 249
Washington, DC 20001
(202) 624-5800 Tel.
(202) 624-5806 Fax
www.aashto.org

**American Bureau of Shipping and Affiliated Companies**
Two World Trade Center, 106th Floor
New York, NY 10048
(212) 839-5000 Tel.
(212) 839-5209 Fax
abs@eagle.org E-mail

**American Conference of Governmental Industrial Hygienists**
1330 Kemper Meadow Drive, Suite 600
Cincinnati, OH 45240-1634
(513) 742-2020 Tel.
(513) 742-3355 Fax
www.acgih.org

**American Gas Association**
400 North Capitol Street, N.W.
Washington, DC 20001
(703) 841-8400 Tel.
(703) 841-8689 Fax
www.aga.com

**American Institute of Steel Construction**
One East Wacker Drive, Suite 3100
Chicago, IL 60601-2001
(312) 670-2400 Tel.
(312) 670-5403 Fax
www.aiscweb.org

**American Iron and Steel Institute**
1101 17th Street, N.W., Suite 1300
Washington, DC 20036-4700
(202) 452-7100 Tel.
(202) 463-6573 Fax
www.steel.org

**American National Standards Institute**
11 West 42nd Street, 13th Floor
New York, NY 10036-8002
(212) 642-4900 Tel.
(212) 398-0023 Fax
www.ansi.org

**American Petroleum Institute**
1220 L Street, N.W.
Washington, DC 20005
(202) 682-8000 Tel.
(202) 682-8115 Fax
www.api.org

**American Railway Engineering and Maintenance of Way Association**
8201 Corporate Drive, Suite 1125
Landover, MD 20785
(301) 459-3200 Tel.
(301) 459-8077 Fax

**American Society for Nondestructive Testing**
1711 Arlingate Lane, P.O. Box 28518
Columbus, OH 43228-0518
(614) 274-6003; (800) 222-2768 Tel.
(614) 274-6899 Fax
www.asnt.org

**American Society for Quality**
P.O. Box 3005
611 East Wisconsin Avenue
Milwaukee, WI 53201-3005
(414) 272-8575; (800) 248-1946 Tel.
(414) 272-1734 Fax
www.asq.org

**American Society for Testing and Materials**
100 Barr Harbor Drive
West Conshohocken, PA 19428
(610) 832-9500 Tel.
(610) 832-9555 Fax
www.astm.org

**American Society of Civil Engineers**
1801 Alexander Bell Drive
Reston, VA 20191-4400
(703) 295-6000; 800 548-2723 Tel.
(703) 295-6351 Fax
www.asce.org

**American Society of Mechanical Engineers**
Three Park Avenue
New York, NY 10016-5990
(212) 591-7000 Tel.
(212) 591-7674 Fax
www.asme.org

**American Society of Safety Engineers**
1800 East Oakton Street
Des Plaines, IL 60018-2187
(847) 699-2929 Tel.
(847) 296-3769 Fax
www.asse.org

**American Water Works Association**
6666 W. Quincy Avenue
Denver, CO 80235-3098
(303) 794-7711 Tel.
(303) 795-1989 Fax
www.awwa.org

**American Welding Society**
550 N.W. LeJeune Road
Miami, FL 33126
(305) 443-9353; (800) 443-9353 Tel.
(305) 443-7559 Fax
www.amweld.org

**ASM International**
9639 Kinsman Road
Materials Park, OH 44073-0002
(440) 338-5151 Tel.
(440) 338-4634 Fax
www.asm-intl.org

**Association of American Railroads**
50 F Street, N.W.
Washington, DC 20001-1564
(202) 639-2100 Tel.
(202) 639-2558 Fax
www.aar.org

**Compressed Gas Association**
1725 Jefferson Davis Highway, Suite 1004
Arlington, VA 22202-4102
(703) 412-0900 Tel.
(703) 412-0128 Fax
www.cganet.com

**Copper Development Association, Inc.**
260 Madison Avenue
New York, NY 10016-2401
(212) 251-7200; (800) 232-3282 Tel.
(212) 251-7234 Fax
www.copper.org

**Electronic Industries Association**
2500 Wilson Boulevard
Arlington, VA 22201
(703) 907-7500 Tel.
(703) 907-7501 Fax
www.eia.org

**Fabricators and Manufacturers Association, International**
833 Featherstone Road
Rockford, IL 61107
(815) 877-7633 Tel.
(815) 399-7279 Fax

**Institute of Industrial Engineers**
25 Technology Park/Atlanta
Norcross, GA 30092-2901
(770) 449-0460 Tel.
(770) 441-3295 Fax
www.iienet.org

**NACE International**
P.O. Box 218340
Houston, TX 77218-8340
(281) 228-6200 Tel.
(281) 228-6300 Fax
www.nace.org

**National Board of Boiler and Pressure Vessel Inspectors**
1055 Crupper Avenue
Columbus, OH 43229
(614) 888-8320 Tel.
(614) 888-0750 Fax
www.nationalboard.org

**National Electrical Manufacturers Association**
1300 N. 17th Street, Suite 1847
Rosslyn, VA 22209
(703) 841-3200 Tel.
(703) 841-3351 Fax
www.nema.org

**National Fire Protection Association**
P.O. Box 9101
1 Battery March Park
Quincy, MA 02269-9101
(617) 770-3000 Tel.
(617) 770-0200 Fax
www.nfpa.org and www.sparky.org

**National Safety Council**
1121 Spring Lake Drive
Itasca, IL 60143-3201
(630) 285-1121 Tel.
(630) 285-1315 Fax
www.nsc.org

**National Welding Supply Association**
1900 Arch Street
Philadelphia, PA 19103-1498
(215) 564-3484 Tel.
(215) 564-2175 Fax
www.nwsa.com

**Pipe Fabrication Institute**
Box 173
612 Lenore Avenue
Springdale, PA 15144-1518
(514) 634-3444 Tel.
(514) 634-9736 Fax

**Resistance Welder Manufacturers Association**
1900 Arch Street
Philadelphia, PA 19103-1498
(215) 564-3484 Tel.
(215) 963-9785 Fax
www.rwma.org

**Society of Automotive Engineers International**
400 Commonwealth Drive
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# Chapter 18
# Metric Practice

## 18.1 Introduction

The American Welding Society is actively promoting the adoption of the International System of Units (SI) within the U.S. welding industry.

