Welding Processes, Inspection, and Metallurgy

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Welding Processes, Inspection, and Metallurgy

1 Scope

This recommended practice (RP) provides guidance to the API authorized inspector on welding inspection as encountered with fabrication and repair of refinery and chemical plant equipment and piping, pipelines, and other related industries. This RP includes descriptions of common welding processes, welding procedures, welder qualifications, metallurgical effects from welding, and inspection techniques to aid the inspector in fulfilling their role implementing API 510, API 570, API 653, and API 582. The level of learning and training obtained from this document is not a replacement for the training and experience required to be a certified welding inspector under one of the established welding certification programs, such as the American Welding Society (AWS) Certified Welding Inspector (CWI), or Canadian and European equivalent schemes such as CWB, CSWIP, PCN, or EFW.

This RP does not require all welds to be inspected, nor does it require welds to be inspected to specific techniques and extent. Welds selected for inspection, and the appropriate inspection techniques, should be determined by the welding inspectors, engineers, or other responsible personnel using the applicable code or standard. The importance, difficulty, and problems that could be encountered during welding should be considered by all involved. A welding engineer should be consulted on any critical, specialized, or complex welding issues.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API 510, *Pressure Vessel Inspection Code: Maintenance, Inspection, Rating, Repair, and Alteration*

API 570, *Piping Inspection Code: Inspection, Repair, Alteration, and Rerating of In-Service Piping Systems*

API Recommended Practice 571, *Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*

API Recommended Practice 574, *Inspection Practices for Piping System Components*

API Recommended Practice 578, *Material Verification Program for New and Existing Alloy Piping Systems*

API Recommended Practice 582, *Recommended Practice and Supplementary Welding Guidelines for the Chemical, Oil, and Gas Industries*

API Recommended Practice 2201, *Procedures for Welding or Hot Tapping on Equipment in Service*

ASME *Boiler and Pressure Vessel Code* [1]

Section VIII, *Rules for Construction of Pressure Vessels*

[1] ASME International, 3 Park Avenue, New York, New York 10016-5990, www.asme.org.

Section IX, *Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*

Section XI, *Rules for Inservice Inspection of Nuclear Power Plant Components*

ASME B31, *Code for Pressure Piping*

B31.1, *Power Piping*

B31.3, *Process Piping*

B31.4, *Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols*

B31.8, *Gas Transmission and Distribution Piping Systems*

ASME PCC-2, *Repair of Pressure Equipment and Piping*

ASNT Central Certification Program CP-189 [2], *Standard for Qualification and Certification of Nondestructive Testing Personnel*

ASNT Central Certification Program SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing*

ASTM A833 [3], *Standard Test Method for Indentation Hardness of Metallic Materials by Comparison Hardness Testers*

ASTM A956, *Standard Test Method for Leeb Hardness Testing of Steel Products*

ASTM A1038, *Standard Practice for Portable Hardness Testing by the Ultrasonic Contact Impedance Method*

ASTM E94, *Standard Guide for Radiographic Examination*

ASTM E1316, *Standard Terminology for Nondestructive Examinations*

AWS A3.0M/A3.0:2010 [4], *Standard Welding Terms and Definitions*

AWS A5.XX, *Series of Filler Metal Specifications*

ISO 9712 [5], *Non-destructive testing—Qualification and certification of NDT personnel*

NACE SP0472 [6], *Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments*

WRC Bulletin 342 [7], *Stainless Steel Weld Metal: Prediction of Ferrite Content*

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[2] American Society for Nondestructive Testing, 1711 Arlingate Lane, P.O. Box 28518, Columbus, Ohio 43228, www.asnt.org.

[3] ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

[4] American Welding Society, 550 NW LeJeune Road, Miami, Florida 33126, www.aws.org.

[5] International Organization for Standardization, 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, www.iso.org.

[6] NACE International (formerly the National Association of Corrosion Engineers), 1440 South Creek Drive, Houston, Texas 77218-8340, www.nace.org.

[7] The Welding Research Council, 3 Park Avenue, 27th Floor, New York, New York 10016-5902, www.forengineers.org.

