

Chapter 16. Nondestructive Testing

Introduction to Nondestructive Testing

Nondestructive Testing (NDT) is a general term used in this text to identify all those inspection methods that permit evaluation of welds and related materials without destroying their usefulness. The majority of prospective weld inspectors already know that visual inspection certainly meets this criterion, but there are other NDT inspection methods. The purpose of this chapter is to acquaint the welding inspector with some of the more commonly used NDT methods and the fundamental conditions for their use.

The essential elements common to most all NDT methods include the following:

- (1) A source of probing energy
- (2) A test specimen that is appropriate for the energy source being used so that discontinuities may be detected
- (3) A detector capable of measuring the distributions or alterations in the probing energy
- (4) A technique for recording or displaying information received from the detector, suitable for evaluation
- (5) The operator must be trained to interpret detector feedback to evaluate probing results

Many forms of energy have been used in NDT methods; similarly, many properties of materials have been the fundamental basis for selecting a particular physical property or NDT technique. For purposes of this text only the

following basic NDT methods will be discussed:

- (1) Visual inspection
- (2) Radiography
- (3) Ultrasonic examination
- (4) Magnetic particle testing
- (5) Penetrant testing
- (6) Eddy current testing
- (7) Acoustic emission testing
- (8) Ferrite determination

Nondestructive testing 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 tests and that each test method may provide support for the other. It is not uncommon for the acceptance-rejection criteria of an NDT method to be developed by destructive test investigations correlated with NDT results. It is not within the scope of this chapter to offer comparative advantages between specific NDT methods, nor to present a full handbook of information on the numerous NDT techniques. Table 16.1 contains a brief summary of typical considerations generally used in selecting an NDT 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 NDT procedures and the highlights of those requirements that complement the decision to establish written procedures.

Inspection by Visual Testing

For many types of welds, integrity is verified principally by visual inspection. Even for weldments with joints specified for testing throughout by nondestructive test methods, visual

inspection still constitutes an important part of practical quality control. Therefore, visual inspection is of the first order of importance.

The most extensively used of any method of

Table 16.1

Visual			
Equipment Needs	Applications	Advantages	Limitations
Magnifiers, color enhancement, projectors, other measurement equipment, i.e., rulers, micrometers, optical comparators, light source.	Welds which have defects on the surface.	Economical, expedient, requires relatively little training 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)			
Equipment Needs	Applications	Advantages	Limitations
Gamma ray sources, gamma ray camera projectors, film holders, films, lead screens, film processing equipment, film viewers, exposure facilities, radiation monitoring equipment.	Most weld discontinuities including cracks, porosity, lack of fusion, incomplete penetration, slag, as well as corrosion and fit-up defects, wall thickness, dimensional evaluations.	Permanent record—enables review by parties at a later date. Gamma sources may be positioned inside of accessible objects, i.e., pipes, etc., for unusual technique radiographs. Energy efficient source requires no electrical energy for production of gamma rays.	Radiation is a safety hazard—requires special 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 must be periodically replaced. Gamma sources have a constant energy of output (wavelength) and cannot be adjusted. Gamma source and related licensing requirements are expensive. Radiography requires highly skilled operating and interpretive personnel.

Table 16.1 (Cont'd)

Radiography
(X-Rays)

Equipment Needs	Applications	Advantages	Limitations
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.

Ultrasonic

Equipment Needs	Applications	Advantages	Limitations
Pulse-echo instrument capable of exciting a piezoelectric material and generating ultrasonic energy within a test piece, and a suitable cathode ray tube scope capable of displaying the magnitudes of received sound energy. Calibration standards, liquid couplant.	Most weld discontinuities including cracks, slag, lack of fusion, lack of bond, thickness. Poisson's ratio may be obtained by determining the modulus of elasticity.	Most sensitive to planar type defects. Test results known immediately. Portable. Most ultrasonic flaw detectors do not require an electrical power outlet. High penetration capability.	Surface condition must 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.

Table 16.1 (Cont'd)

Magnetic Particle			
Equipment Needs	Applications	Advantages	Limitations
Prods, yokes, coils suitable for inducing magnetism into the test piece. Power source (electrical). Magnetic powders, some applications require special facilities and ultraviolet lights.	Most weld discontinuities open to the surface—some large voids slightly subsurface. Most suitable for cracks.	Relatively economical and expedient. Inspection equipment is considered portable. Unlike dye penetrants, magnetic particle can detect some near surface discontinuities.	Must be applied to ferro-magnetic materials. Parts must 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.
Liquid Penetrant			
Equipment Needs	Applications	Advantages	Limitations
Fluorescent or dye penetrant, developers, cleaners (solvents, emulsifiers, etc.). Suitable cleaning gear. Ultraviolet light source if fluorescent dye is used.	Weld discontinuities open to surface, i.e., cracks, porosity, seams.	May be used on all non-porous 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 must be cleaned before and after inspection.
Eddy Current			
Equipment Needs	Applications	Advantages	Limitations
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 open to the surface (i.e., cracks, porosity, fusion) as well as some subsurface inclusions. Alloy content, heat treatment variations, wall thickness.	Relatively expedient, low cost. Automation possible for symmetrical parts. No couplant required. Probe does not have to be in intimate contact with test piece.	Limited to conductive materials. Shallow depth of penetration. Some indications may be masked by part geometry due to sensitivity variations. Reference standard required.

Table 16.1 (Cont'd)

Acoustic Emission			
Equipment Needs	Applications	Advantages	Limitations
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.	Real time and continuous surveillance inspection. May be inspected remotely. Portability of inspection apparatus.	Requires the use of transducers coupled on the test part surface. Part must be in "use" or stressed. More ductile materials yield low amplitude emissions. Noise must be filtered out of the inspection system.
Leak Test			
Equipment Needs	Applications	Advantages	Limitations
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 thru 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.

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nondestructive testing, visual inspection is easy to apply, quick, relatively inexpensive, requires no special equipment other than good eyesight, and gives very important information with regard to the general conformity of the weldment to specifications.

For convenience of presentation, visual inspection is discussed under five main headings: visual inspection practice, inspection prior to welding, inspection during welding, inspection after welding, and marking repair welds.

Practices

The inspector should be familiar with the applicable documents, workmanship standards, and all phases of good shop practice. The weld should be well lighted; an extension lamp or flashlight may be needed. Inaccessible areas can be viewed with a borescope, and, when so required by a customer, a low power magnifier can be used. A low power magnifier must 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 gages are used for checking 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.

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 in 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, edge preparation, and other features of joint preparation that might affect the quality of the welded joint, taking into account structural tolerances. The inspector should check the following conditions for conformity to the appli-

cable 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

During Welding

Visual inspection checks details of the work while fabrication is in progress, such as:

- (1) Welding process and conditions
- (2) Filler metal
- (3) Flux or shielding gas
- (4) Preheat and interpass temperature
- (5) Distortion control
- (6) Interpass chipping, grinding, or gouging
- (7) Inspection intervals

The inspector should be thoroughly familiar with all of 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.

Inspection of successive layers of the weld deposit is sometimes carried out with the assistance of a workmanship standard. Figure 16.1 indicates how such a standard may be prepared. This is a section of a joint similar to the one in manufacture, in which portions of successive weld layers are shown. Each layer of the production weld may be compared with corresponding layers of the workmanship standard. One must realize that this workmanship sample can cover ideal conditions and may not truly represent actual job conditions; allowances must be made for production tolerances.

The first layer, or root pass, is the most important one from the point of view of final 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

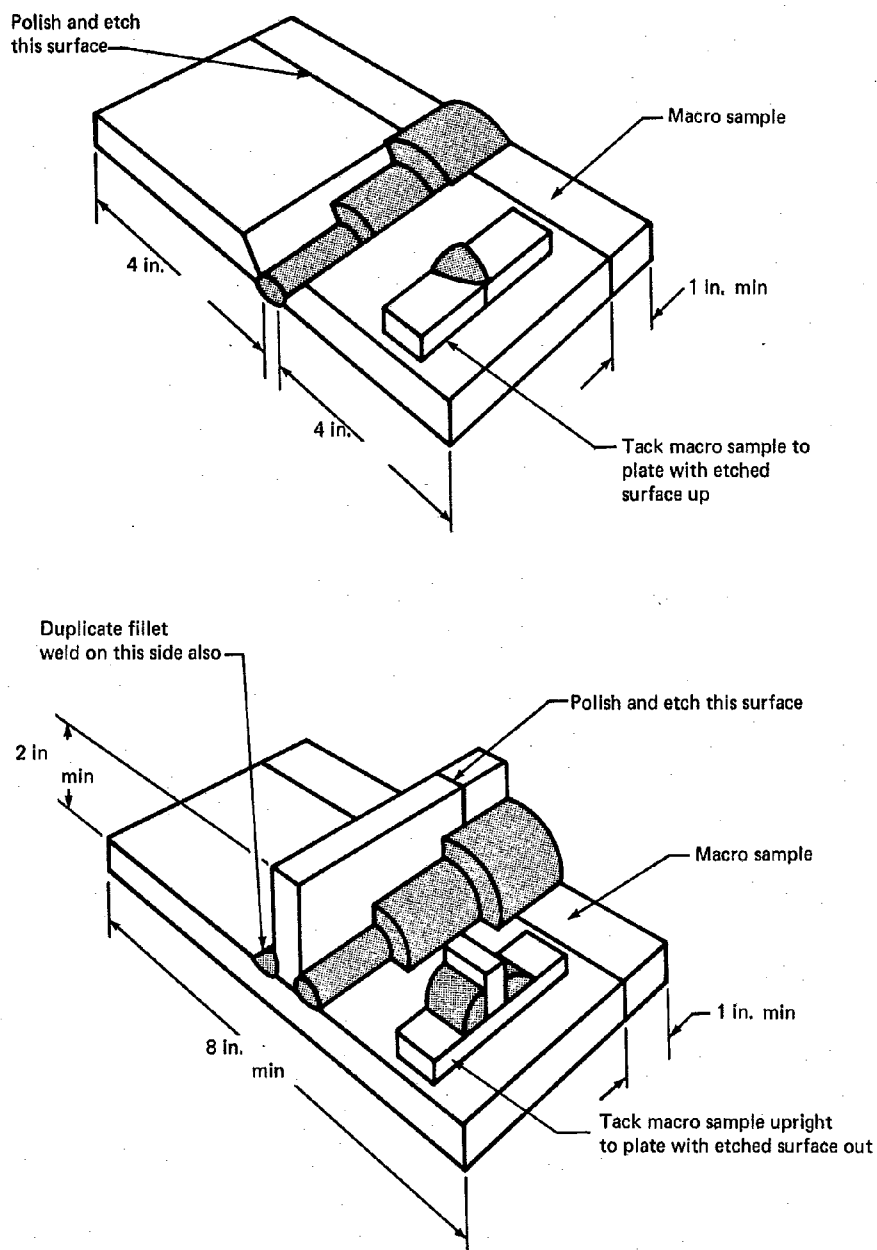


Fig. 16.1—Sample of workmanship standard, illustrating suitable standards for groove welds (top) and fillet welds (bottom)

during this pass is particularly susceptible to cracking. Such cracks may not only remain, but may extend to subsequent layers. Inspection of this pass should be thorough, and a workmanship standard is very useful in this connection. As will be shown later in this section, nondestructive tests may give evidence as to conditions in the root pass, and thus serve as a check on visual inspection.

This inspection of the root pass offers another opportunity to inspect for plate laminations, since these tend to open up because of the effects of heat incident to the welding operation. In the case of double-groove welds, slag from the root pass on one side of the plate may form slag deposits on the other side. 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.)

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)
- (3) Acceptability of welds with regard to appearance (including such items as surface roughness, weld spatter, etc.)
- (4) The presence of unfilled craters, pock marks, undercuts, overlaps, and cracks
- (5) Evidence of mishandling from center

punch or other inspection markings or excessive grinding

- (6) Postweld heat treatment time and temperature

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 a weld gage. 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 gage will determine whether the size is within allowable limits and whether there is excessive concavity or convexity.

Special gages may be made for use where the surfaces are at acute or obtuse angles. An additional measuring gage is also known as the Shenefelt gage.

For groove welds, the width of finished welds will fluctuate in accordance with the required groove angle, root face, root opening, and permissible tolerances. The height of reinforcement should be consistent with specified requirements. Where not specified, the inspector may have to rely on his judgment, guided by what he considers good welding practice. 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 control, 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, a few examples are:

- (1) Cracks
- (2) Undercut
- (3) Overlap
- (4) Excessive weld irregularity
- (5) Dimensional inaccuracies

For accurate detection of such defects, the weld surface should be thoroughly cleaned of

oxide and slag. The cleaning operation must be carried out carefully. For example, if a chipping hammer is used to remove slag, the hammer marks could mask fine cracks. Shot blasting and wire brushing maypeen the surface of relatively soft materials and thus hide possible defects.

Marking Repair Welds

One of the most important details of nondestructive inspection is the proper marking of the areas to be repaired. The 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 so 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
- (6) Removed if not acceptable to service conditions

The repair should be inspected and the inspector must be able to find the markings; there-

fore, the marking medium must 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.

Summary

Visual examination, as indicated above, is invaluable as an inspection method; however, some caution must 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 alone does not prove careful workmanship and is not a reliable indication of subsurface condition. Thus, judgment of weld quality must 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. For instance, if the inspector knows that the plate was free of laminations, that the edge preparation was correct, that root opening was as specified, that the root pass was sound, and that the qualified welding procedure was followed carefully, he may be reasonably safe in judging the completed weld on the basis of visual examination.

Inspection by Radiographic Testing

Radiography is a method of nondestructive testing 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 penetrating radiation is exposed to an object to be examined (see Fig. 16.2), some radiation will be absorbed, some will be scattered, and some radiation will be transmitted through the test object onto the recording device. Radiation (either short wavelength electromagnetic or particulate 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 inspections 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 can be presented in this text. Many excellent sources of reference materials are available to the welding inspector, containing detailed and specific technique con-

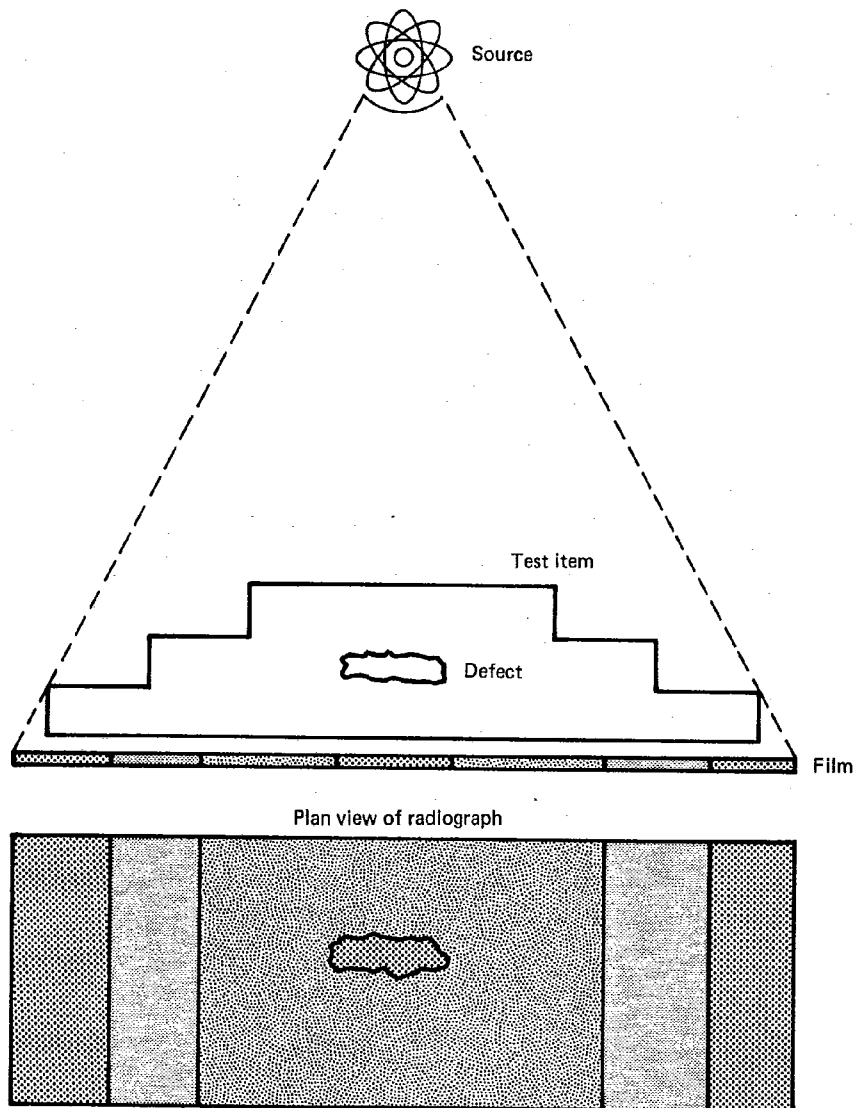


Fig. 16.2—Typical "shadow graph"

siderations, terms and definitions in general use, as well as advanced and highly specialized aspects of the various attributes of the complete radiographic inspection process. Some of these sources are listed at the end of this article and are highly recommended.

Essential Elements

The basic process of radiographic inspection involves (1) the making of the radiograph, and (2) the interpretation of the radiograph. The essential elements needed to carry out these two operations consist of:

- (1) A source of radiation (usually gamma or x-rays)
- (2) An object to be radiographed (weldment)
- (3) An x-ray film enclosed in a lightproof film holder
- (4) A trained person capable of producing an exposure in the most advantageous manner
- (5) A means of chemically processing the exposed film
- (6) A skilled person capable of interpreting the radiographic images

The following is a brief discussion about each of these six essential elements of the radiographic inspection process.

The Source: The illustration shown in Fig. 16.2 details the basic essentials in the making of a radiograph. The heart of radiography is the source of radiation exposure. Radiation, electromagnetic radiant energy with penetrating properties related to its energy potential or wavelength, is unique in that it cannot be detected by any of mankind's natural senses. More important to the radiographic process is radiation's unique ability to ionize elements. The two types of radiation sources most commonly used in weld inspection are x-ray machines and radioactive isotopes. These sources of radiation have extremely short wavelengths (about 1/10,000th of the wavelength or less than that of visible light) that enable them to penetrate materials that absorb or reflect light. X-rays are produced by machines; gamma rays are emitted from the disintegrating nuclei of radioactive substances. Although the wavelength of radiation produced can be quite different, both x- and gamma radiations 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. 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. It should be noted that each source of radiation has advantages and limitations and the welding inspector should familiarize himself 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 related to its image quality producing aspects, 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 aspects will be detailed later in this section. The welding inspector should further note that all radiation producing sources are hazardous and special precautionary measures should be taken when entering or approaching a radiographic area. This will also be discussed later in this section.

The Test Object: The test object is an essential of the radiographic process for rather obvious reasons; however, we should understand some basics about radiation interaction with the test object in order to fully appreciate the resultant film image. As was illustrated in Fig. 16.2, 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 will it penetrate thicker or more dense materials. It is important to remember these two variables, for it is the differences in absorption occurring during the exposure process that account 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.

The Film and Film Holder: Film is a major 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 his work will depend upon his 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 and some have both sides of the base coated with a layer, approximately 0.001 in. (0.02 mm) thick, of this gelatin mixture (emulsion). The film emulsion is not only sensitive to x- and gamma radiation but is also very 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 and the film never "sees" light until the development processing is completed. Films will be discussed in more detail later in this section.