Every inspector should have or should acquire a working knowledge of the metric system of measurements because of the increasing use of SI units to replace the customary U.S. units in American industry. The latest revision of the AWS A1.1, *Metric Practice Guide for the Welding Industry*, may be referred to for more information.

## 18.2 Units

SI consists of seven base units, two supplementary units, a series of derived units, and a series of prefixes for the forming of multiples or sub-multiples of the units.

Base and supplementary units and their symbols are shown in Table 18.1.

**Table 18.1**
**SI Base and Supplementary Units and Symbols**

| Measure | Unit | Symbol |
|---|---|---|
| length | meter | m |
| mass | kilogram | kg |
| time | second | s |
| electric current | ampere | A |
| thermodynamic temperature | kelvin | K |
| luminous intensity | candela | cd |
| amount of substance | mole | mol |
| plane angle | radian | rad |
| solid angle | steradian | sr |

Derived units and their symbols are shown in Table 18.2.

Prefixes are used in the SI system to indicated orders of magnitude. This simplifies numeric terms and may be more convenient than writing powers of ten as is general in computation. As an example, 12 900 meters or $12.9 \times 10^3$ meters would be written 12.9 kilometers. The tabulation in Table 18.3 shows the factors, prefixes, and symbols.

Other units are in widespread use and are acceptable for use with, although not a part of, the SI system. The term "weight," as commonly used in commerce, is a measure of force that depends on the acceleration due to gravity. The SI system does not have a unit for weight. The kilogram is the SI unit for "mass," the term that is used extensively in scientific documents. Other units are in widespread use and are acceptable for use with, although not a part of, the SI system. These are shown in Table 18.4.

## 18.3 Welding—Recommended Units and Conversion Factors

Table 18.5 shows the recommended SI units for welding nomenclature and some useful conversion factors. The recommended SI units are given in parentheses.

## 18.4 Conversions—General

Table 18.6 presents factors for converting numerous U.S. Customary Units to SI Units. These values, though not exact, are useful for making everyday conversions.

Rules for conversion and rounding off have been published by AWS in document AWS A1.1, *Metric Practice Guide for the Welding*

## Table 18.2
## SI Derived Units and Symbols

| Measure | Unit | Symbol | Formula |
|---|---|---|---|
| acceleration | | | |
| —linear | meter per second squared | none | $m/s^2$ |
| —angular | radian per second squared | none | $rad/s^2$ |
| area | square meter | none | $m^2$ |
| density | kilogram per meter cubed | none | $fg/m^3$ |
| electromotive force | volt | V | W/A |
| energy, work, heat, and impact strength | joule | J | N m |
| force | newton | N | $kg\ m/s^2$ |
| luminous flux | lumen | lm | cd sr |
| frequency | hertz | Hz | $s^{-1}$ |
| magnetic flux | weber | Wb | V s |
| power | watt | W | J/s |
| pressure, stress | pascal | Pa | $N/m^2$ |
| velocity | | | |
| —linear | meter per second | none | m/s |
| —angular | radian per second | none | rad/s |
| volume | cubic meter | none | $m^3$ |

## Table 18.3
## SI Factors, Prefixes, and Symbols

| Expression | Multiplication Factor | Prefix | Symbol |
|---|---|---|---|
| $10^6$ | 1 000 000 | mega | M |
| $10^3$ | 1000 | kilo | k |
| $10^2$ | 100 | hecto* | h |
| 10 | 10 | deka* | da |
| $10^{-1}$ | 0.1 | deci* | d |
| $10^{-2}$ | 0.01 | centi* | c |
| $10^{-3}$ | 0.001 | milli | m |
| $10^{-6}$ | 0.000 001 | micro | μ |
| $10^{-9}$ | 0.000 000 001 | nano | n |

*Not recommended. Prefixes should be selected in steps of $10^3$ so that the resultant number before the prefix is between 0.1 and 1000.

**Table 18.4**
**Units Not Part of the SI System**

| Units | Symbol | Value |
|---|---|---|
| minute | min | 1 min = 60 s |
| hour | h | 1 h = 60 min = 3600 s |
| day | d | 1 d = 24 h = 1440 min = 86 400 s |
| degree (angular) | ° | 1° = (/180) rad = 0.0175 rad |
| bar* | bar | 1 bar = 0.1 MPa = $10^5$ Pa |
| liter | L | 1 L = 0.001 $m^3$ = 1 $dm^3$ |
| degree Celsius | °C | 1°C = 1 K (interval) |
| angstrom* | A | 1 A = 0.1 nm = $10^{-10}$ m |
| atmosphere* | atm | 1 atm = 101 325 Pa |
| weight | kg | 1 kgf = 9.806 650 N |

*The lower case "ell" is the recognized symbol for liter but on most typewriters (and typesetting machines) the lower case "ell" and the figure one are nearly identical. Accordingly, it is preferable to spell the word in full or use capital L. However, ml may be used for milliliter, because confusion would no longer be possible.