3 Terms, Definitions, and Acronyms

3.1 Terms and Definitions

In an effort to minimize confusion, definitions in this document have been harmonized with AWS standard welding terms and definitions. Any variances from those definitions are identified with footnotes. The reader should consult the applicable code of construction for definitions of terms as they apply to that specific code. For the purposes of this document, the following terms and definitions apply.

3.1.1
alternating current field measurement
ACFM
Electromagnetic inspection technique that can be used to detect and size surface-breaking (or in some cases near-surface) defects in both magnetic and non-magnetic materials.

3.1.2
actual throat
Shortest distance between the weld root and the face of a fillet weld.

3.1.3
air carbon arc cutting
CAC-A
Carbon arc cutting process variation that removes molten metal with a jet of air.

3.1.4
arc blow
Deflection of an arc from its normal path due to by magnetic forces.

3.1.5
arc length
Distance from the tip of the welding electrode to the adjacent surface of the weld pool.

3.1.6
arc strike
arc burn
Discontinuity resulting from an arc, consisting of any localized remelted metal, heat-affected metal, or change in the surface profile of any metal object.

3.1.7
arc welding
AW
Group of welding processes producing coalescence of workpieces by melting them with an arc, with or without the application of pressure and with or without filler metal.

3.1.8
artifact
radiographic film artifact
Indications on radiographic film that may be caused by damage to the film before, during, or after processing.

NOTE It is extremely important to identify these false indications as such and note them on the interpreter’s report.

3.1.9
autogenous weld
Fusion weld made without filler metal.

3.1.10
back-gouging
Removal of weld metal and base metal from the weld root side of a welded joint to facilitate complete fusion and complete joint penetration upon subsequent welding from that side.

3.1.11
backing
Material or device placed against the back side of the joint adjacent to the joint root, or at both sides of a joint in electroslag or electrogas welding, to support and shield molten weld metal. The material may be partially fused or remain unfused during the welding process.

3.1.12
base metal
base material
substrate
parent metal (nonstandard)
Metal or alloy being welded, brazed, soldered, or cut.

3.1.13
base metal zone
BMZ
Portion of base metal adjacent to a weld, braze, or solder joint or thermal cut and unaffected by welding, brazing, soldering, or thermal cutting.

NOTE See also heat-affected zone and weld metal zone.

3.1.14
bevel angle
Angle between the bevel of a joint member and a plane perpendicular to the surface of the member.

3.1.15
burn-through
Hole or depression in the root bead of a single-groove weld due to excess penetration.

3.1.16
buttering
Surfacing variation depositing surfacing metal on one or more surfaces to provide metallurgically compatible weld metal for the subsequent completion of the weld.

3.1.17
cold crack
Crack occurring in a metal at or near ambient temperatures.

NOTE Cold cracks can occur in base metal, heat-affected, and weld metal zones. See also hot crack.

3.1.18
complete fusion
Fusion over the entire fusion faces and between all adjoining weld beads.

NOTE See also incomplete fusion.

3.1.19
constant-current power source
CC
Arc welding power source with a volt–ampere relationship yielding a small welding current change from a large arc voltage change.

3.1.20
constant-voltage power source
CV
Arc welding power source with a volt–ampere relationship yielding a large welding current change from a small arc voltage change.

3.1.21
controlled deposition welding [8]
CDW
half-bead technique
temper bead technique
Welding technique used to obtain controlled grain refinement and tempering of the underlying heat-affected zone in the base metal.

NOTE Various controlled-deposition techniques, such as temper bead (tempering of the layer below the current bead being deposited) and half bead (requiring removal of one-half of the first layer), are included.

3.1.22
corrosion specialist
Person, acceptable to the owner–user, who has knowledge and experience in corrosion damage mechanisms, metallurgy, materials selection, and corrosion monitoring techniques.

3.1.23
crack
Fracture-type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement.

3.1.24
defect
Discontinuity or discontinuities that, by nature or accumulated effect, render a part or product unable to meet minimum applicable acceptance standards or specifications (e.g. total crack length).