A Trained Person to Make the Exposure:

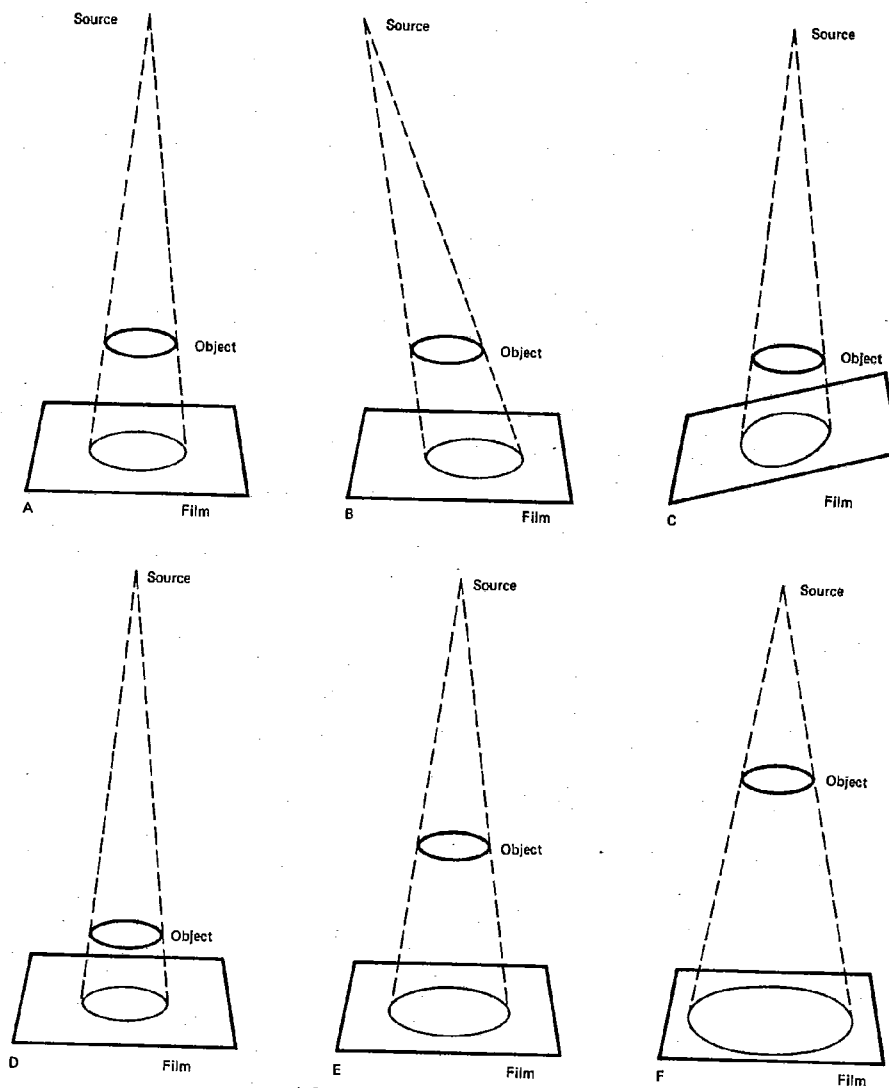
In addition to the basic "material" components

of the radiographic process, the production of successful radiographs is highly dependent upon a trained person capable of making reliable exposures—safely. Earlier, radiography was related to photography, noting that there are some similarities between the two processes. Figure 16.3 shows some of the basic geometric principles of "shadow formation" or image projection common to most all image recording processes. Figure 16.4 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. Usually 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 perpendicularly to the film plane. This will minimize distortion of the specimen image and of flaws within the image.
- (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. Many decisions must be made by the radiographer as to tradeoffs and compromising of exposure variables. Through judgment and experience, the radiographer must develop a "feel" for the geometry of his exposure technique. Arrangement of the position of the radiation source, the specimen, and the film relative to each other will determine the geometric projections and "sharpness" of the radiographic images. Good 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 radi-



A, B, and C show principles of shadow projection.
D, E, and F show principles of shadow enlargement.

Fig. 16.3—Geometric principles of shadow formation; A through C illustrating principles of shadow projection; D through F illustrating principles of shadow enlargement

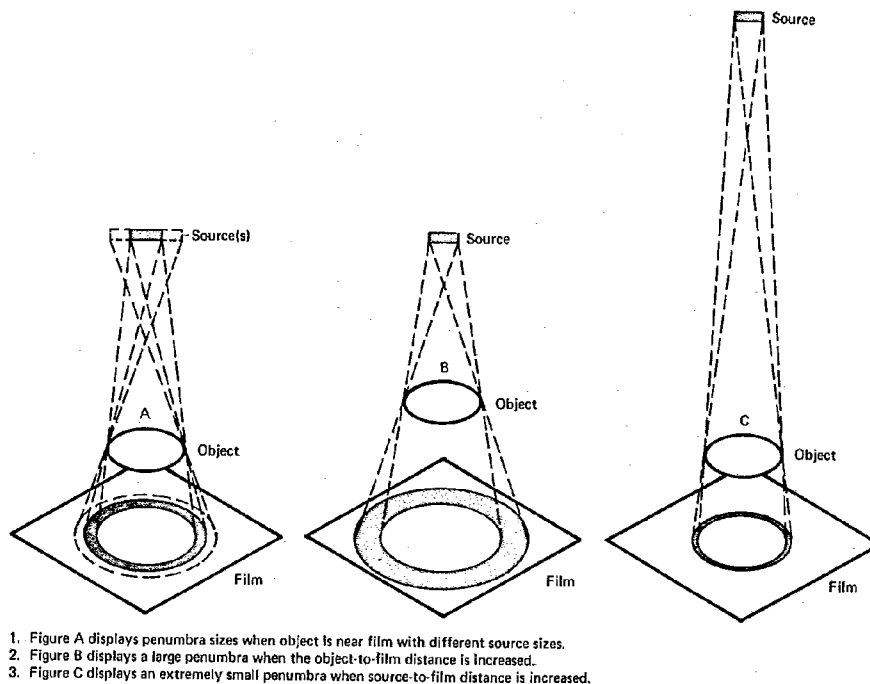


Fig. 16.4—The penumbral shadow

ographer must be capable of selecting the proper film, intensifying screens, filters, and materials to reduce radiation scatter.

It was mentioned earlier that radiation sources can be hazardous and that special precautions must be taken while working with radiation. The radiographer or qualified person making the exposure must 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 certain 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 dose is received by anyone. The welding inspector should be aware of the possibly harmful effects of radiation should he on occasion go into an area where he may be exposed to it.

It should also be mentioned that most fabrication specifications and codes in use today in this country require that personnel engaged in nondestructive testing activities, including radiographic personnel, be certified as to their abilities and levels of technical competence. The American Society for Nondestructive Testing (Ref. 16.9) 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 must obtain minimum levels of education, training, and experience prior to

passing an examination. The welding inspector should assure himself that all necessary requirements have been satisfactorily met.

Processing the Film: The radiographic process is only partially completed once the exposure has been made, the chemical processing of the film being 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 invisible image (produced in the 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 subdued 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 stage 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 the film has received. The second stage is either a water rinse or an acid stop bath to reduce or stop the developing action on the film. The third stage 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 stand drying temperatures. The fourth stage is a water wash bath to remove the fixer and products of the fixing action from the film emulsion. The fifth stage is immersion in a wetting solution (soap) that allows the water to run off the surface of the film. The sixth and final stage is drying.

Radiographic processing techniques are usually automatic or manual (hand tanks and racks). Automatic processing cycles usually do not involve a stop bath or a specific cleaning stage. 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."

A Skilled Person to Interpret the Radiograph: The final essential element of the radiographic inspection process involves evaluation of the finished radiograph and a subsequent disposition of the test object under examination. Evaluation of the finished radiograph is usually called "film interpretation" and the person performing the interpretation is a "film interpreter."

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 he found any kind or amount of discontinuity. 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 under his examination.

The basic essentials of film interpretation are discussed in some detail later in this section. The degree of skill required of a film interpreter is obtained through long experience or extensive training or combinations of both. Sound interpretation requires a wide 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 stepped workmanship samples. Secondly, it is essential that the interpreter be knowledgeable about the types of discontinuities likely to be encountered in a particular welding process and the manner in which their shadow is likely to

vary with the angle at which they are projected onto the film by the radiation beam. Needless to say, the interpreter must possess a basic 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.

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.

Radiographic Image Quality: The radio-

graphic image must 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 Fig. 16.5) and will be briefly discussed.

Radiographic Contrast. In the radiograph of Fig. 16.2, the various intensities of radiation transmitted by the test object are rendered as different film densities in the resultant image. The difference in film density from one area to another contributes "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 additional contrast components of the radiographic system; i.e., subject contrast and

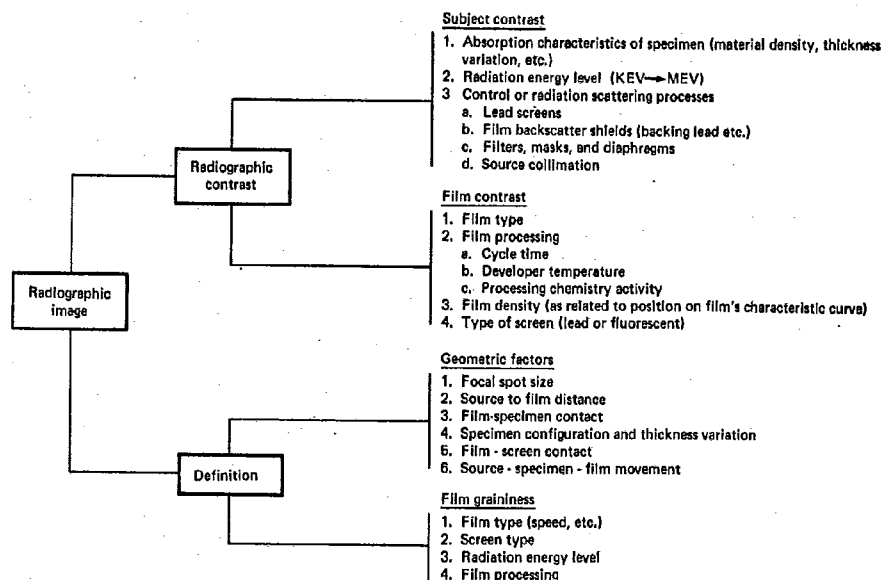


Fig. 16.5—Factors affecting quality of radiographic image

film contrast.

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 reduction would have a very low subject contrast. Conversely, a test object with a large thickness reduction would yield a large difference in absorbed radiation and would, therefore, have a high subject contrast. A given test object with a given thickness reduction (such as Fig. 16.2) 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 16.6 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) 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 object under exposure. Figure 16.6A 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) are commonly employed as filters and are positioned between the test object and the film to absorb the, "softer," less penetrating scattered radiation prior to its reaching the film. 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 16.6B 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. These reflected radiations, then, cause a decrease in the fundamental image contrast ratio in much the same way as internal scattered radiation. Common industrial methods used to control this type of scattering in-

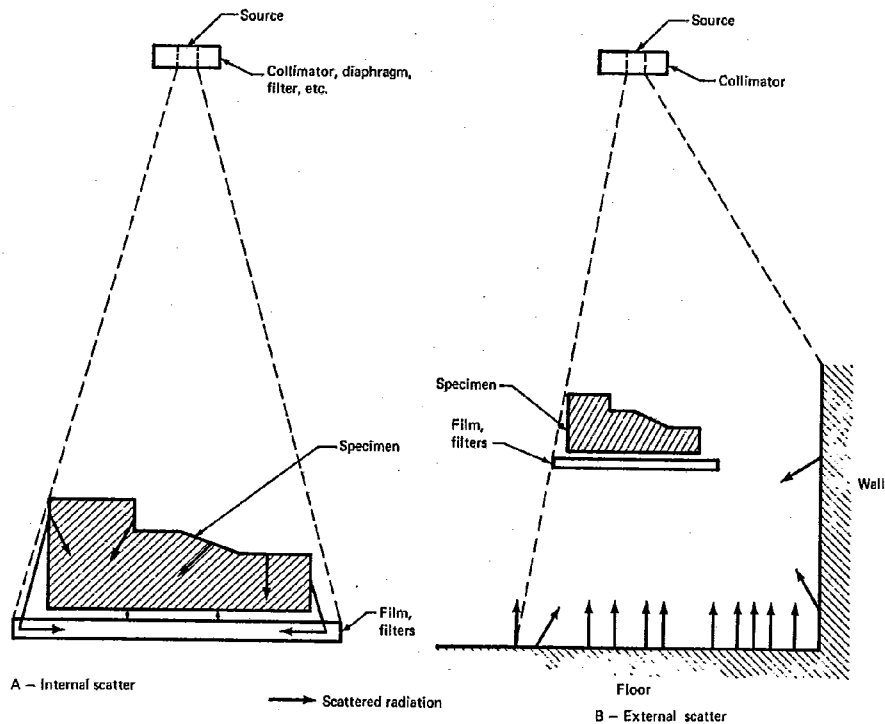


Fig. 16.6—Sources of scattered radiation

clude the use of heavy (0.01 to 0.02 in. [0.2 to 0.5 mm]) lead screens between the film and the floor; 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 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.

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 16.7 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

*H&D curve, named for Hurter and Driffield, the men who devised the characteristic curve.



exposure. The exposure 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:

$$(1) R = I \times t$$

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; (2) on a logarithmic scale, a change in exposure (a radiation or exposure difference, ΔR) has a constant spread throughout the scale, whereas the same ΔR 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:

$$(2) D = \log_{10} \frac{I_0}{I_t}$$

where: D = film density

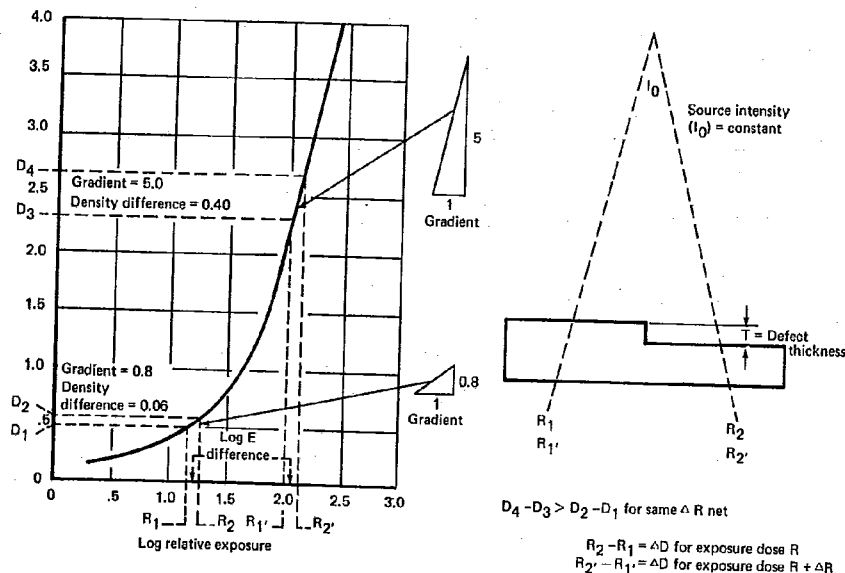
I_0 = intensity of light incident on film

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:

$$D = \log_{10} \frac{10 \text{ units}}{1 \text{ unit}} = 1.0 \text{ H\&D density}$$

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 influ-



The specimen above illustrates a typical defect in terms of a thickness reduction, (T). $R_2 - R_1$ = the dosage 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.

Fig. 16.7—Characteristic curve for a typical industrial x-ray film

enced by the degree of development and the type of intensification screens used. Intensification screens are sheets of thin 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.

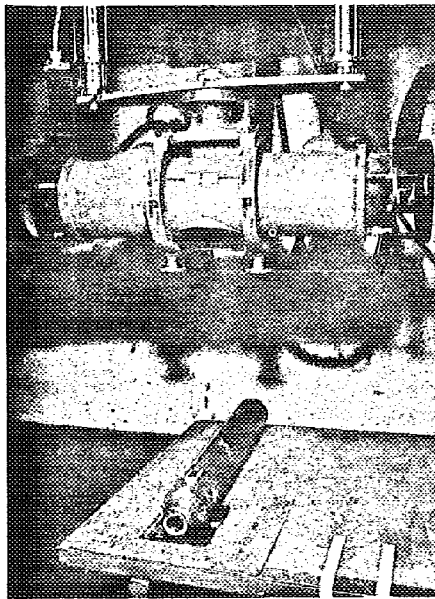
Film contrast (i.e., the difference in film densities resulting from the same percentage change in radiation exposure) then is affected by (1) the shape or slope of the characteristic curve and (2) the film density level of the radiograph. For a better understanding of the fundamentals, refer to the curve shown in Fig. 16.7. 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, ΔR or ($R_2 - R_1$), could arise from different equivalent thicknesses in the exposed specimen, caused by perhaps a defect. The same dosage difference ($R_2 - R_1$) at various positions along the slope of the characteristic curve produces different amounts of film contrast, ΔD or ($D_2 - D_1$). The degree of film contrast (ΔD) 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.

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 Fig. 16.5).

Exposure Geometry: The sharpness aspect of the exposure geometry, illustrated in Fig. 16.4, 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. (13 mm) diameter. X-ray focal spot sizes vary from several mm² (generally 6 to 8) down to a fraction of a square millimeter. However, as may be seen in Fig. 16.4, 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 Fig. 16.4. The variables governing the penumbral shadow or "geometric unsharpness" may be mathematically related as follows:



A typical x-ray machine and exposure setup. The radiographic technique illustrated is similar to Fig. 16.11(B). Note positioning of penetrometer beside the weld and film holder between the pipe and backing lead.

A skilled radiographer is evaluating exposure conditions between a casting and the "end" of the radioactive source tube. Note that the end of the source tube is contained in a square lead collimator device (under his right hand) and that the exposure device (in the square shielded container in the background) is positioned for remote operation.

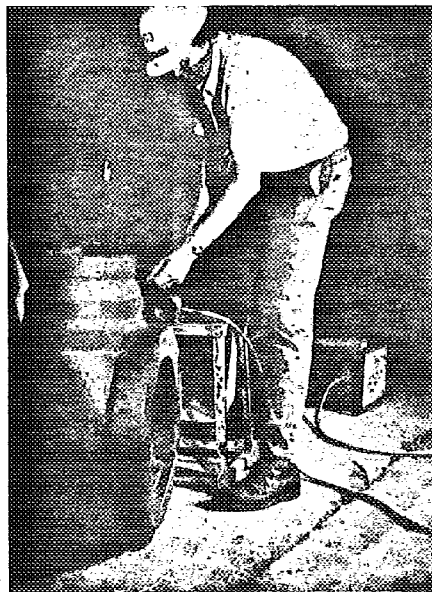


Fig. 16.8—Radiographing a circumferential pipe weld

$$(3) U_g = \frac{FT}{D}$$

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.

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; (2) electron impingement onto the film from the intensifying screen could exaggerate the size of the image, reducing the sharpness.

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. As a rule of thumb, there are four factors that will determine the degree of graininess on a finished radiograph:

- (1) The type and speed of film
- (2) The type of screens used
- (3) The energy of radiation used
- (4) The 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.

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. 16.5).