*Industry*, as well as by other organizations such as ASTM. Generally, rounding and conversion are needed during a transition period, but since they may continue throughout the useful life of this revision of "Welding Inspection," the following guidelines are offered:

(1) Exact conversion from one system to another is seldom used, since most often this results in long decimal numbers that imply a higher degree of precision than was intended originally.

(2) The closest practical equivalency between inch and millimeter values will occur when the SI value contains one less decimal place than its inch equivalent. For example, 0.365 in. equals 9.27 mm. Fractional inch conversions are especially tricky, however, since these usually exaggerate the intended precision. For example, when changing 1-7/8 in. to mm, unless the 1-7/8 in. dimension was intended to be 1.875 in., 47.63 mm may be more precise than necessary. For interchangeability of parts, allowed and required tolerances should be kept in mind in making inch-millimeter conversion, or vice versa, so that neither excessively tight tolerances nor excess clearances are inadvertently introduced. In these cases, the function of the assembly or feature should be addressed. If this requires that maximum and minimum limits in millimeters be within inch limits, maximum limits are rounded down and minimum limits are rounded up.

(3) Two round-off methods, designated A and B are described in document AWS A1.1 and in Appendix B of the AWS *Welding Handbook*, Volume One, Eighth Edition. One of these sources should be consulted when more detailed information is needed.

The commonly used inch-millimeter conversions are listed in Table 18.7.

Table 18.8 may be used to obtain SI equivalents of values expressed in psi or ksi. SI values are usually expressed in kPa when original value is in psi and in MPa when original value is ksi. This table may be extended to values below 1 or above 100 psi (or ksi) by manipulation of the decimal point and addition.

Conversions for Fahrenheit—Celsius temperature scales are shown in Table 18.9.

**Table 18.5**
**SI Unit Conversion Factors**

| Property | To Convert From | To | Multiply By |
|---|---|---|---|
| area dimensions | in.$^2$ | mm$^2$ | $6.451\,600 \times 10^2$ |
| (mm$^2$) | mm$^2$ | in.$^2$ | $1.550\,003 \times 10^{-3}$ |
| current density | A/in.$^2$ | A/mm$^2$ | $1.550\,003 \times 10^{-3}$ |
| (A/mm$^2$) | A/mm$^2$ | A/in.$^2$ | $6.451\,600 \times 10^2$ |
| deposition rate** | lb/h | kg/h | 0.45** |
| (kg/h) | kg/h | lb/h | 2.2** |
| electrical resistivity | cm | m | $1.000\,000 \times 10^{-2}$ |
| (Ωm) | m | cm | $1.000\,000 \times 10^2$ |
| electrical force | pound-force | N | 4.448 222 |
| (N) | kilogram-force | N | 9.806 650 |
| | N | lbf | $2.248\,089 \times 10^{-1}$ |
| energy, work, heat, and impact energy | foot pound force | J | 1.356 |
| | foot poundal | J | $4.214 \times 10^{-2}$ |
| | Btu* | J | $1.054 \times 10^3$ |
| | calorie* | J | 4.184 |
| | watt hour | J | $3.600 \times 10^3$ |
| flow rate | ft$^3$/h | L/min | $4.719\,475 \times 10^{-1}$ |
| (L/min) | gallon per hour | L/min | $6.309\,020 \times 10^{-2}$ |
| | gallon per minute | L/min | 3.785 412 |
| | cm$^3$/min | L/min | $1.000 \times 10^{-3}$ |
| | liter/min | ft$^3$/h | 2.119 |
| | cm$^3$/min | ft$^3$/h | $2.119 \times 10^{-3}$ |
| fracture toughness | ksi in.$^{1/2}$ | MN m$^{-3/2}$ | 1.098 855 |
| (MN m$^{-3/2}$) | MN m$^{-3/2}$ | ksi in.$^{1/2}$ | 0.910 038 |
| heat input | J/in. | J/m | $3.937\,008 \times 10$ |
| (J/m) | J/m | J/in. | $2.540\,000 \times 10^{-2}$ |
| linear measurements | in. | mm | $2.540\,000 \times 10$ |
| (mm) | ft | mm | $3.048\,000 \times 10^2$ |
| | mm | in. | $3.937\,008 \times 10^{-2}$ |
| | mm | ft | $3.280\,840 \times 10^{-3}$ |
| power density | W/in.$^2$ | W/m$^2$ | $1.550\,003 \times 10^3$ |
| (W/m$^2$) | W/m$^2$ | W/in.$^2$ | $6.451\,600 \times 10^{-4}$ |
| pressure (gas and liquid) | psi | kPa | 6.894 757 |
| (kPa) | lb/ft$^2$ | kPa | $4.788\,026 \times 10^{-2}$ |
| | N/mm$^2$ | kPa | $1.000\,000 \times 10^3$ |
| | kPa | psi | $1.450\,377 \times 10^{-1}$ |
| | kPa | lb/ft$^2$ | $2.088\,543 \times 10$ |
| | kPa | N/mm$^2$ | $1.000\,000 \times 10^{-3}$ |

*(Continued)*

## Table 18.5 (Continued)
## SI Unit Conversion Factors

| Property | To Convert From | To | Multiply By |
|---|---|---|---|
| tensile strength (MPa) | psi | MPa | $6.894\ 757 \times 10^{-3}$ |
| | lb/ft$^2$ | MPa | $4.788\ 026 \times 10^{-5}$ |
| | N/mm$^2$ | MPa | 1.000 000 |
| | kg/mm$^2$ (kgf/mm$^2$) | MPa | 9.806 650 |
| | MPa | psi | $1.450\ 377 \times 10^{2}$ |
| | MPa | lb/ft$^2$ | $2.088\ 543 \times 10^{4}$ |
| | MPa | N/mm$^2$ | 1.000 000 |
| thermal conductivity (W/[m K]) | cal/(cm s °C) | W/(m K) | $4.184\ 000 \times 10^{2}$ |
| travel speed, wire feed speed (mm/s) | in./min | mm/s | $4.233\ 333 \times 10^{-1}$ |
| | mm/s | in./min | 2.362 205 |

## Table 18.6
## General Conversion Factors

| Property | To Convert From | To | Multiply By |
|---|---|---|---|
| acceleration (angular) | revolution per minute squared | rad/s$^2$ | $1.754\ 329 \times 10^{-3}$ |
| acceleration (linear) | in./min$^2$ | m/s$^2$ | $7.055\ 556 \times 10^{-6}$ |
| | ft/min$^2$ | m/s$^2$ | $8.466\ 667 \times 10^{-5}$ |
| | in./min$^2$ | mm/s$^2$ | $7.055\ 556 \times 10^{-3}$ |
| | ft/min$^2$ | mm/s$^2$ | $8.466\ 667 \times 10^{-2}$ |
| | ft/s$^2$ | m/s$^2$ | $3.048\ 000 \times 10^{-1}$ |
| angle, plane | deg | rad | $1.745\ 329 \times 10^{-2}$ |
| | minute | rad | $2.908\ 882 \times 10^{-4}$ |
| | second | rad | $4.848\ 137 \times 10^{-6}$ |
| area | in.$^2$ | m$^2$ | $6.451\ 600 \times 10^{-4}$ |
| | ft$^2$ | m$^2$ | $9.290\ 304 \times 10^{-2}$ |
| | yd$^2$ | m$^2$ | $8.361\ 274 \times 10^{-1}$ |
| | in.$^2$ | mm$^2$ | $6.451\ 600 \times 10^{2}$ |
| | ft$^2$ | mm$^2$ | $9.290\ 304 \times 10^{4}$ |
| | acre (U.S. Survey) | m$^2$ | $4.046\ 873 \times 10^{3}$ |
| density | pound mass per cubic inch | kg/m$^3$ | $2.767\ 990 \times 10^{4}$ |
| | pound mass per cubic foot | kg/m$^3$ | $1.601\ 846 \times 10$ |

*(Continued)*

**Table 18.6 (Continued)**
**General Conversion Factors**

| Property | To Convert From | To | Multiply By |
|---|---|---|---|
| energy, work, heat, and impact energy | foot pound force | J | 1.355 818 |
| | foot poundal | J | $4.214\ 011 \times 10^{-2}$ |
| | Btu* | J | $1.054\ 350 \times 10^{3}$ |
| | calorie* | J | 4.184 000 |
| | watt hour | J | $3.600\ 000 \times 10^{3}$ |
| force | kilogram-force | N | 9.806 650 |
| | pound-force | N | 4.448 222 |
| impact strength length | (see energy) | | |
| | in. | m | $2.540\ 000 \times 10^{-2}$ |
| | ft | m | $3.048\ 000 \times 10^{-1}$ |
| | yd | m | $9.144\ 000 \times 10^{-1}$ |
| | mile (statute) | m | $1.609\ 300 \times 10^{3}$ |
| mass | pound mass (avdp) | kg | $4.535\ 924 \times 10^{-1}$ |
| | metric ton | kg | $1.000\ 000 \times 10^{3}$ |
| | ton (short, 2000 lbm) | kg | $9.071\ 47 \times 10^{2}$ |
| | slug | kg | $1.459\ 390 \times 10$ |
| power | horsepower (550 ft lbf/s) | W | $7.456\ 999 \times 10^{2}$ |
| | horsepower (electric) | W | $7.460\ 000 \times 10^{2}$ |
| | Btu/min* | W | $1.757\ 250 \times 10$ |
| | calorie per minute* | W | $6.973\ 333 \times 10^{-2}$ |
| | foot pound-force per minute | W | $2.259\ 697 \times 10^{-2}$ |
| pressure | pound force per square inch | kPa | 6.894 757 |
| | bar | kPa | $1.000\ 000 \times 10^{2}$ |
| | atmosphere | kPa | $1.013\ 250 \times 10^{2}$ |
| | kip/in.$^2$ | kPa | $6.894\ 757 \times 10^{3}$ |
| temperature | degree Celsius, $t_C$ | K | $t_K = t_C + 273.15$ |
| | degree Fahrenheit, $t_F$ | K | $t_K = (t_F + 459.67)/1.8$ |
| | degree Rankine, $t_R$ | K | $t_K = t_R/1.8)$ |
| | degree Fahrenheit, $t_F$ | C° | $t_C = (t_F - 32)/1.8$ |
| | kelvin, $t_K$ | C° | $t_C = t_K - 273.15$ |
| tensile strength (stress) | ksi | MPa | 6.894 757 |
| torque | inch pound force | N m | $1.129\ 848 \times 10^{-1}$ |
| | foot pound force | N m | 1.355 818 |
| velocity (angular) | revolution per minute | rad/s | $1.047\ 198 \times 10^{-1}$ |
| | degree per minute | rad/s | $2.908\ 882 \times 10^{-4}$ |
| | revolution per minute | deg/min | $3.600\ 000 \times 10^{2}$ |