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 Fig. 16.5), some assurance is needed that adequate radiographic technique has been achieved. The tool used by the radiographer to demonstrate technique is the image quality indicator (IQI) or penetrameter. Figure 16.9 shows images of typical conventional penetrameters used extensively in this country. Other design types used abroad are available. Conventional penetrameters (ASTM, Armed Forces) consist of a strip of material of simple geometric shape that has absorption characteristics similar to the weld metal under investigation (see Fig. 16.10). 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 2 percent of the weld thickness is generally selected. A lead identification number at one end of the plaque 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

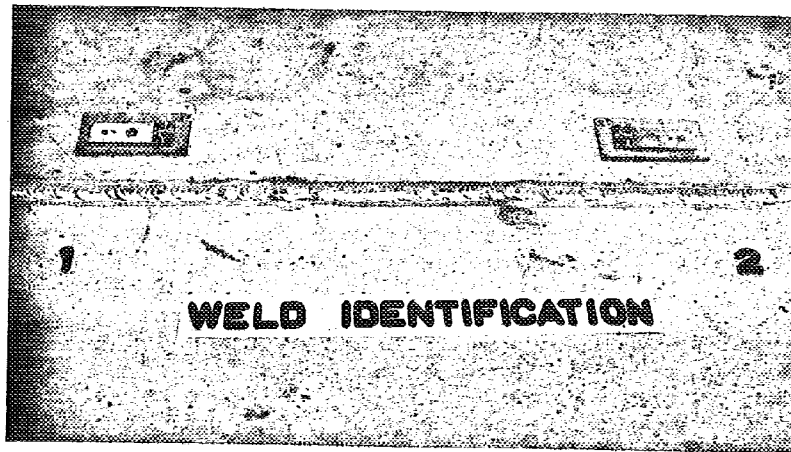


Fig. 16.9—The “tools of the trade” for the radiographer

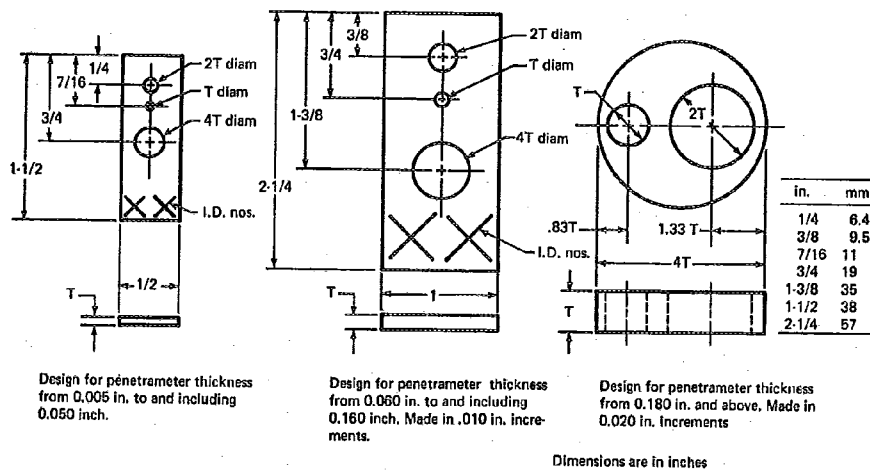


Fig. 16.10—Typical penetrometer design



plaque thickness. As may be seen in Fig. 16.10, 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 material into a minimum of five absorption categories, ranging from lighter metals (Group I) to heavy metals (Group V). The specimen to be examined must have its penetrameter made from the same grouping as the specimen material.

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 16.9 also illustrates typical placement relationship of penetrameter and weldment. 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 pipe is inaccessible from the inside. In this case, a special penetrameter may be located on the "film side" of the weldment. Most specifications and codes will specify special circum-

stances or conditions when such a penetrameter may be used and will also stipulate how the film side penetrameter size shall be selected.

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 gage 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.

Exposure Techniques

In determining the most proficient arrangement of the essentials needed to make a radiograph, a radiographer must select the best locations for positioning of the radiation source and film in conjunction with the test object. The following are typical factors that must be considered:

- (1) Which arrangement will provide optimization of image quality and weldment 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 Fig. 16.11F) type of exposure be used?
- (5) Which arrangement will require the least amount of exposure duration?
- (6) Can the exposure be made safely?

Figure 16.11 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

*Used mostly on weld repairs in castings or on some pipe circumferential weldments (Ref. 16.6).

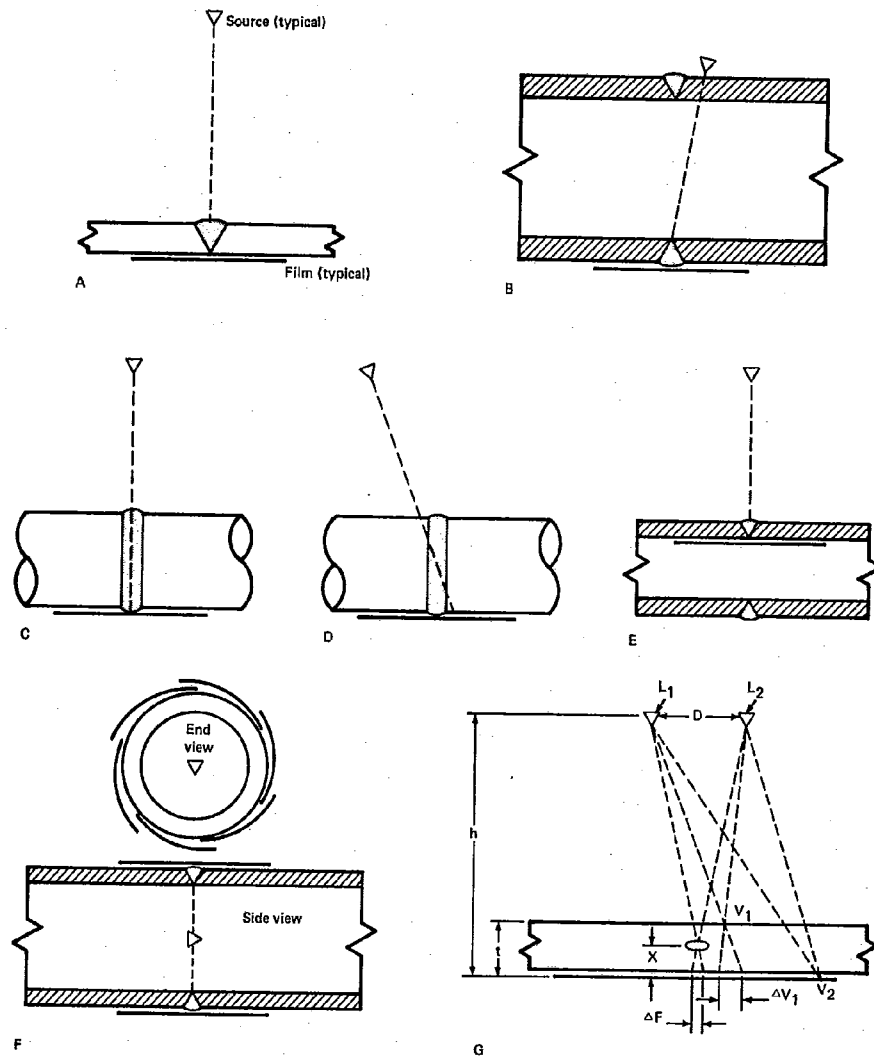


Fig. 16.11—Typical radiographic exposure arrangements

good radiography can be easily applied; i.e., good exposure geometry and proper positioning of radiographic tools for the most practical set-up.

Figures 16.11 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 the entire circumferential weldment with one exposure straight through both walls as shown in view C. Unfortunately, in this case the image of both walls would be projected 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 his 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 (Fig. 16.11 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); (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 first wall (closest to the

source) is treated as if it were not there (source is usually offset). Sufficient numbers of exposures must be made to ensure complete weld coverage without the benefit of 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.

Exposure arrangement G will 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 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, ΔF and ΔV_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:

$$X = \frac{h\Delta F}{d + \Delta F}$$

where: X = distance of flaw above film
 h = focus-to-film distance
 ΔF = change in position of flaw image
 d = distance source has shifted from L_1 to L_2 (see Fig. 16.11G)

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 ample 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.

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 harmful 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.

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 particular 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.

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 a pre-processed film results in typical "pressure 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 or do not function properly. Further data on film processing may be obtained from reference to processing literature published by film 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.

"Pitfalls" in Interpretation: As a general rule radiographs fall into one of three evaluation categories: (1) unquestionably acceptable; (2) clearly rejectable; (3) borderline. There will be many borderline cases in radiographic interpretation. This category arises from honest dif-

ferences 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 this discontinuity is similar to an inclusion in nature and in appearance on the radiograph. Generally, the two are indistinguishable with total certainty. The inspector must decide whether the radiograph indicates a rejectable lack of fusion or an acceptable conclusion.

The inspector may be called upon to judge repair welds in castings or assembly welds of cast items. Here, he 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 would be acceptable; yet, if interpreted as a weld discontinuity, it would 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.

Radiographic Acceptance Standards in Specifications, Codes, and 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:

- The Armed Forces (military standards)
- American Welding Society
- American Society of Mechanical Engineers
- American Society for Testing and Materials
- American Petroleum Institute
- Ship Structure Committee

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 specifications and codes will sometimes refer to an alternate standard or practice and will adopt such criteria as requirements for complying with their own requirements.

Coverage Requirements: Specifications and codes will specify what sections or components of an assembly will require radiographic inspection. In addition, they will usually state conditions under 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 inspection after a defect has been located. Some specifications and codes provide options for using a different NDT 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.

Acceptance Criteria: An essential of most specifications or codes is the specification of the particular acceptance criteria to be used for film interpretation. 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 one will be used. It is beyond the scope of this section to discuss acceptance criteria in minute detail, as there are many different applications and rules; however, the welding inspector should familiarize himself with the particular specification or code with which he is working and be able to evaluate workmanship on its own merit.

Procedure Approvals: Some specifications and codes require qualification of radiographic techniques and procedures. Usually, the major emphasis is on the ability of the NDT method (radiography) to detect discontinuities that are of concern to the product service. Such a quali-

fication for radiography usually involves radiographing a test object with known defects, using those technique essentials contained in the basic specification or code. If these qualification radiographs are judged capable of rendering a meaningful examination of the said test object, that technique is said to be qualified or to have a "demonstrated proficiency." Qualifications of radiographic techniques are an added assurance feature of the capabilities of radiographic techniques, since most techniques will require a penetrameter indicator showing a specified level of image quality.

Radiographs of Weld Discontinuities

Generally, defects in welds consist either of a void in the weld metal itself or an inclusion that differs in density from surrounding weld metal. Radiographs may show both internal discontinuities as well as surface discontinuities (see Chapter 9). Figure 16.12 provides some photographs of some typical weldments and related radiographic images of discontinuities.

Radiography: Advantages and Limitations

Advantages: Since radiography operates on principles of radiation absorption, it is noteworthy that some of the physical dilemmas that affect other NDT methods pose little or no significant problems for radiography. Irregularities in metallic grain structure size do not cause grave concern. Radiography is not restricted to ferrous materials—or any other one type of material. Since radiation is penetrating, radiography is good for both 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 exposures may yield valid indications. Another advantage is that a permanent film 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.

Limitations: Certainly, a major limitation is the hazard of radiation exposure to the radiographer and nearby personnel. In certain industries, radiographic inspection can be disruptive. Radiography usually requires special facilities or areas where radiation may be exposed in a controlled manner without endangering other personnel.

Radiography can detect cracks that are aligned parallel with the radiation beam; such cracks are usually normal to the plane surfaces. However, radiography usually cannot detect laminations in the plate. Other NDT 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. Crack orientation, then, is a major consideration when specifying radiography as an inspection 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 radiographic inspection is another limitation. A typical 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 inspection disposition is rendered. Many other NDT methods reveal more "on-the-spot" results, without such time delays.

Other possible limitations include the need for accessibility to both 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. Very seldom does one individual perform all aspects of the inspection process.

Much 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.

Table 16.2
Radiographic Isotopes used in industrial radiography

Isotope	Half-Life	Energy Levels MEV	Approximate Mean Effective Energy Level—MEV	Characteristic Intensity- Roentgens per hour per curie at 1 meter
Cobalt-60	5.3 years	1.17 & 1.33	1.2	1.35
Cesium-137	33 years	0.66	0.66	0.39
Iridium-192	75 days	0.137 to 0.651	0.38	0.55

Table 16.3
**Approximate radiographic equivalence factors
of several metals**

METAL	X-rays							Gamma Rays			
	50 kv	100 kv	150 kv	220 kv	400 kv	1000 kv	2000 kv	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.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
18-8 (steel) alloy		12.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Copper		18.	1.6	1.4	1.4				1.1	1.1	1.1
Zinc			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			14.	12.		5.0	2.5		4.0	3.2	2.3

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.



Slag inclusions are usually indicated by elongated shadows of irregular shape, occurring singly, in a linear distribution, or scattered randomly.



Undercutting shows up as a dark, linear shadow of wavy contour, occurring adjacent to the edge of the weld. This defect is usually detected visually, but its correct identification on the radiograph is needed to prevent misinterpretation as another type of discontinuity.



Porosity is shown as rounded shadows of varying size and density, occurring singly, in clusters, or randomly scattered.



Incomplete penetration is usually indicated as a straight, dark, continuous or intermittent line near the center of the weld.



Cracks usually appear as fine, dark lines which may be straight or wandering.



Burn-thru gives individual light circular indications or darkened areas of elongated or rounded contour that may be surrounded by light rings.

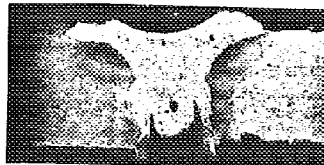


Fig. 16.12—Typical radiographs of weld discontinuities



Ultrasonic Testing of Welds and Weld Related Materials

General Principle

Ultrasonic testing 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 beam into the test material on a predictable path, which, upon reflecting back from an interruption in material continuity, produces a wave that is amplified and usually displayed as a vertical displacement on a cathode ray tube (CRT).

The detection, location, and evaluation of material discontinuities become 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.

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 Fig. 16.13). The pulse-echo equipment produces repeated bursts of high frequency sound with a rest time interval between bursts to allow for return signals from sound reflectors. The time rate between bursts, called the pulse rate, usually occurs at about 500 pulses per second, depending upon 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 side 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 both horizontal and vertical directions to facilitate measurement of pulse displays.

The horizontal time interval (sweep length) is adjustable with a control knob, making it possible to translate the reflected 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 beam might be directed into material, a search unit must be used. The search unit consists of some kind of holder and a transducer. The transducer element is usually a piezoelectric crystalline substance. When excited with the 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 physical 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 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 location 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.

Sound Behavior

The behavior of ultrahigh frequency sound resembles that of visible light in the following ways:

- (1) The sound beam divergence can be controlled by focusing.
- (2) The sound beam will reflect predictably from surfaces of different densities.
- (3) The sound beam will refract at an interface between materials of different density.

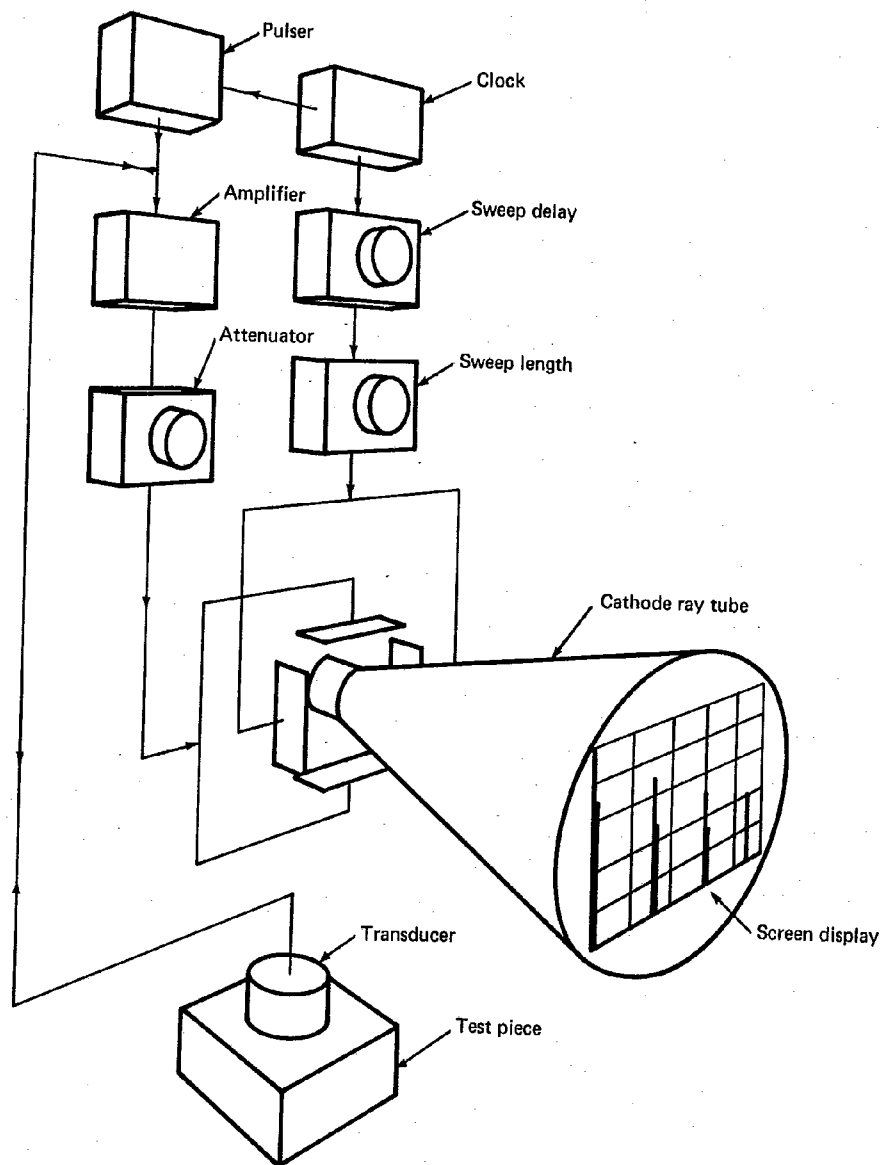


Fig. 16.13—Block diagram, pulse-echo flaw detector

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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 beam to the initial surface.

Unlike audible sound, ultrahigh frequency sound is very highly 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 interface, using a hydraulic couplant.

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 overlaid 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 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 attenuation amplitude losses, but may disturb the linearity of the vertical scale, especially when used in conjunction with decibel amplitude readings.

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:

$$D_N = 20 \log_{10} \frac{V_1}{V_2}$$

Where D_N = decibel difference; V_1 = voltage one; and V_2 = voltage two. Screen percentages can be substituted for voltages in the equation. The nomograph shown on Fig. 16.14 is a graphical solution to the equation.

By connecting the first screen percent or voltage (V_1) on the A scale to its decibel rating D_1 on the C scale with a straight line, and pivoting another straight line through the first line intersection with the B scale to either the second screen percent or voltage V_2 , or the second decibel rating (D_2), the unknown value on either the A or C scale can be found.

Example: Given $V_1 = 67$ volts, $V_2 = 80$ volts, and Gain $D_1 = 6$ decibels. Connect 67 on the A scale with 6 on the gain designation of the C scale. This line will cross the B scale at some point, such as B_1 . Now connect 80 on the A scale and B_1 with another straight line. This line will pass through 7.5 decibel gain on the C scale, which is the resultant decibel value.

Ultrasound Attenuation and Wave Form

Ultrasound attenuation is a combination of sound loss due to the inverse square law of amplitude-to-distance ratios, in addition to losses due to dispersion of sound from grain boundaries and impurity inclusions in materials.