*(Continued)*

**Table 18.6 (Continued)**
**General Conversion Factors**

| Property | To Convert From | To | Multiply By |
|---|---|---|---|
| velocity (linear) | in./min | m/s | $4.233\,333 \times 10^{-4}$ |
| | ft/min | m/s | $5.080\,000 \times 10^{-3}$ |
| | in./min | mm/s | $4.233\,333 \times 10^{-1}$ |
| | ft/min | mm/s | 5.080 000 |
| | mile/hour | km/h | 1.609 344 |
| volume | $in.^3$ | $m^3$ | $1.638\,706 \times 10^{-5}$ |
| | $ft^3$ | $m^3$ | $2.831\,685 \times 10^{-2}$ |
| | $yd^3$ | $m^3$ | $7.645\,549 \times 10^{-1}$ |
| | $in.^3$ | $mm^3$ | $1.638\,706 \times 10^{4}$ |
| | $ft^3$ | $mm^3$ | $2.831\,685 \times 10^{7}$ |
| | $in.^3$ | L | $1.638\,706 \times 10^{-2}$ |
| | $ft^3$ | L | $2.831\,685 \times 10$ |
| | gallon | L | 3.785 412 |

*Thermochemical

## Table 18.7
## Commonly Used Metric Conversions (Inch–Millimeter Conversion)

1 in. = 25.4 mm exactly.

To convert inches to millimeters, multiply the inch millimeter value by 25.4.
To convert millimeters to inches, divide the value by 25.4.

Inch and Millimeter Decimal Equivalents of Fractions of an Inch

| Inch | | | Inch | | |
|---|---|---|---|---|---|
| Fraction | Decimal | Millimeter | Fraction | Decimal | Millimeter |
| 1/64 | 0.015 625 | 0.396 875 | 33/64 | 0.515 625 | 13.096 875 |
| 1/32 | 0.031 250 | 0.793 750 | 17/32 | 0.531 250 | 13.493 750 |
| 3/64 | 0.046 875 | 1.190 625 | 35/64 | 0.546 875 | 13.890 625 |
| 1/16 | 0.062 500 | 1.587 500 | 9/16 | 0.562 500 | 14.287 500 |
| 5/64 | 0.078 125 | 1.984 375 | 37/64 | 0.578 125 | 14.684 375 |
| 3/32 | 0.093 750 | 2.381 250 | 19/32 | 0.593 750 | 15.081 250 |
| 7/64 | 0.109 375 | 2.778 125 | 39/64 | 0.609 375 | 15.478 125 |
| 1/8 | 0.125 000 | 3.175 000 | 5/8 | 0.625 000 | 15.875 000 |
| 9/64 | 0.140 625 | 3.571 875 | 41/64 | 0.640 625 | 16.271 875 |
| 5/32 | 0.156 250 | 3.968 750 | 21/32 | 0.656 250 | 16.668 750 |
| 11/64 | 0.171 875 | 4.365 625 | 43/64 | 0.671 875 | 17.065 625 |
| 3/16 | 0.187 500 | 4.762 500 | 11/16 | 0.687 500 | 17.462 500 |
| 13/64 | 0.203 125 | 5.159 375 | 45/64 | 0.703 125 | 17.859 375 |
| 7/32 | 0.218 750 | 5.556 250 | 23/32 | 0.718 750 | 18.256 250 |
| 15/64 | 0.234 375 | 5.953 125 | 47/64 | 0.734 375 | 18.653 125 |
| 1/4 | 0.250 000 | 6.350 000 | 3/4 | 0.750 000 | 19.050 000 |
| 17/64 | 0.265 625 | 6.746 875 | 49/64 | 0.765 625 | 19.446 875 |
| 9/32 | 0.281 250 | 7.143 750 | 25/32 | 0.781 250 | 19.843 750 |
| 19/64 | 0.296 875 | 7.540 625 | 51/64 | 0.796 875 | 20.240 625 |
| 5/16 | 0.312 500 | 7.937 500 | 13/16 | 0.812 500 | 20.637 500 |
| 21/64 | 0.328 125 | 8.334 375 | 53/64 | 0.828 125 | 21.034 375 |
| 11/32 | 0.343 750 | 8.731 250 | 27/32 | 0.843 750 | 21.431 250 |
| 23/64 | 0.359 375 | 9.128 125 | 55/64 | 0.859 375 | 21.828 125 |
| 3/8 | 0.375 000 | 9.525 000 | 7/8 | 0.875 000 | 22.225 000 |
| 25/64 | 0.390 625 | 9.921 875 | 57/64 | 0.890 625 | 22.621 875 |
| 13/32 | 0.406 250 | 10.318 750 | 29/32 | 0.906 250 | 23.018 750 |
| 27/64 | 0.421 875 | 10.715 625 | 59/64 | 0.921 875 | 23.415 625 |
| 7/16 | 0.437 500 | 11.112 500 | 15/16 | 0.937 500 | 23.812 500 |
| 29/64 | 0.453 125 | 11.509 375 | 61/64 | 0.953 125 | 24.209 375 |
| 15/32 | 0.468 750 | 11.906 250 | 31/32 | 0.968 750 | 24.606 250 |
| 31/64 | 0.484 375 | 12.303 125 | 63/64 | 0.984 375 | 25.003 125 |
| 1/2 | 0.500 000 | 12.700 000 | 1 | 1.000 000 | 25.400 000 |

## Table 18.8
## Pressure and Stress Equivalents—psi and ksi to kPa and MPa

1 psi = 6894.757 Pa

To convert psi to pascals, multiply the psi value by $6.894\ 757 \times 10^3$
To convert pascals to psi, divide the pascal value by $6.894\ 757 \times 10^3$

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| psi or ksi | kPa or MPa | | | | | | | | | |
| 0 | 0.0000 | 6.8948 | 13.7895 | 20.6843 | 27.5790 | 34.4738 | 41.3685 | 48.2633 | 55.1581 | 62.0528 |
| 10 | 68.9476 | 75.8423 | 82.7371 | 89.6318 | 96.5266 | 103.4214 | 110.3161 | 117.2109 | 124.1056 | 131.0004 |
| 20 | 137.8951 | 144.7899 | 151.6847 | 158.5794 | 165.4742 | 172.3689 | 179.2637 | 186.1584 | 193.0532 | 199.9480 |
| 30 | 206.8427 | 213.7375 | 220.6322 | 227.5270 | 234.4217 | 241.3165 | 248.2113 | 255.1060 | 262.0008 | 268.8955 |
| 40 | 275.7903 | 282.6850 | 289.5798 | 296.4746 | 303.3693 | 310.2641 | 317.1588 | 324.0536 | 330.9483 | 337.8431 |
| 50 | 344.7379 | 351.6326 | 358.5274 | 365.4221 | 372.3169 | 379.2116 | 386.1064 | 393.0012 | 399.8959 | 406.7907 |
| 60 | 413.6854 | 420.5802 | 427.4749 | 434.3697 | 441.2645 | 448.1592 | 455.0540 | 461.9487 | 468.8435 | 475.7382 |
| 70 | 482.6330 | 489.5278 | 496.4225 | 503.3173 | 510.2120 | 517.1068 | 524.0015 | 530.8963 | 537.7911 | 544.6858 |
| 80 | 551.5806 | 558.4753 | 565.3701 | 572.2648 | 579.1596 | 586.0544 | 592.9491 | 599.8439 | 606.7386 | 613.6334 |
| 90 | 620.5281 | 627.4229 | 634.3177 | 641.2124 | 648.1072 | 655.0019 | 661.8967 | 668.7914 | 675.6862 | 682.5810 |
| 100 | 689.4757 | | | | | | | | | |

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## Table 18.9
## Conversions for Fahrenheit–Celsius Temperature Scales

Find the number to be converted in the center (**boldface**) column. If converting Fahrenheit degrees, read the Celsius equivalent in the column headed "C°". If converting Celsius degrees, read the Fahrenheit equivalent in the column headed "F°".

| °C | | °F | °C | | °F | °C | | °F | °C | | °F |
|---|---|---|---|---|---|---|---|---|---|---|---|
| –273 | **–459** | | –40 | **–40** | –40 | 24.4 | **76** | 168.8 | 199 | **390** | 734 |
| –268 | **–450** | | –34 | **–30** | –22 | 25.6 | **78** | 172.4 | 204 | **400** | 752 |
| –262 | **–440** | | –29 | **–20** | –4 | 26.7 | **80** | 176.0 | 210 | **410** | 770 |
| –257 | **–430** | | –23 | **–10** | 14 | 27.8 | **82** | 179.6 | 216 | **420** | 788 |
| –251 | **–420** | | –17.8 | **0** | 32 | 28.9 | **84** | 183.2 | 221 | **430** | 806 |
| –246 | **–410** | | –16.7 | **2** | 35.6 | 30.0 | **86** | 186.8 | 227 | **440** | 824 |
| –240 | **–400** | | –15.6 | **4** | 39.2 | 31.1 | **88** | 190.4 | 232 | **450** | 842 |
| –234 | **–390** | | –14.4 | **6** | 42.8 | 32.2 | **90** | 194.0 | 238 | **460** | 860 |
| –229 | **–380** | | –13.3 | **8** | 46.4 | 33.3 | **92** | 197.6 | 243 | **470** | 878 |
| –223 | **–370** | | –12.2 | **10** | 50.0 | 34.4 | **94** | 201.2 | 249 | **480** | 896 |
| –218 | **–360** | | –11.1 | **12** | 53.6 | 35.6 | **96** | 204.8 | 254 | **490** | 914 |
| –212 | **–350** | | –10.0 | **14** | 57.2 | 36.7 | **98** | 208.4 | 260 | **500** | 932 |
| –207 | **–340** | | –8.9 | **16** | 60.8 | 37.8 | **100** | 212.0 | 266 | **510** | 950 |
| –201 | **–330** | | –7.8 | **18** | 64.4 | 43 | **110** | 230 | 271 | **520** | 968 |
| –196 | **–320** | | –6.7 | **20** | 68.0 | 49 | **120** | 248 | 277 | **530** | 986 |
| –190 | **–310** | | –5.6 | **22** | 71.6 | 54 | **130** | 266 | 282 | **540** | 1004 |
| –184 | **–300** | | –4.4 | **24** | 75.2 | 60 | **140** | 284 | 288 | **550** | 1022 |
| –179 | **–290** | | –3.3 | **26** | 78.8 | 66 | **150** | 302 | 293 | **560** | 1040 |
| –173 | **–280** | | –2.2 | **28** | 82.4 | 71 | **160** | 320 | 299 | **570** | 1058 |
| –168 | **–270** | –454 | –1.1 | **30** | 86.0 | 77 | **170** | 338 | 304 | **580** | 1076 |
| –162 | **–260** | –436 | 0.0 | **32** | 89.6 | 82 | **180** | 356 | 310 | **590** | 1094 |
| –157 | **–250** | –418 | 1.1 | **34** | 93.2 | 88 | **190** | 374 | 316 | **600** | 1112 |
| –151 | **–240** | –400 | 2.2 | **36** | 96.8 | 93 | **200** | 392 | 321 | **610** | 1130 |
| –146 | **–230** | –382 | 3.3 | **38** | 100.4 | 99 | **210** | 410 | 327 | **620** | 1148 |
| –140 | **–220** | –364 | 4.4 | **40** | 104.0 | 100 | **212** | 414 | 332 | **630** | 1166 |
| –134 | **–210** | –346 | 5.6 | **42** | 107.6 | 104 | **220** | 428 | 338 | **640** | 1184 |
| –129 | **–200** | –328 | 6.7 | **44** | 111.2 | 110 | **230** | 446 | 343 | **650** | 1202 |
| –123 | **–190** | –310 | 7.8 | **46** | 114.8 | 116 | **240** | 464 | 349 | **660** | 1220 |
| –118 | **–180** | –292 | 8.9 | **48** | 118.4 | 121 | **250** | 484 | 354 | **670** | 1238 |
| –112 | **–170** | –274 | 10.0 | **50** | 122.0 | 127 | **260** | 500 | 360 | **680** | 1256 |
| –107 | **–160** | –256 | 11.1 | **52** | 125.6 | 132 | **270** | 518 | 366 | **690** | 1274 |
| –101 | **–150** | –238 | 12.2 | **54** | 129.2 | 138 | **280** | 536 | 371 | **700** | 1292 |
| –96 | **–140** | –220 | 13.3 | **56** | 132.8 | 143 | **290** | 554 | 377 | **710** | 1310 |
| –90 | **–130** | –202 | 14.4 | **58** | 136.4 | 149 | **300** | 572 | 382 | **720** | 1328 |
| –84 | **–120** | –184 | 15.6 | **60** | 140.0 | 154 | **310** | 590 | 388 | **730** | 1346 |
| –79 | **–110** | –166 | 16.7 | **62** | 143.6 | 160 | **320** | 608 | 393 | **740** | 1364 |
| –73 | **–100** | –148 | 17.8 | **64** | 147.2 | 166 | **330** | 626 | 399 | **750** | 1382 |
| –68 | **–90** | –130 | 18.9 | **66** | 150.8 | 171 | **340** | 644 | 404 | **760** | 1400 |
| –62 | **–80** | –112 | 20.0 | **68** | 154.4 | 177 | **350** | 662 | 410 | **770** | 1418 |
| –57 | **–70** | –94 | 21.1 | **70** | 158.0 | 182 | **360** | 680 | 416 | **780** | 1436 |
| –51 | **–60** | –76 | 22.2 | **72** | 161.6 | 188 | **370** | 698 | 421 | **790** | 1454 |
| –46 | **–50** | –58 | 23.3 | **74** | 165.2 | 193 | **380** | 716 | 427 | **800** | 1472 |