Ultrasound 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 ultrasound is introduced into the test medium in a direction normal to the inter-

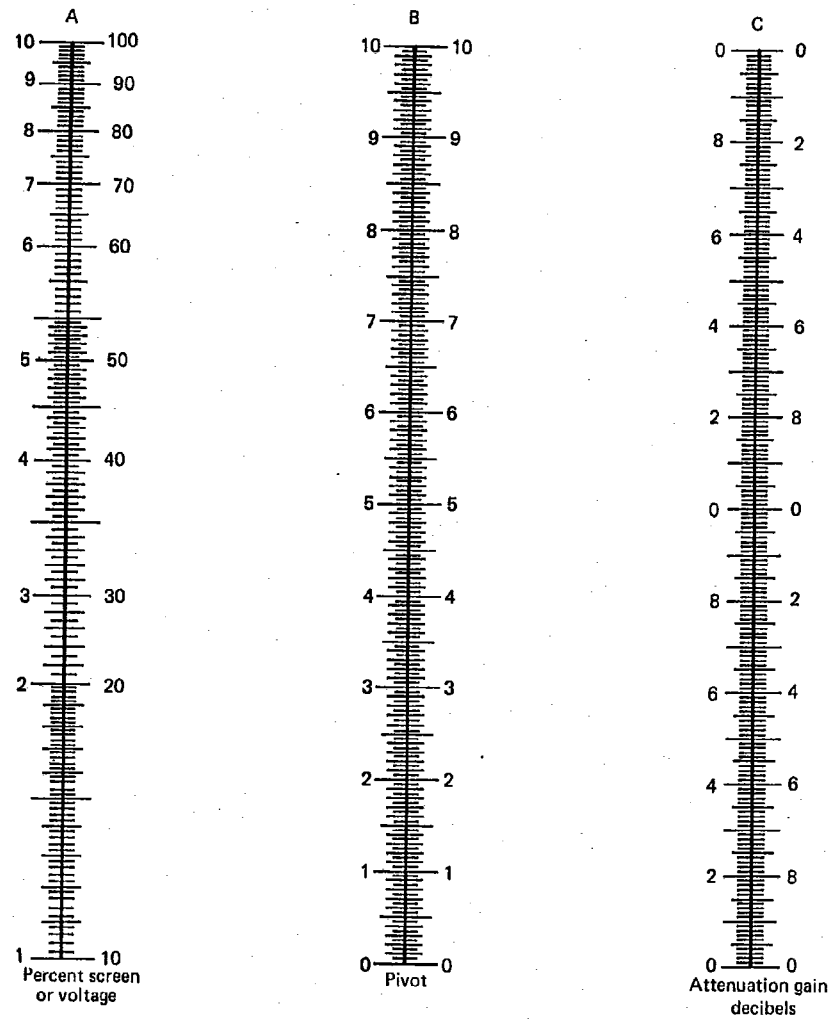


Fig. 16.14—Decibel-to-screen height or voltage nomograph

face between the search unit and test material. In this mode, the principal material particle vibration is in a direction parallel to the direction of sound beam propagation.

Another mode is the shear (transverse) mode in which the principal material particle vibration is in a direction perpendicular to the direction of sound beam 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 ultrasound 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.

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 Fig. 16.15A). 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 Fig. 16.15B).

For example, in views A and B of Fig. 16.15, the sine of incident angle *a* is to the sine of refracted reflected angle *c* as the sound 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:

$$\frac{\sin a}{\sin d} = \frac{\text{velocity (Medium 1, long.)}}{\text{velocity (Medium 2, long.)}}$$

$$\frac{\sin a}{\sin e} = \frac{\text{velocity (Medium 1, long.)}}{\text{velocity (Medium 2, shear)}}$$

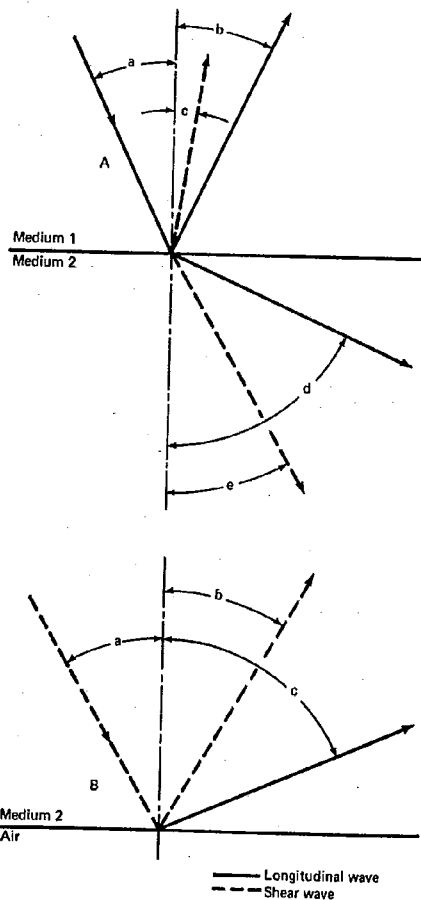


Fig. 16.15—Snell's law of reflection and refraction

or

$$\frac{\sin a (\text{long.})}{\sin c (\text{shear})} = \frac{\text{velocity (Medium 1, long.)}}{\text{velocity (Medium 1, shear)}}$$

View B:

$$\frac{\sin a (\text{shear})}{\sin c (\text{long.})} = \frac{\text{velocity (Medium 2, shear)}}{\text{velocity (Medium 2, long.)}}$$

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 α is further increased, the shear angle θ 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.

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 testing can commence.

Various types of reflectors can be machined in blocks of material similar in acoustic qualities to those of the test material. 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 reflection 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 Fig. 16.16).

When a shear wave ultrasonic beam is introduced into material at an angle other than normal to its parallel surfaces, almost all of the sound is propagated away from the sound entry point, with none being reflected back to the search

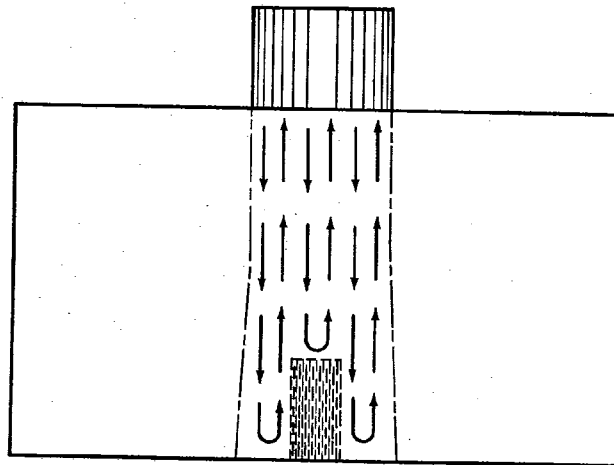


Fig. 16.16—Amplitude calibration using flat bottom holes

unit (see Fig. 16.20). For this reason, certain types of reflectors must be introduced into material to provide reflectance for calibration purposes.

In addition to providing distance calibration, a calibration block usually must provide amplitude standardization for flaw size evaluation. Figure 16.17 illustrates most of the types of reflectors used for this purpose. Holes drilled normal to the test surface (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 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 Fig. 16.17B, 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 elements 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 must 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-line 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 Fig. 16.17 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 sound beam-to-reflector surface. This type of evaluation is usually limited to straight beam (longitudinal) probing.

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.

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 must 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 must be considered when calculating angles in plastics for use as wedge material for shear wave search units.

The frequency of ultrasound 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 highest amplitude. The frequency is related to the transducer element thickness, increasing as its thickness is reduced. The electrical pulse that excites the transducer element must 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 ultrasound is about one-half wave length as measured in a direction perpendicular to the direction of sound propagation.

Equipment Selection

Longitudinal wave ultrasound 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 (see Fig. 16.15A, angle "e"). 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 must 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.

Coupling

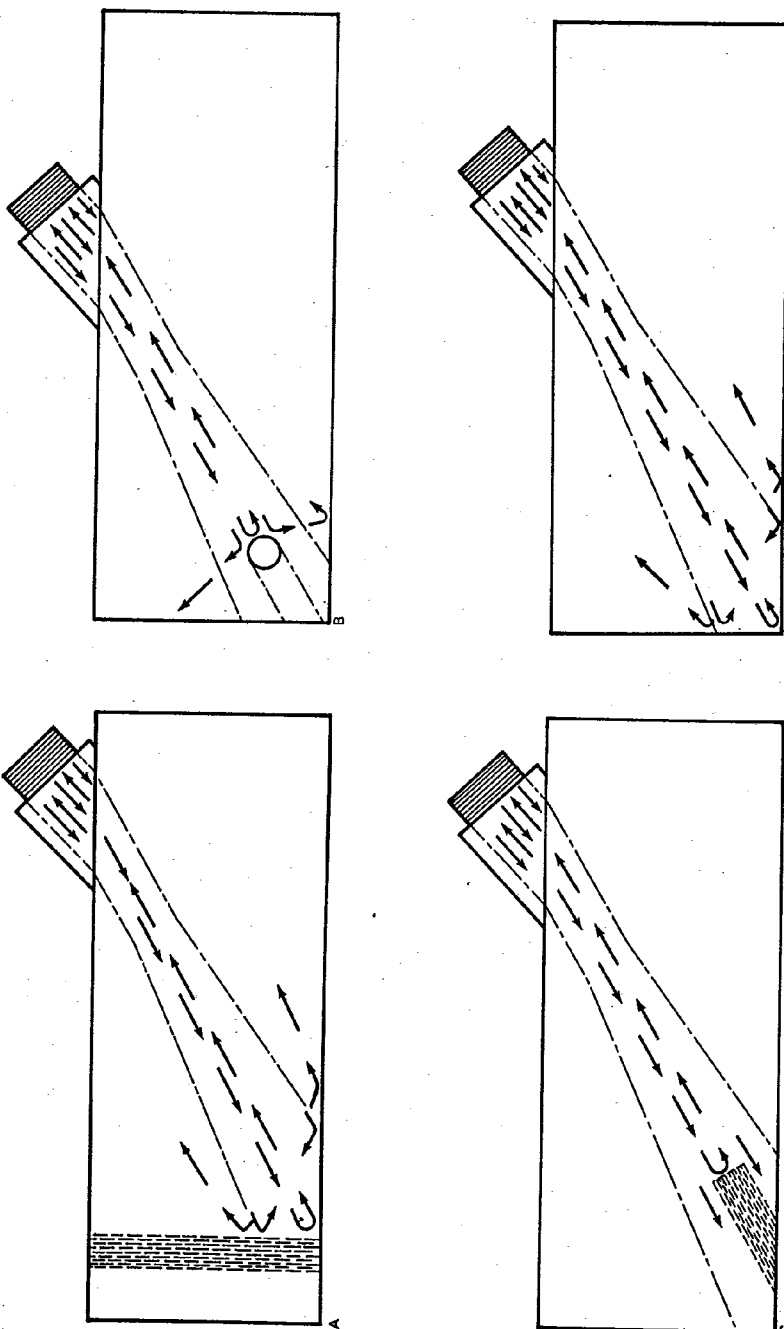
It is not usually necessary to remove weld reinforcement to attain satisfactory results in testing a weld, as the sound beam is directed under the weld bead at an angle from the base material. If a weld is to be ground flush to satisfy contractual requirements, final testing should be done after grinding 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 must be removed for complete weld coverage; this can quite 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 must be hydraulic in nature and have enough body to maintain coverage of the test surface during

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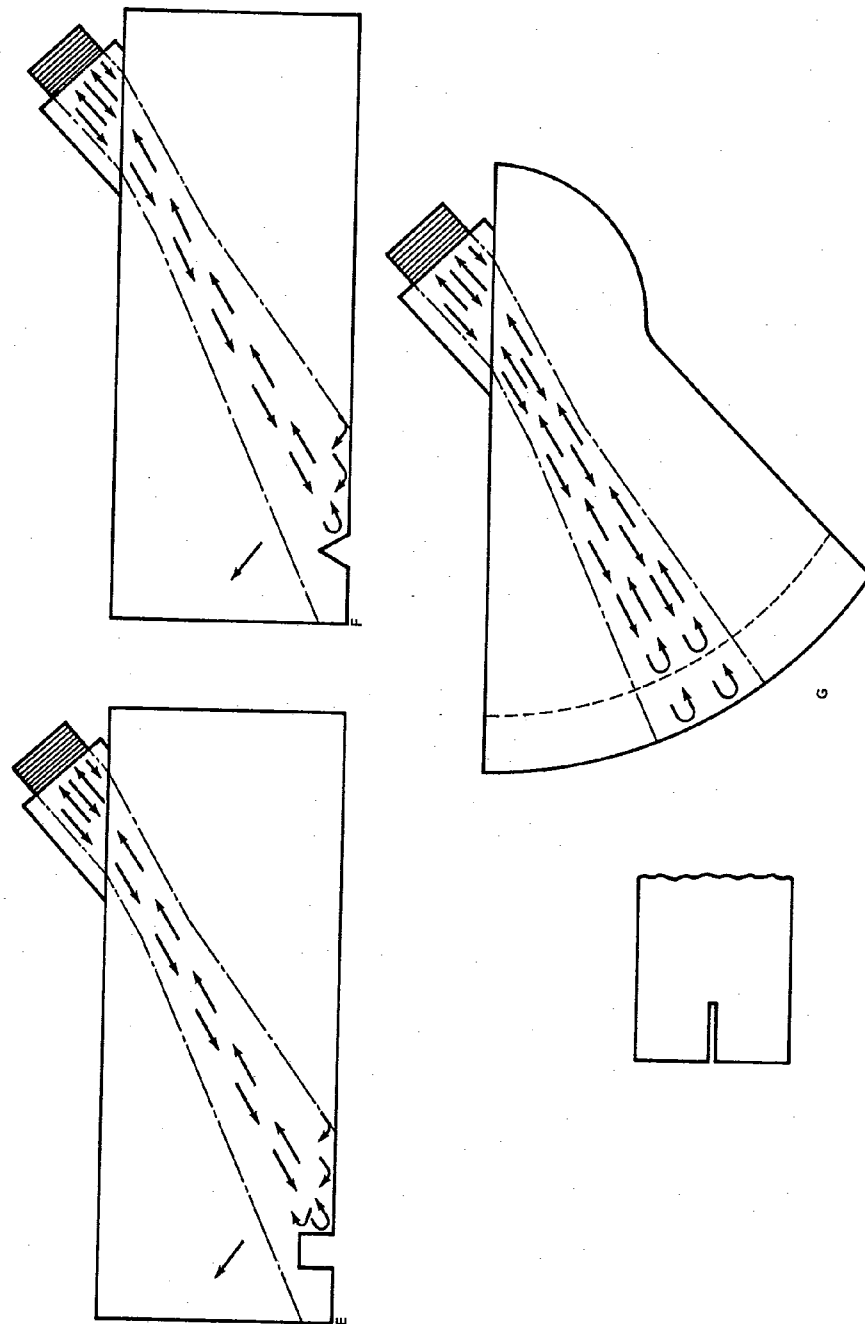


Fig. 16.17—Amplitude calibration

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 must be considered in the selection of a couplant material are viscosity, safety (slipping hazard), ease of removal, and effects of residue on future operations, such as hydrocarbon pick-up in weld repair and effects on paint application.

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.

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 Fig. 16.18.

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 Fig. 16.18 relates a 4 in. sound path to a 3-3/4 in. (94 mm) surface mea-

surement 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 Fig. 16.19.

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. $\times$ 1/2 in. (13 $\times$ 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 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, Structural Welding Code, 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 Fig. 16.21).

(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

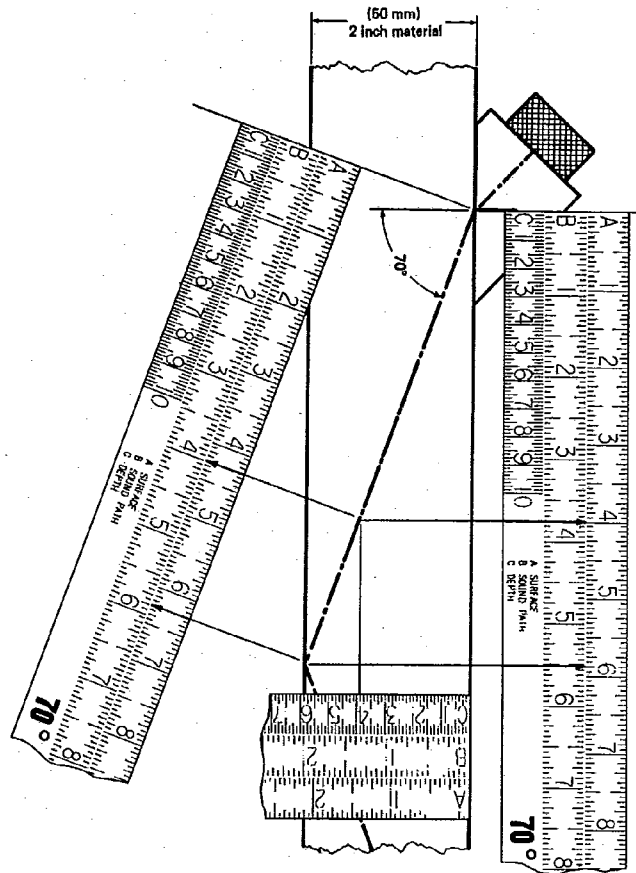


Fig. 16.18—Ultrasonic ruler application

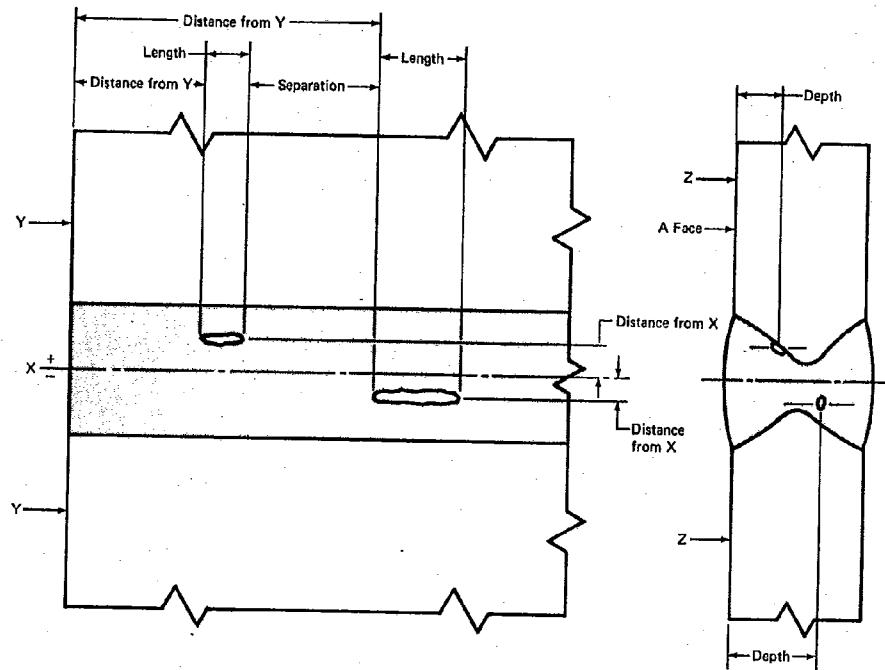


Fig. 16.19—Flaw orientation

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 the first inch. Example: a five inch sound path would produce an attenuation factor of $(5-1) \times 2 = 8$.

(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.

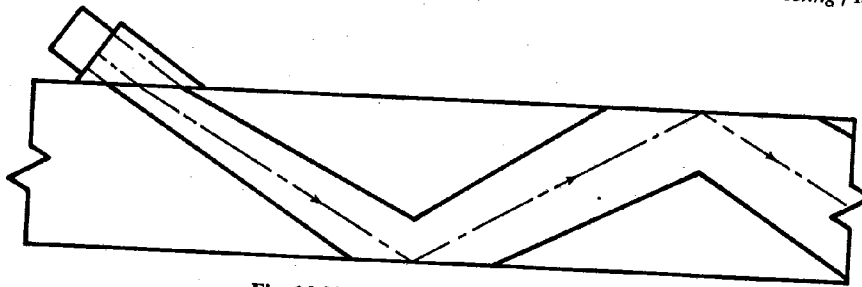


Fig. 16.20—Sound beam propagation

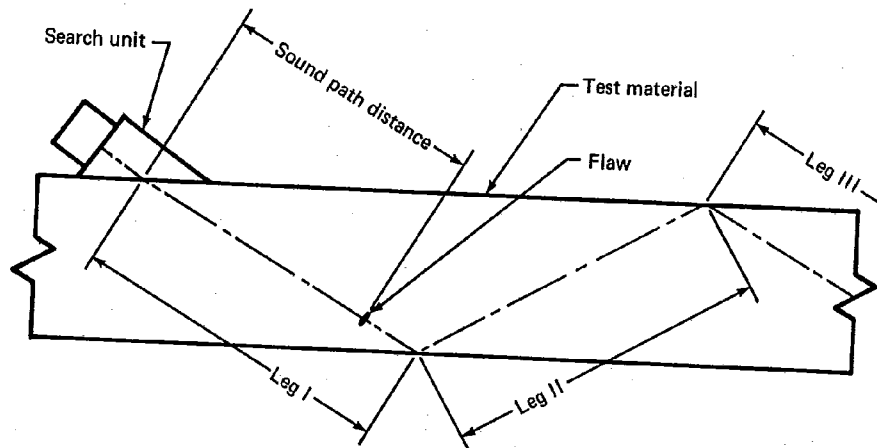


Fig. 16.21—Sound beam propagation showing sound path distance

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.

Reporting

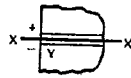
In the past, a major objection to the use of ultrasonics in determining the quality of welds was its inability to produce permanent records. Careful tabulation of information on a report form similar to that in AWS D1.1 will usually satisfy these objections (see Fig. 16.22). The welding inspector should be familiar with the kinds of data that must 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 inspected.

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REPORT OF ULTRASONIC TESTING OF WELDS

Project _____

Report no. _____



Weld identification _____

Material thickness _____

Weld joint AWS _____

Welding process _____

Quality requirements - section no. _____

Remarks _____

Line number	Indication number	Transducer angle	From Face	Leg*	Decibels				Discontinuity				Discontinuity evaluation	Remarks	
					Indication level	Reference level	Attenuation factor	Indication rating	Length	Angular distance (sound path)	Depth from "A" surface	Distance			
												From X			From Y
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
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22															
23															
24															
25															
26															

We, the undersigned, certify that the statements in this record are correct and that the welds were prepared and tested in accordance with the requirements of 6C of AWS D1.1, Structural Welding Code.

Inspected by _____

Manufacturer or contractor _____

Note: This form is applicable to Sections 8 and 9 (Buildings and Bridges). Do NOT use this form for Tubular Structures (Section 10).

Authorized by _____

Form E-6

Date _____

Notes:

- In order to attain Rating "d"
 - With instruments with gain control, use the formula $a - b - c = d$.
 - With instruments with attenuation control, use the formula $b - a - c = d$.
 - A plus or minus sign must accompany the "d" figure unless "d" is equal to zero.
- Distance from X is used in describing the location of a weld discontinuity in a direction perpendicular to the weld reference line. Unless this figure is zero, a plus or minus sign must accompany it.
- Distance from Y is used in describing the location of a weld discontinuity in a direction parallel to the weld reference line. This figure is attained by measuring the distance from the "Y" end of the weld to the beginning of said discontinuity.
- Evaluation of Retested Repaired Weld Areas must be tabulated on a new line on the report form. If the original report form is used, R_n shall prefix the indication number. If additional forms are used, the R number shall prefix the report number.

*Use Leg I, II, or III. See glossary of terms (Appendix 1).

Fig. 16.22—Form E-6, AWS D1.1, report of ultrasonic examination

Magnetic Particle Testing

Magnetic particle inspection is a nondestructive method of detecting discontinuities in magnetic materials. This method will detect surface discontinuities including those that are too fine to be seen with the naked eye; those that lie slightly below the surface; and, when special equipment is used, the more deeply seated 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 defects. Since a wide variation in the evaluation of results is to be expected, the following points should be agreed upon when inspection 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 of discontinuities shall be rejected
- (4) What types of discontinuities may be accepted
- (5) Definition of reworking and subsequent retesting permissible

A great deal of information regarding the soundness of weldments can be obtained from proper application of magnetic particle inspection. This method may be used to inspect welds and plate edges prior to welding and for the inspection 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 over radiography 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 method of inspection 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 indications even though the joints themselves are sound. Subsurface porosity and slag inclusions produce powder patterns that are not clearly defined.

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 in lengthy, cracklike form. Maximum sensitivity is obtained when defects are essentially perpendicular to the surface inspected.

A discontinuity must sufficiently interrupt or distort the magnetic field to cause external 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 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 sur-

face 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. It also interferes mechanically with the formation of powder patterns.

Principles of Magnetic Particle Inspection

The basic principle of magnetic particle inspection 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. These poles have a stronger attraction for the magnetic particles than the surrounding surface of the material.

The piece to be inspected is magnetized by introducing high 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, and magnetization assumes the approximate shape of the discontinuity.

Two types of magnetization are generally encountered. One of these is the permanent bar magnet with a north and south pole at opposite ends (longitudinal magnetization). These poles produce a flow of imaginary lines of force between them to create a magnetic field in the surrounding medium (see Fig. 16.23).

The most apparent characteristic of a magnet is its ability to attract any magnetic material 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 be-

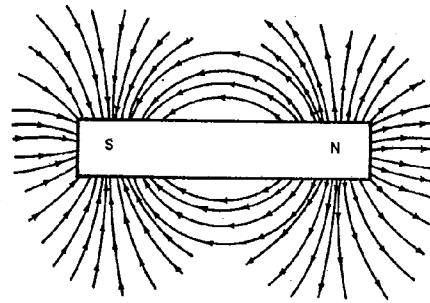


Fig. 16.23—Magnetic field in a bar magnet

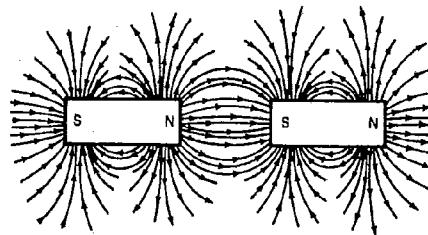


Fig. 16.24—Magnetic field in a bar magnet that has been cut in half

comes an individual magnet with two poles, and the opposite faces of the cut assume opposite polarity (see Fig. 16.24).

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 Fig. 16.25).

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, and the

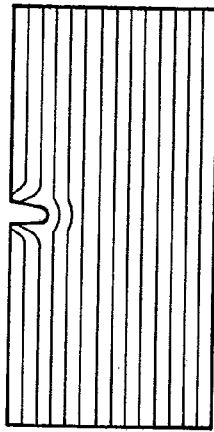


Fig. 16.25—Magnetism around a notch cut in a bar magnet

one more commonly employed in magnetic particle inspection, 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 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 Fig. 16.26. The intensity of the field is proportional to the strength of the current.

The flux flows through the conductor as well as around it, and when the conductor is a ferromagnetic material (as it is when used in magnetic particle inspection), the field is almost entirely confined to the conductor itself (see Fig. 16.27).

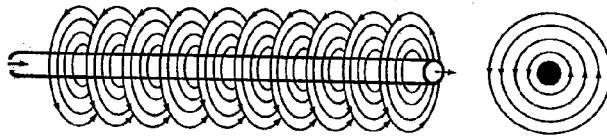
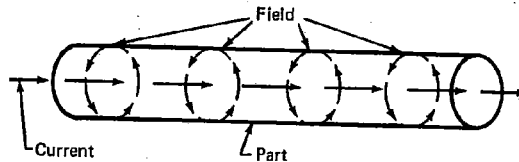


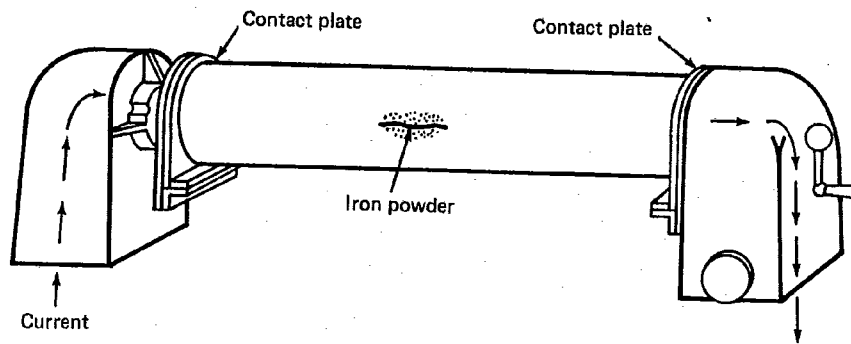
Fig. 16.26—Magnetic field around a conductor carrying current



Current passing through the part creates a magnetic field within the part. This is circular magnetization — to detect lengthwise cracks.

Fig. 16.27—Field of ferromagnetic conductor is confined almost entirely to the conductor itself

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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.

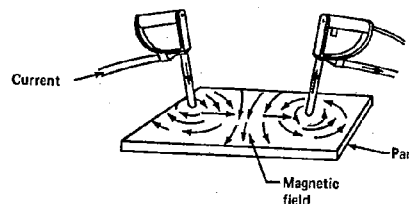
Fig. 16.28—Magnetic particles near a defect are attracted to the local poles

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, however, 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 with the current 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 (Fig. 16.28). If the 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, 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 Fig. 16.29).

Orientation of Magnetic Field

The magnetic field must 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, the best 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.



High amperage current passing through a part creates a magnetic field within the part between the prods. This is circular magnetization — used to detect defects parallel to current flow.

Fig. 16.29—In large parts, local areas can be magnetized; arrows indicate field

Longitudinal Magnetization: The part to be inspected can be made the core of an electromagnet by placing it within a solenoid (see Fig. 16.30). 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 bi-polar 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, it becomes a temporary solenoid.

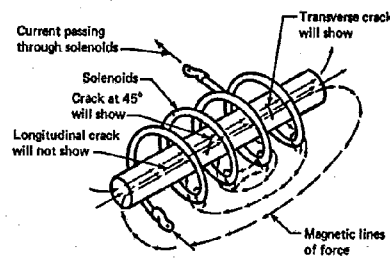


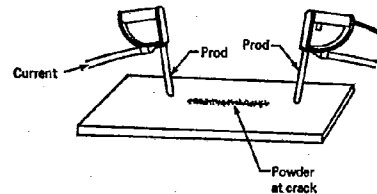
Fig. 16.30—Part to be inspected can be magnetized by making it the core of a solenoid

Overall Circular Magnetization: Circular magnetization is normally obtained by passing high current through the piece itself (see Fig. 16.28). The magnetic field produced is usually circular in 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. The surface of the bore of a hollow part is not magnetized when current is passed through the part.

When circular magnetization is used, the field is normally contained within the contours of the part itself. This provides maximum field strength and, therefore, maximum sensitivity to subsurface discontinuities.

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 Fig. 16.31). This produces a local circular field in the area between the contact points. The technique is generally used in the inspection of heavy 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



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.

Fig. 16.31—Crack in large plate is indicated by alignment of particles between prods

while the current is passed through.

The contact prods and the areas to be inspected 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 make contact directly on the weld and, when a second inspection is necessary, to place the prods at right angles to the previous line.

It is desirable 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 field circuit of the generator or in the primary circuit of the step-down transformer.

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 currents should be avoided because they produce irrelevant patterns. Magnetizing currents should be determined by specifications, standards, or purchase orders. If these are unavailable, current requirements may be determined by experience or actual experiment. The voltage has no effect on the magnetic fields and should be kept low to prevent arcing and overheating. The following indicate approximate amperage ranges for this type of inspection:

- (1) Longitudinal magnetization—3000 to 10,000 ampere turns
- (2) Overall circular magnetization—100 to 1000 amperes per inch (4 to 40 A/mm) of the outside diameter of the part
- (3) Prod magnetization—100 to 125 ampere per inch (4 to 5 A/mm) of prod spacing
 - Dry method—prod spacings of from 3 to 12 inches (75 to 340 mm)
 - Wet method—prod spacings of from 2 to 12 inches (50 to 340 mm)

Type of Magnetizing Current

Alternating current, direct current, and rectified current all may be used for magnetizing the parts to be inspected. High amperage, low voltage current is usually employed.

Portable equipment that makes use of electromagnets and permanent magnets is occasionally used. These are satisfactory for the detection of surface cracks only.

Alternating Current: Only the surface of the metal is magnetized by alternating current. The method is effective for locating discontinuities that extend to the surface, such as fatigue or service cracks. It may be used to inspect welds where subsurface evaluation is not required. Surface cracks would be indicated, but the deeper discontinuities or incomplete fusion would not.

Direct Current: Direct current produces a field that penetrates throughout the part and is, therefore, more sensitive than alternating current for the detection of subsurface discontinuities. Full-wave, three-phase rectified current pro-

duces 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.

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. Some of the methods are detailed below.

Continuous Method: The dry powder is 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 height while the force is 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 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.

Residual Method: This method relies on the residual field remaining after the magnetizing current has been switched off, since the indicating material 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).

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 selected.

Dry Method: Additional information on 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 bag, 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 the

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 16.32 shows the dry powder method in use.

When inspecting 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. When used with the wet method, the oil must 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

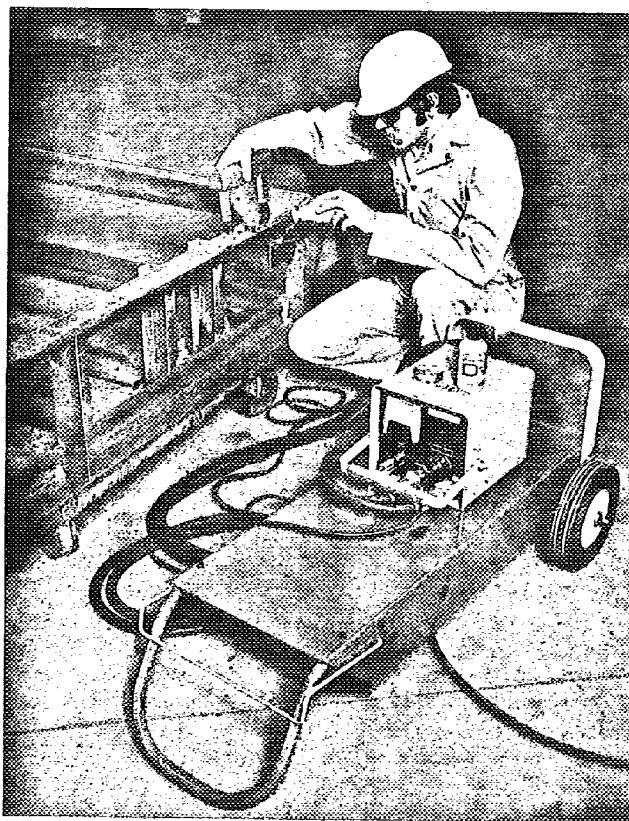


Fig. 16.32—Dry powder magnetic particle inspection of welds with portable equipment

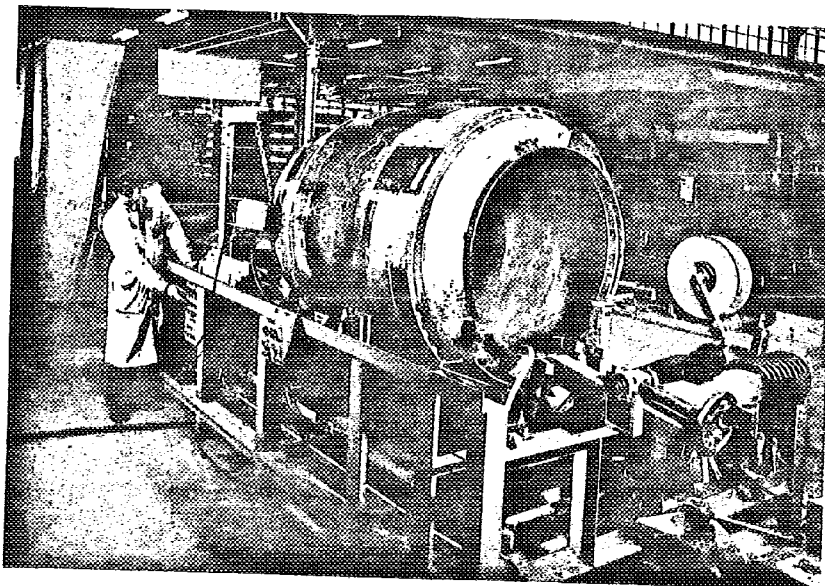


Fig. 16.33—Wet fluorescent magnetic particle inspection of a welded missile case to show fine surface defects

hours or drying the part with warm air or careful application of a volatile solvent.

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. Because of the small particle size, the wet method is more sensitive to fine surface defects (see Fig. 16.33), 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.

The bath must 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, 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 material 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 without difficulty. The material is available in red or black; the red material improves visibility on dark surfaces. 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 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 particles with their greater sensitivity can be used then to bring out the fine discontinuities.

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.

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 must 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 solenoid 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. 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).

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 correct magnetizing force has been created for each inspection.

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. 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.

Common Applications

Inspection of Heavy Weldments: Magnetic particle inspection may be applied to all types of heavy weldments as long as the materials are magnetic. It is usually used to inspect the finished welds (see Fig. 16.34). On heavy, multiple-pass welds, however, it is sometimes used to inspect each pass immediately it has been deposited. It is also used to inspect roots of joints that have been back-chipped 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, and there is also the possibility that small subsurface cracks may have been extended by the stress relief treatment.

The dry continuous method, using some type

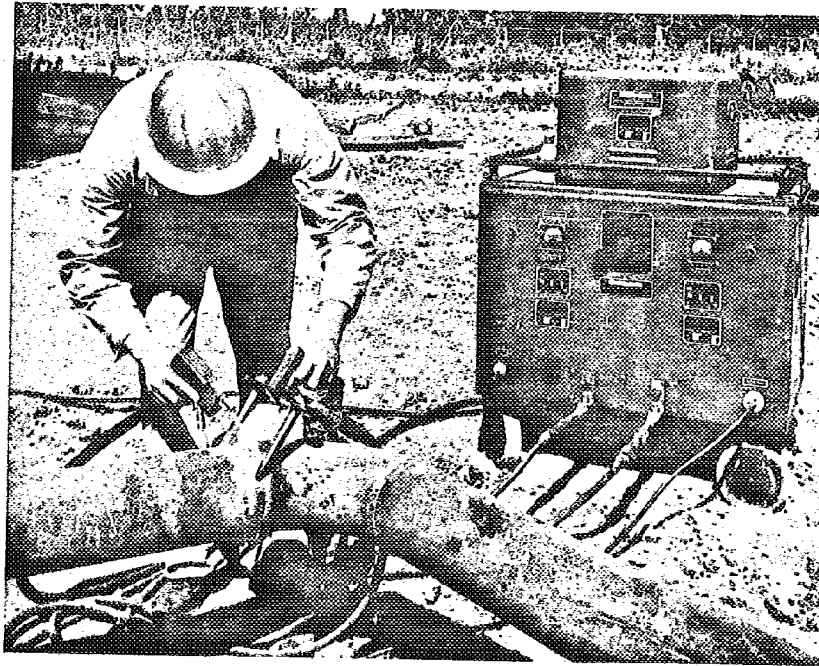


Fig. 16.34—Magnetic particle inspection unit with powder blower and prods; portable unit in background

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 prod by passing about 600 to 1000 A along the length of the weld, using a prod spacing of from 4 to 10 in. (100 to 250 mm). The prod positions should be overlapped slightly on consecutive shots.

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 inspection at a standard stationary type inspection setup are given two inspections that use both longitudinal and circular fields. Larger weldments are inspected by local circular magnetization. This is accomplished by making contact to the structure with clamps or other suitable contacts. A longitudinal field may be used on large structures by wrapping several turns of cable around the weld area.

Plate Inspection: Magnetic particle inspection is frequently used to inspect plate edges prior to

welding. The purpose of this inspection is to detect cracks, laminations, inclusions, and segregations. It will reveal only those discontinuities that are near or extend to the edge being inspected.

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 inspection. When alternating current is used, the inspection is limited to discontinuities that extend to the edge being inspected.

Repair or Rework Inspection: Magnetic particle inspection 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, radiographic, visual, or other inspection methods may be removed by chipping, gouging, or grinding, and the repair made by welding. In this type of work, it is useful to inspect the cavity after the defective material has been removed to make certain that the discontinuity has been entirely eliminated before proceeding with the repair weld. It may also be advisable to check the repair weld itself after it has been completed to find any cracks or other objectionable discontinuities in the weld or in the adjacent metal, if they exist.

In general, the same inspection procedures should be used in connection with repair or rework procedures as would be used on the original parts.

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.

Surface Cracks: Powder patterns are sharply defined, tightly held, and usually built up heavily with powder. The deeper the crack, the heavier the buildup of the indication (see Fig. 16.35).