*(Continued)*

## Table 18.9 (Continued)
## Conversions for Fahrenheit–Celsius Temperature Scales

Find the number to be converted in the center (**boldface**) column. If converting Fahrenheit degrees, read the Celsius equivalent in the column headed "C°". If converting Celsius degrees, read the Fahrenheit equivalent in the column headed "F°".

| °C | | °F | °C | | °F | °C | | °F | °C | | °F |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 432 | **810** | 1490 | 738 | **1360** | 2480 | 1043 | **1910** | 3470 | 1349 | **2460** | 4460 |
| 438 | **820** | 1508 | 743 | **1370** | 2498 | 1049 | **1920** | 3488 | 1354 | **2470** | 4478 |
| 443 | **830** | 1526 | 749 | **1380** | 2516 | 1054 | **1930** | 3506 | 1360 | **2480** | 4496 |
| 449 | **840** | 1544 | 754 | **1390** | 2534 | 1060 | **1940** | 3524 | 1366 | **2490** | 4514 |
| 454 | **850** | 1562 | 760 | **1400** | 2552 | 1066 | **1950** | 3542 | 1371 | **2500** | 4532 |
| 460 | **860** | 1580 | 766 | **1410** | 2570 | 1071 | **1960** | 3560 | 1377 | **2510** | 4550 |
| 466 | **870** | 1598 | 771 | **1420** | 2588 | 1077 | **1970** | 3578 | 1382 | **2520** | 4568 |
| 471 | **880** | 1616 | 777 | **1430** | 2606 | 1082 | **1980** | 3596 | 1388 | **2530** | 4586 |
| 477 | **890** | 1634 | 782 | **1440** | 2624 | 1088 | **1990** | 3614 | 1393 | **2540** | 4604 |
| 482 | **900** | 1652 | 788 | **1450** | 2642 | 1093 | **2000** | 3632 | 1399 | **2550** | 4622 |
| 488 | **910** | 1670 | 793 | **1460** | 2660 | 1099 | **2010** | 3650 | 1404 | **2560** | 4640 |
| 493 | **920** | 1688 | 799 | **1470** | 2678 | 1104 | **2020** | 3668 | 1410 | **2570** | 4658 |
| 499 | **930** | 1706 | 804 | **1480** | 2696 | 1110 | **2030** | 3686 | 1416 | **2580** | 4676 |
| 504 | **940** | 1724 | 810 | **1490** | 2714 | 1116 | **2040** | 3704 | 1421 | **2590** | 4694 |
| 510 | **950** | 1742 | 816 | **1500** | 2732 | 1121 | **2050** | 3722 | 1427 | **2600** | 4712 |
| 516 | **960** | 1760 | 821 | **1510** | 2750 | 1127 | **2060** | 3740 | 1432 | **2610** | 4730 |
| 521 | **970** | 1778 | 827 | **1520** | 2768 | 1132 | **2070** | 3758 | 1438 | **2620** | 4748 |
| 527 | **980** | 1796 | 832 | **1530** | 2786 | 1138 | **2080** | 3776 | 1443 | **2630** | 4766 |
| 532 | **990** | 1814 | 838 | **1540** | 2804 | 1143 | **2090** | 3794 | 1449 | **2640** | 4784 |
| 538 | **1000** | 1832 | 843 | **1550** | 2822 | 1149 | **2100** | 3812 | 1454 | **2650** | 4802 |
| 543 | **1010** | 1850 | 849 | **1560** | 2840 | 1154 | **2110** | 3830 | 1460 | **2660** | 4820 |
| 549 | **1020** | 1868 | 854 | **1570** | 2858 | 1160 | **2120** | 3848 | 1466 | **2670** | 4838 |
| 554 | **1030** | 1886 | 860 | **1580** | 2876 | 1166 | **2130** | 3866 | 1471 | **2680** | 4856 |
| 560 | **1040** | 1904 | 866 | **1590** | 2894 | 1171 | **2140** | 3884 | 1477 | **2690** | 4874 |
| 566 | **1050** | 1922 | 871 | **1600** | 2912 | 1177 | **2150** | 3902 | 1482 | **2700** | 4892 |
| 571 | **1060** | 1940 | 877 | **1610** | 2930 | 1182 | **2160** | 3920 | 1488 | **2710** | 4910 |
| 577 | **1070** | 1958 | 882 | **1620** | 2948 | 1188 | **2170** | 3938 | 1493 | **2720** | 4928 |
| 582 | **1080** | 1976 | 888 | **1630** | 2966 | 1193 | **2180** | 3956 | 1499 | **2730** | 4946 |