Subsurface Discontinuity Indications: Powder patterns have a fuzzy appearance, less sharply defined and less tightly adherent (see Fig. 16.36).

Crater Cracks: Cracks are recognized by their patterns, which are small and occur at the terminal point of the weld. They may be a single line in almost any direction, or possibly multiple, or star-shaped.

Incomplete Fusion: Accumulation of powder will generally be pronounced, and the edge of the weld will be seen. The pattern will be sharper the nearer it is to the surface.

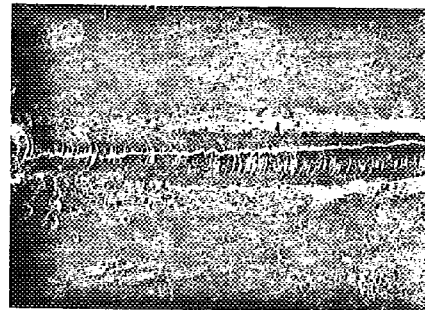


Fig. 16.35—Typical indication of surface crack in a weld

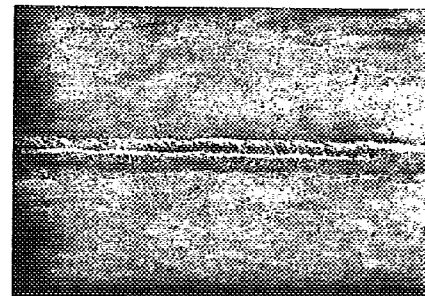


Fig. 16.36—Indication of a subsurface crack in a weld (the dry magnetic particles assume a less defined pattern)

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Undercut: A pattern that adheres less strongly than the indications obtained by incomplete fusion is produced at the weld edge. Undercut can also be detected by visual examination.

Inadequate Joint Penetration or Gap Between Plates at Root: The powder pattern may resemble that produced by a subsurface crack. The requirements of the particular weld will determine whether such inadequate penetration constitutes a defect.

Subsurface Porosity: The powder patterns are not clearly defined in this case. They are neither strong nor pronounced, yet are readily distinguished from indications of surface conditions.

Slag Inclusions: A pattern similar to subsurface porosity appears when a high magnetizing field strength is used and slag inclusions are present.

Seams: The indications are straight, sharp, fine, and often intermittent. Buildup is smaller. A magnetizing current greater than that required for the detection of cracks is necessary.

Irrelevant Indications: Irrelevant or false indications that do not indicate the presence of cracks or other defects, which have no significance concerning the soundness of the welds, are frequently produced. They occur when some factor causes the magnetic field to change direction suddenly. This causes leakage, which causes the magnetic particles to form false indications on the surface.

Physical Contour: A thin area, a change in section, an oil vent, or a hole drilled in the part will all tend to produce indications that have no significance with respect to joint performance. The magnetic particle patterns are usually identified readily by their location and the shape of the part.

Change in Magnetic Characteristics: Abrupt changes in magnetic properties may occur at the edge of the heat-affected zone. The pattern will be diffused and fuzzy and will run along the base metal in a line parallel and quite close to the edge of the weld. This pattern resembles closely that caused by undercutting, but it is very loosely adherent. Postweld thermal treatment may restore the magnetic characteristics, in which case the indications will not reappear.

Magnetic to Nonmagnetic Metal. A similar pattern may occur when a magnetic (ferritic) base metal is welded with nonmagnetic (austenitic) filler metal. Magnetic particle inspection is not normally recommended for the inspection of welds of this type.

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 to austenitic steel by the resistance welding process.

When a magnetized steel part is struck by another part or dragged over it, leakages will 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 inspection or transportation.

Evaluation

The inspection will determine the soundness of the weld and the existence, if any, of discontinuities. The weld will be judged acceptable, repairable, or will be rejected according to evaluation of the discontinuities disclosed by inspection. The decision may be governed by applicable specifications, standards, or purchase orders.

Indications of subsurface discontinuities, unless clearly understood, should be investigated by radiographic inspection or 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 focal points for corrosion.

Standards

Many standards have been developed in which the service conditions alone dictate the rejection level of a part. When indications are found on a part that has performed satisfactorily in ser-

vice, 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 direction 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, an unusually large discontinuity may be

acceptable with a wide margin of safety.

When usual patterns are produced, it may be necessary to establish identity by correlating the results with other test 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.

Penetrant Testing

The liquid penetrant inspection method is based 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 inspection, when done properly, is a reliable and revealing method for detecting discontinuities open to the surface. Very small and tight imperfections can usually be shown. The several variations of the method each have their advantages and disadvantages.

Technique

The penetrant liquids and, therefore, the penetrant inspection techniques are divided into two basic categories: type A, fluorescent; and type B, visible dye.

The fluorescent methods offer exceptionally good resolution of indications; the visible dye penetrant 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 brought to a routine inspection area, whereas non-water-washable methods can be performed on location or where water spray is not available or should not be used.

Inspection 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 radiation are necessary to this technique and are marketed as standard equipment by nondestructive testing equipment suppliers. To be effective, the inspection must be performed under subdued or darkened overall lighting conditions.

Inspection 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 approved procedure in liquid penetrant testing cannot be overstated. The simplicity of the test may mislead the user: there are many variables that, if uncontrolled, influence test results. For example, inadequate cleaning may not permit the penetrant to enter the discontinuity, and the test 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 inspected
- (2) Apply penetrant
- (3) Allow sufficient penetrant dwell time
- (4) Remove excess penetrant

(5) Apply developer to indicate retained penetrant

(6) Examine and inspect

(7) Clean, if required

Fluorescent Penetrant Method, Type A:

Fluorescent penetrants can be either water washable for removal of excess 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 effectiveness.

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 inspection are as follows:

Precleaning. All extraneous material such as scale, slag, grease, oil, paint, water, and the like must 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.

Application of Penetrant. The penetrant should be applied to the dry part over the areas to be inspected. This may be done by dipping, brushing, or spraying.

Sufficient Dwell Time. Sufficient dwell time for the penetrant to enter discontinuities must be allowed. The dwell time may vary depending upon conditions, materials, and temperatures. Approved procedures should be followed.

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 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. 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 must be applied to render the excess penetrant water-removable. The emulsifier may be applied by dipping, flowing on, or spraying. The length of dwell time necessary for the emulsifier is important, and recommendations of the producer should be followed. Following emulsification, the part is water washed as detailed above.

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 recirculating warm air or by a mild air draft. Pools of excess developer should be avoided because it might flow the penetrant out of discontinuities.

Nonaqueous wet developers are also obtainable. These are suspensions in volatile, nonaqueous liquids. The part must 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 smooth, even coating of developer. If brushing is employed, care should be taken to avoid a too thick coating. Pressurized cans of developer are marketed for spraying, or other pressurized equipment, such as paint spray units, may be employed. It is necessary to keep the suspension well agitated in spray equipment, and coagulation of the solid particles must be avoided. Pools of developer should be avoided as they dry to a thick coating that could mask fine indications.

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. 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 under the excitation of black light and contrast sharply with the darker background.

Final Cleaning. If required, the part or area may be cleaned with solvents following completion of the inspection.

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 less critical inspection 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 inspection are as follows:

- (1) Precleaning.
- (2) Cleaning as stated for precleaning for fluorescent methods.
- (3) 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.
- (4) Allow 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 50 and 100° F (10 and 38° C) for best results. The penetrant must 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.)
- (5) 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 must 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 inspection accuracy, and as required by some specifications, most of the excess is first wiped off with clean lint-free cloth or absorbent paper, fol-

lowed by a wiping with a clean cloth or paper dampened with solvent. This process should be repeated until the dampened wiping cloth or paper shows substantially no red stain. The surface should not be overcleaned once all excess is shown to be removed.

For some critical applications, flushing of the surface with solvent cleaner should be prohibited. In any event, when less demanding inspection may be satisfactory, or when cleaning as previously described cannot be done, flushing the surface with cleaner will detract significantly from the accuracy of the results.

The solvent may be trichlorethylene, perchlorethylene, acetone, or a volatile petroleum distillate. The former two are somewhat toxic; the latter two are flammable. Proper precautions should be observed. Producers of the inspection equipment market cleaner for their penetrant products, and their use is recommended.

(6) Application of developer. If water rinsing has been employed, the part must be dried before application of developer, except when an aqueous suspension developer is used. In this case, drying is accomplished after the application of 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.

(7) 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 shown as a bright red indication against the white background of the developer.

(8) Final Cleaning. The part or area may be cleaned with solvents following completion of inspection.

Applications

As-welded surfaces are suitable for penetrant

inspection 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 inspection.

In setting acceptance or rejection standards for dye penetrant inspection, the severity of service of the piece should be considered. In most weld standards, cracks are considered unacceptable. Cracks are shown by liquid penetrant inspection as a solid linear indication or, for very tight cracks, as a series of small, aligned, adjacent indications that may join up 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 inspecting 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 inspection, these will all show on casting surfaces. This must be taken into consideration when judging such weld assemblies.

Some specifications call for liquid penetrant inspection for nonmagnetic materials, and magnetic particle inspection for ferromagnetic materials. Except that magnetic particle inspection 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.

Liquid Penetrant Comparator

When it is not practical to make a liquid penetrant examination within the temperature range of 60 to 125° F (28 to 52° C), the examination procedure at the proposed temperature requires further 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 pro-

posed temperature and the other section at a temperature in the range of 60 to 125° F.

The liquid penetrant comparator shown in Fig. 16.37 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 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 16.37 illustrates the comparator after the grooves, if used, are cut. It may also be possible to heat a weldment to a temperature between 60 and 125° F (28 and 52° C).

Comparator Application: If it is desired to qualify a liquid penetrant examination procedure at a temperature less than 60° F (28° 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 (28 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

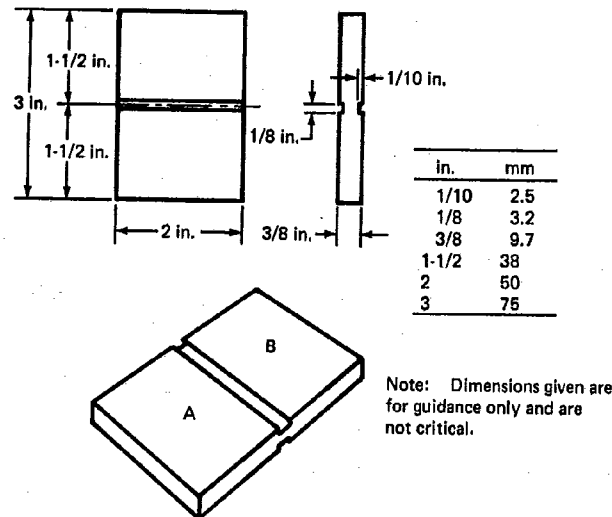


Fig. 16.37—Liquid penetrant comparator

and area "A" is examined and compared as described in the previous paragraph.

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 false 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 inspection materials.

Eddy Current (Electromagnetic) Testing

This section contains basic technical data on the testing of all types of metals, both ferromagnetic and nonferromagnetic, by means of alternating magnetic fields, for determining various physical properties of the materials and for the detection of discontinuities, or inhomogeneities, or both within the material.

General

Eddy current (electromagnetic) testing is a nondestructive test method 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 nonmag-

netic materials and is particularly useful in testing bars, billets, welded pipe, and tubes. The frequency may vary from 50 Hz to 1 MHz, depending on the type and thickness of material (see Fig. 16.38).

History

While the investigation of electromagnetic wave test methods preceded the development of practically every other modern technique of nondestructive testing, the field was slow to develop commercially. Until recently, the electromagnetic method had only limited applications. Without provisions for discrimination between responses to different conditions (such as discontinuities or defects, heat treatment variations, internal stresses due to forming operations, and small vibrations of the part or of test coils during testing), electromagnetic tests were, at best, limited in usefulness.

Theory

Nondestructive testing by eddy current methods involves inducing electric currents (eddy or foucault currents) in a test piece and measuring the changes produced in those currents by discontinuities or other physical differences in the test piece. Thus, such tests 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 tests where the magnetic permeability of a material is the factor affecting the test results and the latter to tests 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 (see Fig. 16.39). 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 has been developed for measuring either the resistive or inductive impedance components singly or both simultaneously.

Electric and Magnetic Properties of Metals

Electronic test equipment does not directly measure such things as hardness, crack depth, coating thickness, etc., but indirectly measures their relationship to things that can be measured directly, such as conductivity, permeability, or a combination of both. The characteristics of a metal that are measured directly and are of importance to electromagnetic testing follow.

Electrical Conductivity: An important property of metals is the ease with which electrons flow within them, commonly referred to as conductivity. Conductivity can be expressed mathematically as the reciprocal of the electrical resistivity of the metal.

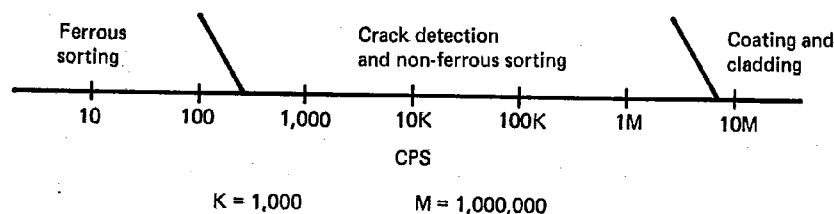


Fig. 16.38—Frequencies used for various test problems

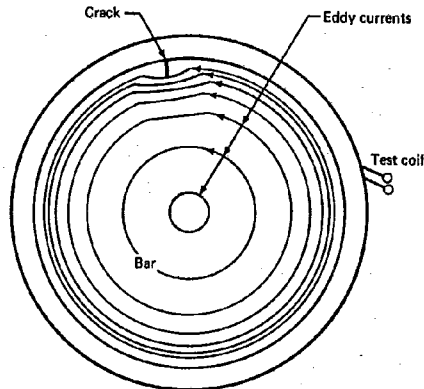


Fig. 16.39—Cross-sectional view of a bar with a small crack, surrounded by an exciting coil and a pickup coil, showing eddy current distribution

$$\sigma = \frac{L}{R \cdot A} = \frac{L}{\rho}$$

Where: σ = Conductivity (mho/unit length)

ρ = Resistivity (ohm•unit length)

L = Length

R = Resistance (ohm)

A = Cross-section area

Conductivity varies widely among various metals (see Fig. 16.40). A convenient means of categorizing metals is to refer to them as either conductors or nonconductors. For a pure metal,

the conductivity value is unique (see Table 16.4). The addition of impurities to a pure metal will normally change its conductivity sometimes markedly. For example, only 0.005 percent phosphorus present as an impurity in copper will decrease the conductivity from the value for pure copper to less than 96 percent of that conductivity (see Fig. 16.41). It can be seen from Fig. 16.41 that most other impurities, as well as variations in alloy composition, also affect the conductivity of pure copper, although not as severely as phosphorus.

The current distribution within a test piece may also be changed by the presence of inhomogeneities. 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. 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. In general, a conductivity measuring device can be shown to be applicable in detecting any condition that causes the mean free path of an electron passing through it to vary by an amount lying within the measuring capacity of the device used. If an electric wave is considered instead of electrons, the same factors impeding the flow of a single electron

Table 16.4
Resistivity and conductivity of some metals

Metal	Resistivity ρ (ohm-m) $\times 10^{-8}$	Conductivity		Temp. °C
		σ (mho/m) $\times 10^7$	°F	
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

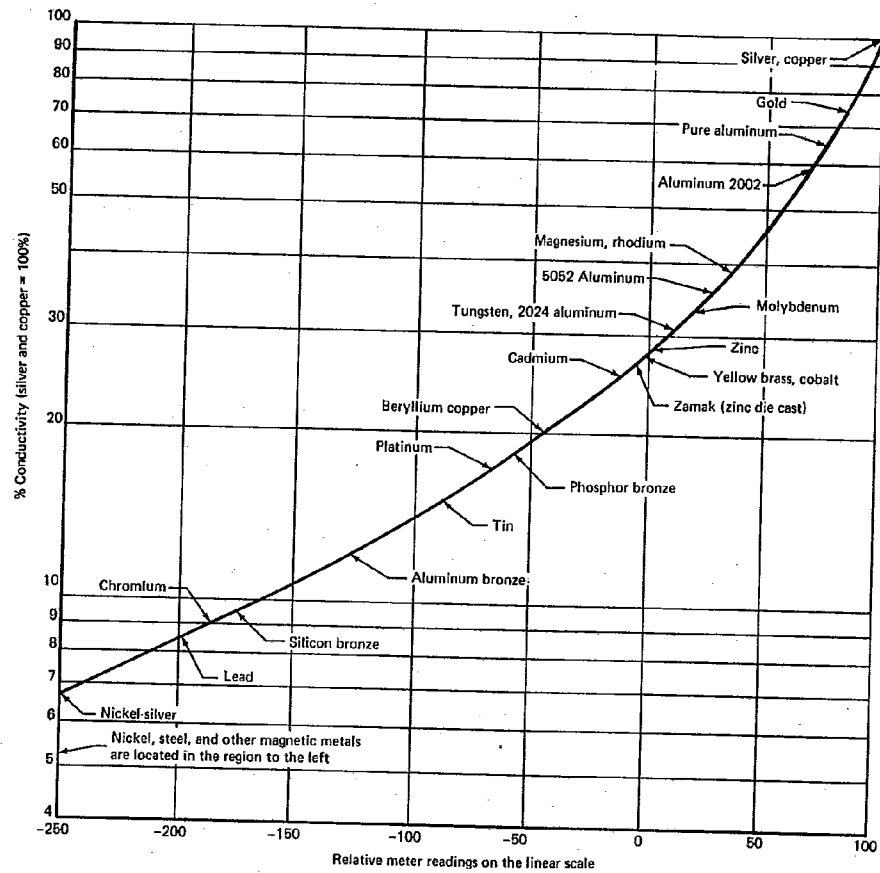


Fig. 16.40—Relative conductivity of metals and alloys related to eddy current meter readings

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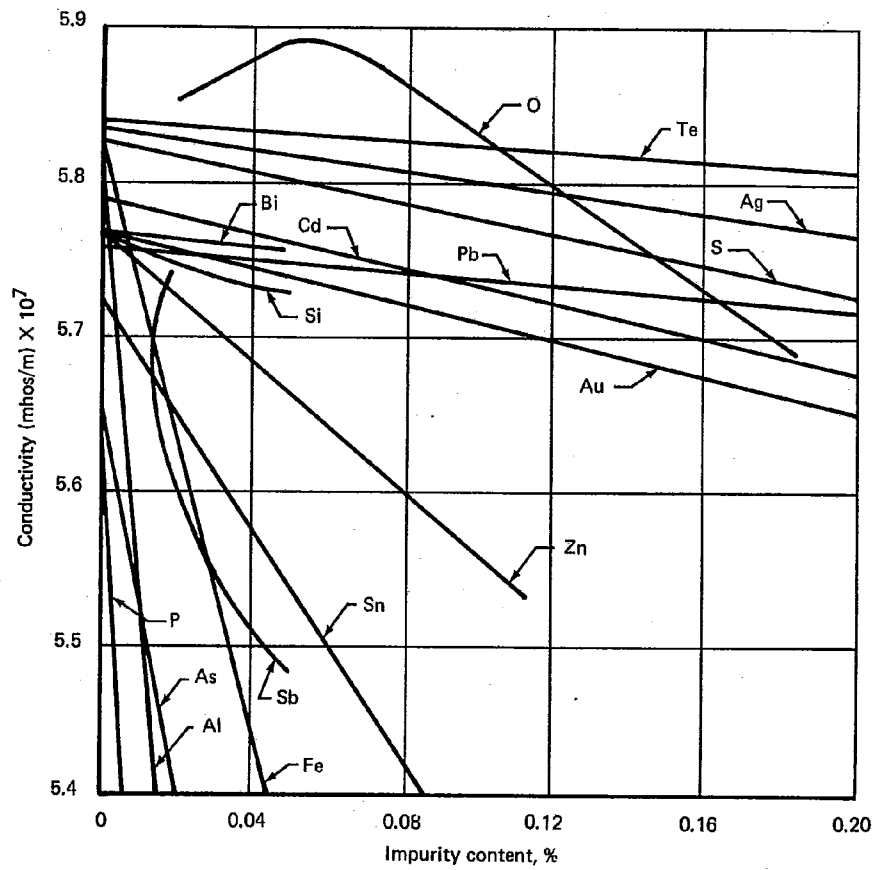


Fig. 16.41—Influence of impurities on the conductivity of pure copper

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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.

Magnetic Domains: Any metal placed within the region of a magnetic field will be affected somewhat. Among various metals, the individual magnetic responses vary widely, as was the case with electric conductivity. Metals that react only slightly to magnetic fields are called either "diamagnetic" or "paramagnetic"; or more simply, "nonmagnetic." Those metals that are greatly affected by the presence of a magnetic field are called "ferromagnetic" (or to a design engineer, "magnetic"). Three elements that display ferromagnetism are iron, nickel, and cobalt.

Magnetism occurs basically at the atomic level. The uncompensated (off-balance) planetary spin of the electrons in the third incomplete shell, together with specific dimensional characteristics, creates a "magnetic moment" (a measure of the magnetizing force). Figure 16.42 is one type of atomic model showing the inner structure of a ferromagnetic atom. This illustrates the unbalanced arrangement necessary for

the creation of magnetism. This condition is met in iron, cobalt, nickel, and in the rare earth groups (atomic numbers 58-71).

Magnetic moments in neighboring atoms are held parallel by quantum mechanical forces (see Fig. 16.43). These are likened to the forces holding the sun, moon, stars, and earth in their relative positions. The probabilities of magnetism occurring in any one of six possible directions (see Fig. 16.44) are about equal. The atoms of a metal showing magnetic characteristics are grouped into regions called "domains." A domain is the smallest known permanent magnet. Six thousand domains would occupy an area comparable in size to the head of a common pin.

In unmagnetized ferromagnetic materials, the domains are randomly oriented and neutralize each other. However, the magnetic forces are still present. Application of an external magnetic field to a metal test piece causes the randomly oriented magnetic domains to become so aligned that their magnetic moments are added to each other and to that of the applied force field (see Fig. 16.45). Soft, weak materials, such as iron, require only a small external field for domain alignment; when the field is removed, little magnetism will remain. With hard

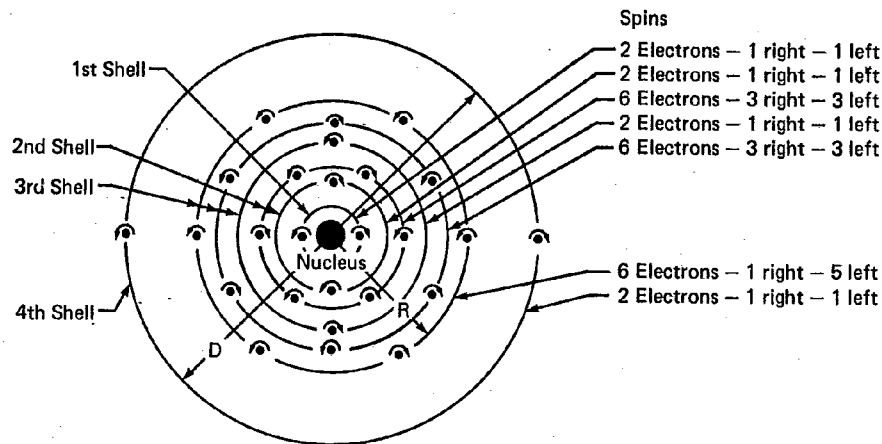


Fig. 16.42—Atomic model

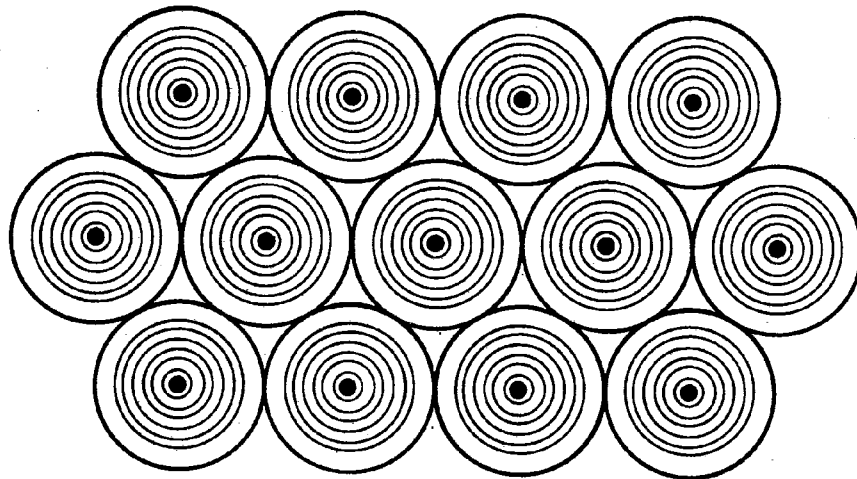


Fig. 16.43—Magnetic moments in neighboring atoms held parallel by quantum mechanical forces

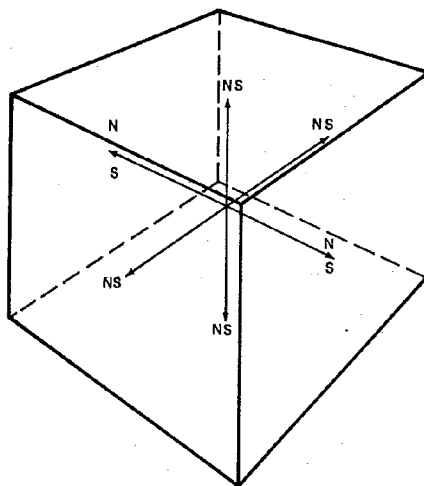


Fig. 16.44—Six possible directions of magnetization

(strong) magnetic materials, such as the aluminum-nickel-iron alloys (Alnico alloys), a strong external field must be applied to cause alignment of the domains, but most of the alignment will be retained upon removal of the external field, thus leaving the material permanently magnetized, having one major north pole and one major south pole.

Magnetic Induction: As mentioned, the phenomenon contributing to the magnetic behavior of a metal occurs at the atomic level. Within a given metal, it is possible for individual atoms to so align themselves that the net result is the creation of a strong magnetic field.

When a magnetic material is placed within an applied field (H), there is induced into that material another magnetic field (B) that may be stronger than the original applied field. As H is increased from zero, B also increases, but the relationship is not linear. A valuable piece of information to have for any magnetic material is a plot of the relationship of B and H (see Fig. 16.46 for a typical curve). Notice that the virgin curve does not retrace itself. The two anti-symmetrical curves are referred to as the "hysteresis loop."

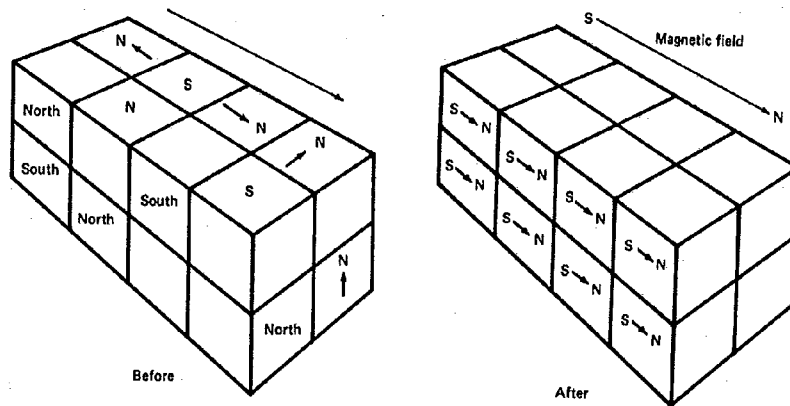


Fig. 16.45—Domain alignment before and after magnetization

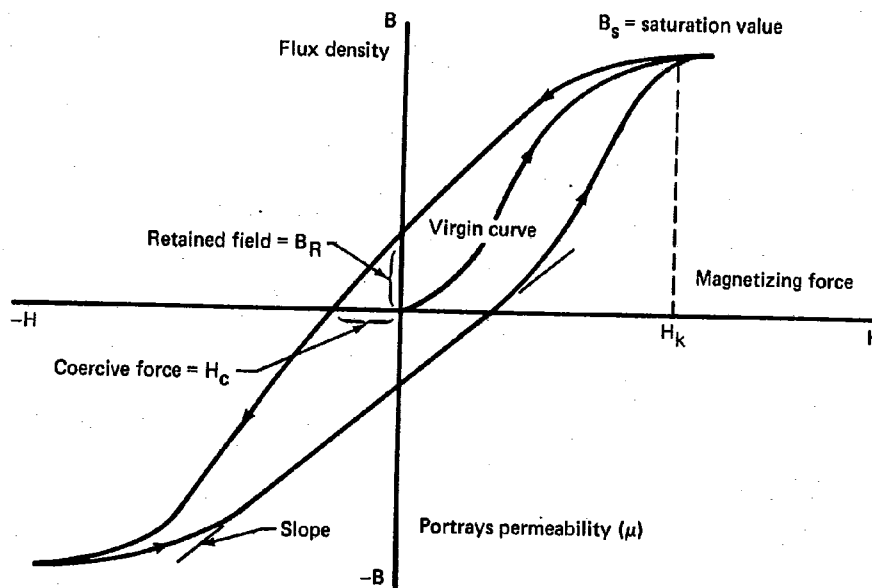


Fig. 16.46—Typical B/H (hysteresis) curve

Magnetic Permeability: It can be seen in Fig. 16.46 that there is a region over which the ratio of B to H is fairly constant. It is in this region that magnetic materials are designed to work. The constant ratio of B to H is defined as permeability (μ).

$$\mu = \frac{B}{H} = \frac{L}{R \cdot A}$$

μ = Permeability (Gauss/Oersted)

B = Magnetic flux or induction (Gauss)

H = Applied field or magnetic intensity (Oersted)

L = Length

R = Reluctance (Gilbert/Maxwell)

A = Cross-sectional area

One criterion of a good electromagnetic core is that the area of the hysteresis loop is small. Magnetization curves and hysteresis loops can be drawn for all magnetic materials to show the relationship between flux density (B) and magnetizing force (H).

Electromagnetic Properties of Coils

When an energized coil (see Fig. 16.47) is brought near a metal specimen, eddy currents are induced into the specimen and set up a magnetic field that acts in opposition to the original magnetic field. The impedance (Z) of the exciting coil, or, for that matter, any coil in close proximity to the specimen is affected by the presence of the induced eddy currents in the specimen. The path of the eddy currents in the specimen is distorted by the presence of defects or other inhomogeneities. The apparent impedance of the coil is also altered by the presence of defects in the specimen. This change in impedance can be measured and is useful in giving indications of defects or differences in physical, chemical, and metallurgical structure. Instrumentation and circuitry read-out of the coil impedance are shown in Fig. 16.48.

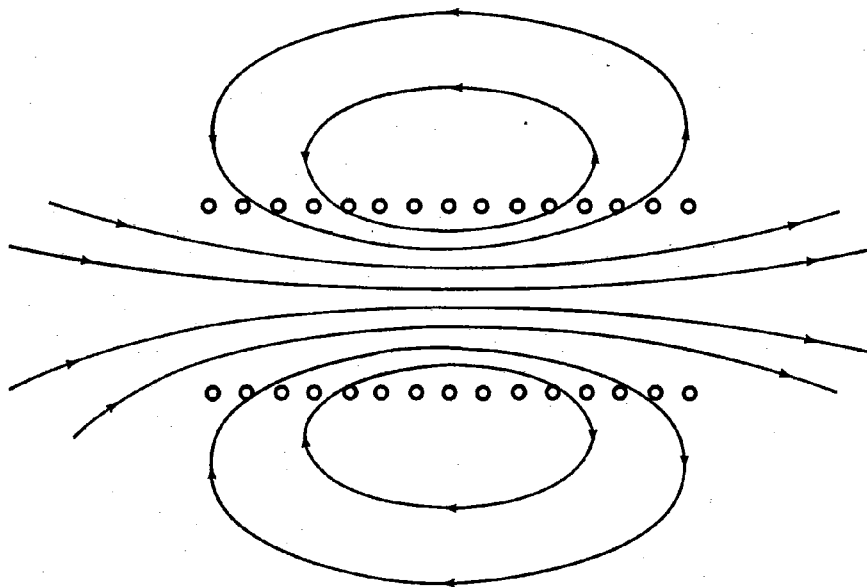
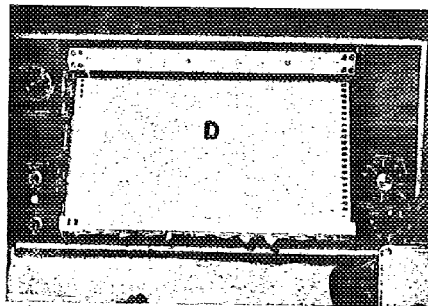
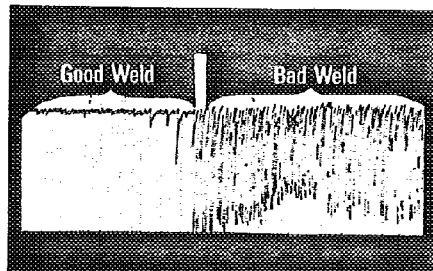


Fig. 16.47—Lines of induction surrounding a solenoid



(A)



Courtesy U.S. Steel Corporation

(B)

Fig. 16.48—Instrumentation readout for electromagnetic testing (A) X-Y strip recorder (B) Typical eddy current readout from strip chart illustrating good and bad weld areas.

In electromagnetic testing, the applied magnetic field strength (H) is of great importance in determining the validity of a test procedure. The field strength of a system is determined by the current in the primary coil. In magnetoinductive testing, the field strength and its selection are of prime importance. Magnetoinductive testing is electromagnetic testing 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. **Properties of Eddy Currents:** Eddy currents are induced into the conducting test specimen by alternating electromagnetic induction or transformer action (see Fig. 16.49). Eddy currents are electrical in nature and have all the properties associated with electric currents. In generating eddy currents, the test piece, which

must be a conductor, is brought into the field of a coil carrying alternating current. 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 (see Fig. 16.50 and 16.51). 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 second coil 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 sensing or pick up coil (see Fig. 16.39). The path of the eddy current is distorted by the presence of a discontinuity or other inhomogeneity. Figure 16.39 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 defect. This change can be measured and is used to give an indication of defects or differences in physical, chemical, and metallurgical structure. Subsurface discontinuities may also be detected, but the current falls off with depth as shown in Fig. 16.52.

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 for defect detection equipment. This in-

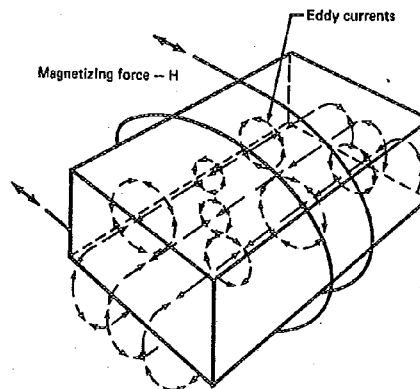
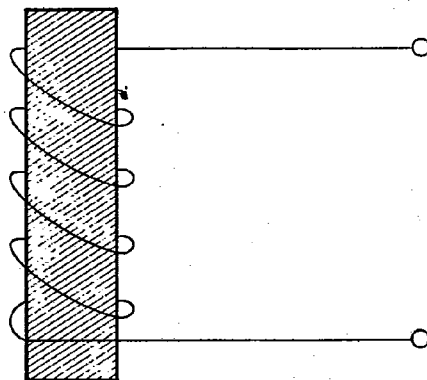
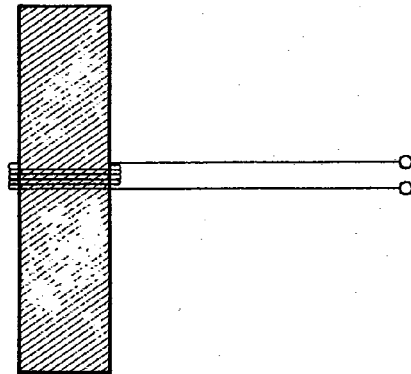


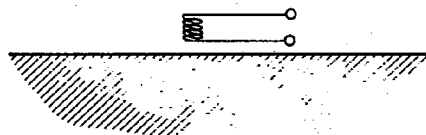
Fig. 16.49—Production of eddy currents by an alternating field



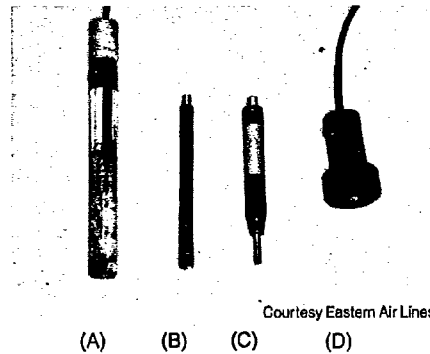
Wide encircling coils for conductivity determinations



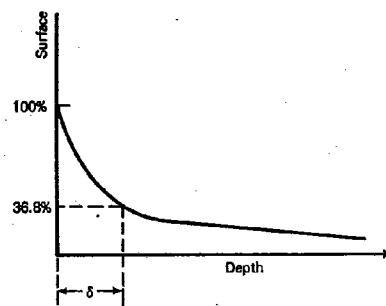
Narrow encircling coils for detection of small flaws and local diameter variations



Small probe coil for best sensitivity to small flaws; also for testing plates and irregularly formed parts

Fig. 16.50—Testing coils carrying alternating current

Courtesy Eastern Air Lines

Fig. 16.51 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)**Fig. 16.52—Eddy current strength drops off with distance from surface**

creases the penetration of the eddy currents and suppresses the influence of 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. This residual field may be large or small, depending upon the nature of the magnetizing force applied.

Demagnetization is necessary whenever the residual field (1) may affect the operation or accuracy of instruments when placed in service, (2) interferes with inspection of the part at low field strengths or with 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 test piece. The selected method should give the required degree of removal of the residual field (see Fig. 16.53).

Electromagnetic Testing

Electromagnetic testing consists of observing the interaction between electromagnetic fields and metals. The three things required for an electromagnetic test are:

- (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

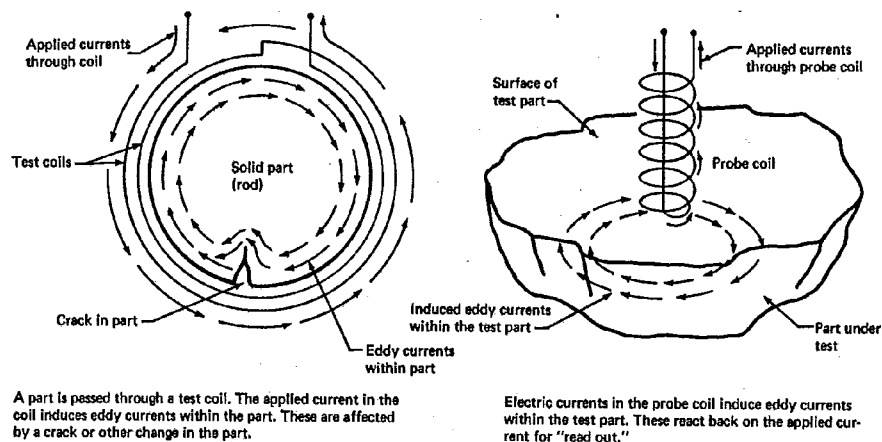
As specialized sensing elements, the test coils are in some ways analogous to lenses in an optical system, and their design is a fundamental consideration depending upon the nature of the test. Probe coils that are brought up against

the surface to be tested are used in testing 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 inspecting tubing, rods, bars, wires, and small parts.