| 588 | **1090** | 1994 | 893 | **1640** | 2984 | 1199 | **2190** | 3974 | 1504 | **2740** | 4964 |
| 593 | **1100** | 2012 | 899 | **1650** | 3002 | 1204 | **2200** | 3992 | 1510 | **2750** | 4982 |
| 599 | **1110** | 2030 | 904 | **1660** | 3020 | 1210 | **2210** | 4010 | 1516 | **2760** | 5000 |
| 604 | **1120** | 2048 | 910 | **1670** | 3038 | 1216 | **2220** | 4028 | 1521 | **2770** | 5018 |
| 610 | **1130** | 2066 | 916 | **1680** | 3056 | 1221 | **2230** | 4046 | 1527 | **2780** | 5036 |
| 616 | **1140** | 2084 | 921 | **1690** | 3074 | 1227 | **2240** | 4064 | 1532 | **2790** | 5054 |
| 621 | **1150** | 2102 | 927 | **1700** | 3092 | 1232 | **2250** | 4082 | 1538 | **2800** | 5072 |
| 627 | **1160** | 2120 | 932 | **1710** | 3110 | 1238 | **2260** | 4100 | 1543 | **2810** | 5090 |
| 632 | **1170** | 2138 | 938 | **1720** | 3128 | 1243 | **2270** | 4118 | 1549 | **2820** | 5108 |
| 638 | **1180** | 2156 | 943 | **1730** | 3146 | 1249 | **2280** | 4136 | 1554 | **2839** | 5126 |
| 643 | **1190** | 2174 | 949 | **1740** | 3164 | 1254 | **2290** | 4154 | 1560 | **2840** | 5144 |
| 649 | **1200** | 2192 | 954 | **1750** | 3182 | 1260 | **2300** | 4172 | 1566 | **2850** | 5162 |
| 654 | **1210** | 2210 | 960 | **1760** | 3200 | 1266 | **2310** | 4190 | 1571 | **2860** | 5180 |
| 660 | **1220** | 2228 | 966 | **1770** | 3218 | 1271 | **2320** | 4208 | 1577 | **2870** | 5198 |

*(Continued)*

## Table 18.9 (Continued)
## Conversions for Fahrenheit–Celsius Temperature Scales

Find the number to be converted in the center (**boldface**) column. If converting Fahrenheit degrees, read the Celsius equivalent in the column headed "C°". If converting Celsius degrees, read the Fahrenheit equivalent in the column headed "F°".

| °C | | °F | °C | | °F | °C | | °F | °C | | °F |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 666 | **1230** | 2246 | 971 | **1780** | 3236 | 1277 | **2330** | 4226 | 1582 | **2880** | 5216 |
| 671 | **1240** | 2264 | 977 | **1790** | 3254 | 1282 | **2340** | 4244 | 1588 | **2890** | 5234 |
| 677 | **1250** | 2282 | 982 | **1800** | 3272 | 1288 | **2350** | 4262 | 1593 | **2900** | 5252 |
| 682 | **1260** | 2300 | 988 | **1810** | 3290 | 1293 | **2360** | 4280 | 1599 | **2910** | 5270 |
| 688 | **1270** | 2318 | 993 | **1820** | 3308 | 1299 | **2370** | 4298 | 1604 | **2920** | 5288 |
| 693 | **1280** | 2336 | 999 | **1830** | 3326 | 1304 | **2380** | 4316 | 1610 | **2930** | 5306 |
| 699 | **1290** | 2354 | 1004 | **1840** | 3344 | 1310 | **2390** | 4334 | 1616 | **2940** | 5324 |
| 704 | **1300** | 2372 | 1010 | **1850** | 3362 | 1316 | **2400** | 4352 | 1621 | **2950** | 5342 |
| 710 | **1310** | 2390 | 1016 | **1860** | 3380 | 1321 | **2410** | 4370 | 1627 | **2960** | 5360 |
| 716 | **1320** | 2408 | 1021 | **1870** | 3398 | 1327 | **2420** | 4388 | 1632 | **2970** | 5278 |
| 721 | **1330** | 2426 | 1027 | **1880** | 3416 | 1332 | **2430** | 4406 | 1638 | **2980** | 5396 |
| 727 | **1340** | 2444 | 1032 | **1890** | 3434 | 1338 | **2440** | 4424 | 1643 | **2990** | 5414 |
| 732 | **1350** | 2462 | 1038 | **1900** | 3452 | 1343 | **2450** | 4442 | 1649 | **3000** | 5432 |

°C = 5/9 (F – 32) °F = 9/5 C + 32

# Index

## N



## P