Electromagnetic testing 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 test 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 test 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 (see Fig. 16.54)



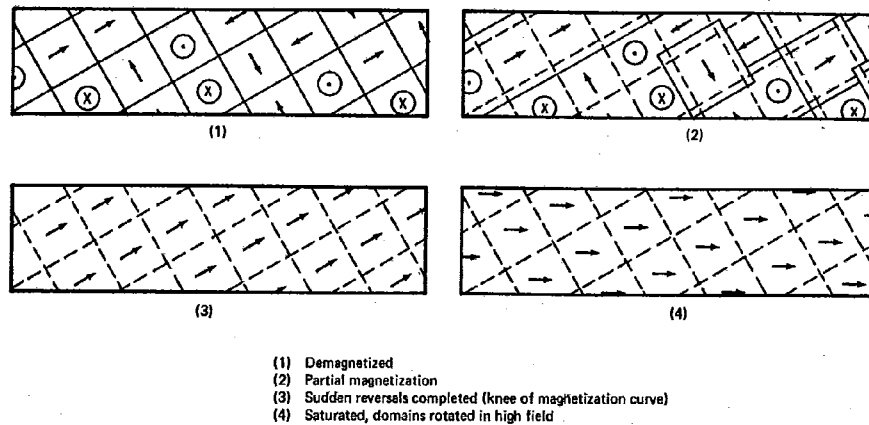


Fig. 16.54—Induction of eddy currents by the applied field

- (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 testing of ferromagnetic and nonferromagnetic metals.

Among the physical and metallurgical variables that affect electromagnetic tests 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, grain size, etc.)
- (6) Lattice dislocations caused by heavy working or radioactive bombardment
- (7) Temperature

- (8) Discontinuities and inhomogeneities, including most types of defects

- (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 test signal. The resulting voltage, which is the variable usually sensed by electromagnetic testing devices, must be very carefully analyzed to isolate the sought-after effects from the extraneous effects.

Associated with any electromagnetic test signal are three important attributes: amplitude, phase, and frequency. The test signal may contain either a single frequency (that selected for the test), or a multitude of frequencies (harmonics of the test 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 him to discriminate between test



variables. The important techniques used are amplitude discrimination, phase discrimination, harmonic analysis, coil design, choice of test frequency, and magnetic saturation.

Because each test involves straightforward scanning of the test part surface by a test coil or coils, either manually or by mechanical methods, the following section will emphasize the results of selected standard specimens or examples.

Equipment Calibration and Quality Assurance Standards

In using electromagnetic test methods for inspection 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 imperfections (defects) are cause for rejection of the sample. The imperfections 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 any imperfection or discontinuity in a metal that is cause for rejection. A defect is always a discontinuity but a discontinuity is not necessarily a defect.

It is not the imperfection itself that is detected by the test equipment, but rather the effect that it has on the electromagnetic properties of the metal being inspected. It is necessary, therefore, that it be possible to correlate the change in electromagnetic properties with the cause of the change. For this reason, it is necessary, when calibrating an electromagnetic testing unit, that standards be available that contain either natural or artificial imperfections that can accurately reproduce the exact change in the electromagnetic characteristics expected when production items containing defects are tested. Such standards are usually considered equipment calibration standards; that is, they demonstrate that the equipment is, in fact, picking up the defect or discontinuities for which the metal is being inspected.

These standards are not only used to facilitate the initial adjustment or calibration of the test

instrument, but also used to periodically check on the reproducibility of the measurements.

It is not enough just to be able to locate imperfections in a test piece; the inspector must be able to determine if the discontinuity is severe enough to be cause for rejection. The inspector must decide whether the discontinuity is, in fact, a defect. For this purpose, quality assurance standards are required against which the test instrument can be calibrated to show the limits of acceptability or rejectability for any type of discontinuity. The responsibility of quality assurance engineers is to specify limits. Once these are established, quality assurance standards are either selected from actual production items representing the limits of acceptability or samples are prepared containing artificial defects that serve the same purpose.

A quality assurance standard performs a function altogether different from that of an equipment calibration standard. While the 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.

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 test techniques to a greater extent than ever. Although comparatively little use was made of electromagnetic testing techniques prior to 1950, in more recent years, industry has found electromagnetic testing most useful and particularly adaptable to rapid, 100 percent automatic inspection of production items and materials. The urgent need of industry to inspect 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 (see Figs. 16.55 and 16.56). This has been particularly true in the application of electromagnetic methods to the

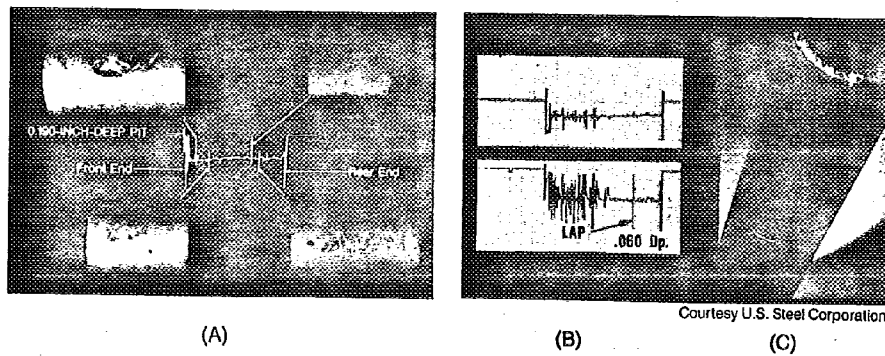
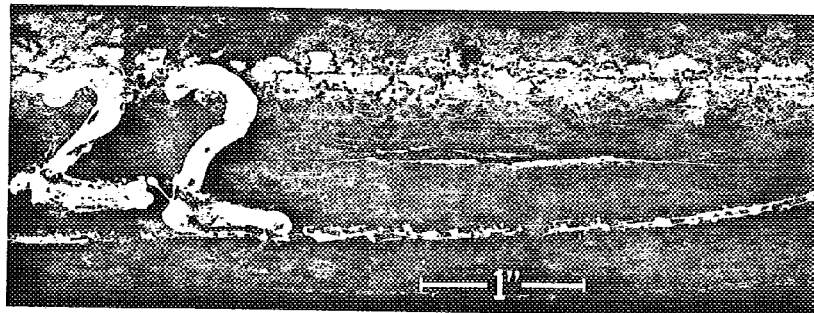
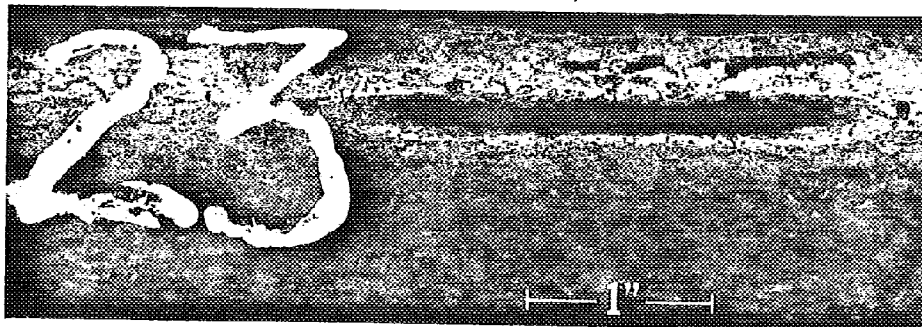


Fig. 16.55—Electromagnetic inspection of seamless pipe at 2000° F (1095° C) (A) Strip chart readout from various sections of a pipe and illustration of the actual flaws. (B) Readout showing a lap in a pipe (C) The lap in pipe as shown in readout (B)



A



B

Courtesy U.S. Steel Corporation

Fig. 16.56—Electromagnetic inspection of continuous welded pipe at 2000°F (1095°C) (A) Embedded sliver in pipe (B) A weld flaw in pipe

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critical inspection of items having high quality requirements (see Fig. 16.57).

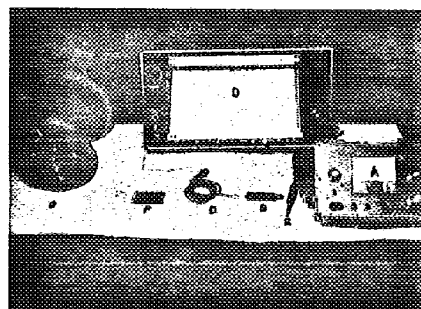
Advantages

There are two most significant advantages of electromagnetic testing.

(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 tests can be useful for grading and classifying.

EXAMPLE: Tubing now can be electromagnetically tested for minute cracks and other flaws at speeds of 300 ft/min (1.5 m/s) or more, while a comparable visual inspection would usually proceed at much less than a tenth of this speed and would fail to detect flaws that were not on the surface.



Courtesy Eastern Air Lines

Fig. 16.57—Arrangement of components for electromagnetic inspection of bearing journals of large diameter: (A) eddy current sensing unit, (B) probe coil (fits in slot in G, (C) connecting cable from G to A, (D) X-Y recorder, (E) connecting cable from A to D, (F) test block which contains minimum acceptable flaw size, and (G) fixture for rotating probe B on inner surface of bearing.

Acoustic Emission Testing

Acoustic emission testing (AET) or surveillance methods are currently considered supplementary to other nondestructive testing methods. They have been applied, however, during proof testing, during recurrent inspections, during service, and during fabrication.

Acoustic emission testing 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 pressur-

ization. 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 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 opera-

tion 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. It is fair to state that equipment is available and proven, laboratory assessments have been favorable, and few technical problems remain. 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 much 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.

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 users 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).

Ferrite Testing

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 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 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 1940's, 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 1700°F (480 to 930°C) ferrite tends to transform in part to a brittle intermetallic compound (sigma phase) that severely embrittles the weldment.

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 (AWS A4.2-74, Standard Procedures 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. The American Welding Society's A5.4-78, Specification for Corrosion-Resisting Chromium and Chromium-Nickel Steel Covered Electrodes, describes a procedure for 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 the AWS specification A4.2-74.

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.

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 16.58 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 micro-

fissures, 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 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 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 Fig. 16.59. 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 Fig. 16.60. The DeLong diagram provides more accuracy and accounts for the contribution of nitrogen content.

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:

- (1) Use of the term "ferrite number" (FN) instead of percent ferrite
- (2) Use of National Bureau of Standards (NBS) coating thickness specimens as

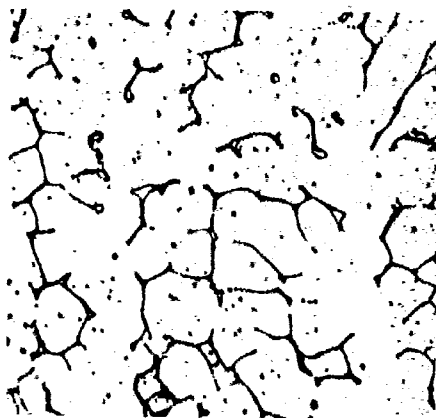


Fig. 16.58—Microstructure of austenitic weld specimen containing some delta ferrite.

reference and calibration standards, and ferrite numbers assigned by Welding Research Council (WRC) for calibrating ferrite gages

- (3) Provisions for calibration of all other magnetic instruments through weld metal standards that have been rated for ferrite number (FN)

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. Förster,

and the Severn gage by Severn Engineering Co. The WRC procedure is based on a sensitive instrument, the Magne-Gage 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.

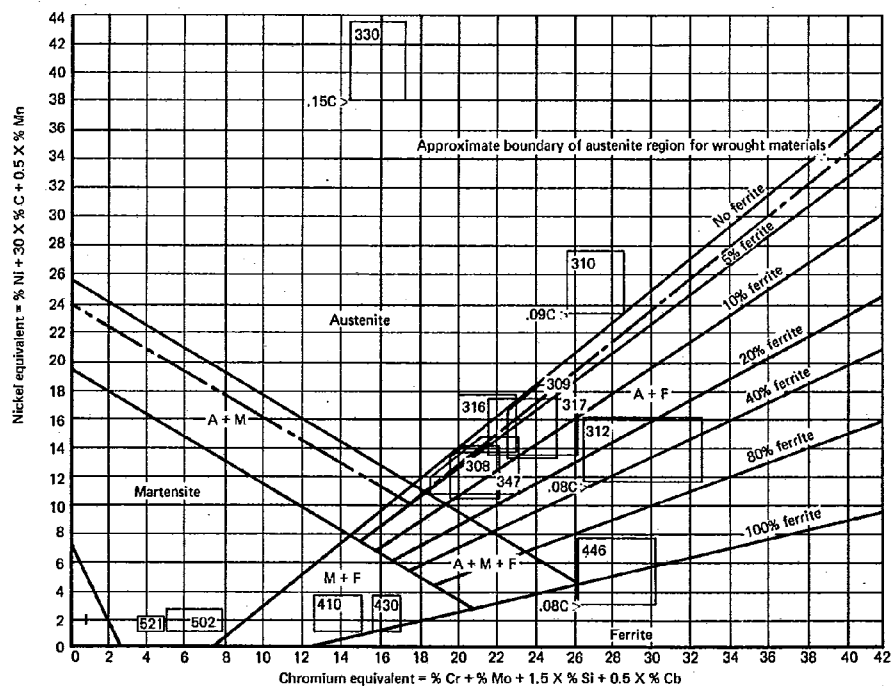


Fig. 16.59—Schaeffler diagram for stainless steel weld metal

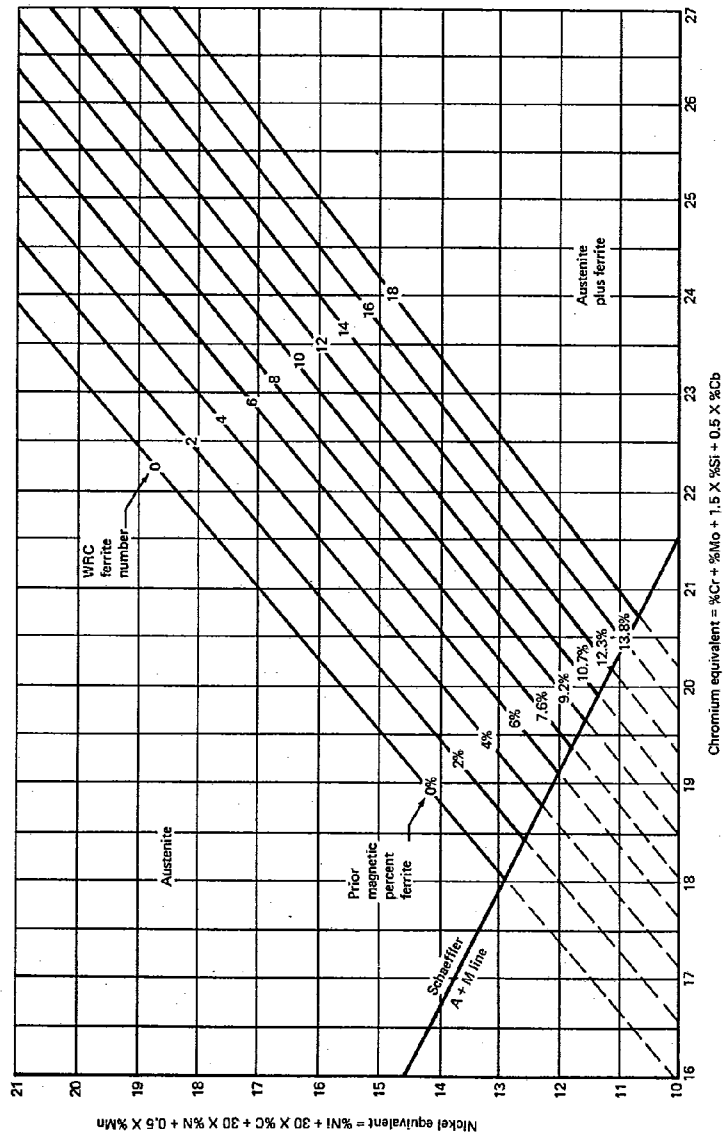


Fig. 16.60—DeLong diagram for stainless steel weld metal

Nondestructive Testing Procedures

The previous sections of this chapter have been devoted to fundamental concepts of individual NDT methods. In applying these NDT methods to weld inspections, the welding inspector will discover that each particular NDT 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 NDT procedures are commonly employed to ensure uniformity and continuity in the inspection process. Preplanned NDT 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 NDT procedures, the following text expands upon some of the typical sources of requirements.

Engineering a Procedure

There are several approaches to engineering nondestructive testing 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 must receive due consideration if the nondestructive testing operation is to function successfully. The flow diagram (see Fig. 16.61) shows how requirements invoked in the contract may be transformed into a written operational procedure.

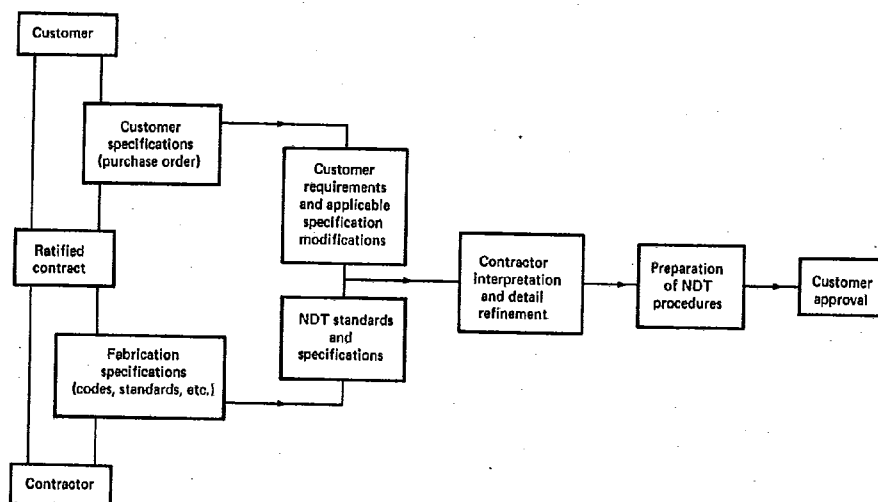


Fig. 16.61—Typical flow diagram from contract to approved operations procedures

Specifications, Codes, Standards

The requirements for the technical content of a typical NDT 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 his own 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 relate 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:

- (1) Extent of inspection coverage (what is required?)
- (2) Inspection method required
- (3) NDT techniques for the method
- (4) Qualification of inspection 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 inspection should be performed and what inspection 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, follow-

up discussion should ensue until a finalized agreement is reached on the complete requirements for inspection of the welds. At this point, an NDT 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.

NDT Procedures

Nondestructive testing 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 NDT 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 inspection 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 inspection 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.

Procedure Mechanics: An effectively written procedure sustains the primary objective of providing nondestructive testing 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 invoking document to 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 must 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 testing 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 inspection is being performed in accordance with up-to-date requirements.

References and Suggested Reading Material

Radiography

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- 16.4 "Nondestructive Inspection and Quality Control." ASM Metals Handbook, vol. 11, pp. 105-156.
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- 16.6 McMaster, Robert C. *Nondestructive Testing Handbook*, chap. 20. New York: The Ronald Press Company, 1963.
- 16.7 Richardson, H.D. *Industrial Radiography Manual*. U.S.A.E.C., Contract #OE-84036. March, 1968.
- 16.8 Hinkel, J.E. "Assuring Weld Quality,"

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- 16.9 ASNT No. SNT-TC-1A. "Personnel Qualification and Certification in Nondestructive Testing." Columbus, Ohio: The American Society for Nondestructive Testing.

Acoustic Emission

- 16.10 Liptai, R.G., D.O. Harris, and C.A. Tatro. "Acoustic Emission, A Symposium," presented at December (1971) Committee Week. ASTM Special Technical Publication 505.
- 16.11 Spanner, J.C., and J.W. McElroy. "Monitoring Structural Integrity by Acoustic Emission, A Symposium," presented at Ft. Lauderdale, Florida, 1974. ASTM Special Technical Publication 571.
- 16.12 Spanner, J.C. "Acoustic Emission Techniques and Applications." Evanston, Illinois: Intex Publishing Co.