NOTE The term designates rejectability.

3.1.25
direct current electrode negative
DCEN
straight polarity
Arrangement of direct current arc welding leads in which the electrode is the negative pole and the workpiece is the positive pole of the welding arc.

3.1.26
direct current electrode positive
DCEP
reverse polarity
Arrangement of direct current arc welding leads in which the electrode is the positive pole and the workpiece is the negative pole of the welding arc.

3.1.27
discontinuity
Interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics.

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[8] Term not defined in AWS A3.0M/A3.0:2010; definition is based on the definition in the International Association of Drilling Contractors (IADC) Lexicon.

NOTE A discontinuity is not necessarily a defect. See also defect and flaw.

3.1.28
distortion
Change in shape or dimensions, whether temporary or permanent, of a part as a result of heating or welding.

3.1.29
eddy current examination technique
ET
Inspection method that applies primarily to nonferromagnetic materials.

3.1.30
examiner
Person who assists the inspector by performing specific NDE on components but does not evaluate the results of those examinations in accordance with the appropriate inspection code, unless specifically trained and authorized to do so by the owner or user.

3.1.31
flaw
Undesirable discontinuity.

NOTE See also defect.

3.1.32
filler metal
Metal or alloy to be added in making a brazed, soldered, or welded joint.

3.1.33
fillet weld size
For equal leg fillet welds, the leg lengths of the largest isosceles right triangle that can be inscribed within the fillet weld cross section. For unequal leg fillet welds, the leg lengths of the largest right triangle that can be inscribed within the fillet weld cross section.

3.1.34
groove angle
Included angle between faces of a weld or groove between work pieces.

3.1.35
heat-affected zone
HAZ
Portion of base metal whose mechanical properties or microstructure have been altered by the heat of welding, brazing, soldering, or thermal cutting.

NOTE See also base metal zone and weld metal zone.

3.1.36
heat input
Energy applied to the workpiece during welding.

3.1.37
hot crack
Crack occurring in a metal during solidification or at elevated temperatures. Hot cracks can occur in both heat-affected zones and weld metal zones.

NOTE See also cold crack.

3.1.38
image quality indicator[9]
IQI
penetrameter (archaic)
Device used to determine the sensitivity and ability of a radiograph to discern an image, or confirm the adequacy of the radiographic technique to produce radiographs with the required image quality level or radiographic sensitivity.

3.1.39
Imperfection [10]
Discontinuity or irregularity in a weld or deviation from the intended geometry that is detectable by methods outlined in this standard.

3.1.40
inclusion
Entrapped foreign solid material, such as slag, flux, tungsten, or oxide.

3.1.41
incomplete fusion
IF
lack of fusion
Weld discontinuity in which fusion did not occur between the weld metal and the fusion faces or adjoining weld beads.

NOTE See also complete fusion.

3.1.42
incomplete joint penetration
Joint root condition in a groove weld in which weld metal does not extend through the joint thickness.

NOTE See also joint penetration.

3.1.43
inert gas
Gas that does not react chemically with materials.

3.1.44
indication
Signal of discontinuity in the material under NDE.

3.1.45
inspector
Person who is qualified and certified to perform inspections under the appropriate inspection code or standard.

3.1.46
interpass temperature, welding [11]
Highest temperature in the weld joint immediately prior to welding, or in the case of multiple pass welds, the highest temperature in the section of the previously deposited weld metal, immediately before the next pass is started.

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[9] Term not defined in AWS A3.0M/A3.0:2010; definition is based on ASME V (2015), Article 1, I-121.1.

[10] Term not defined in AWS A3.0M/A3.0:2010; definition is loosely based on ASME V (2017), Article 1, I-121.

[11] Definition from ASME IX used as it is more descriptive than that in AWS.

3.1.47
joint penetration
Distance that the weld metal extends from the weld face into a joint, exclusive of weld reinforcement.

3.1.48
joint type
Weld joint classification based on the relative orientation of the member being joined.

NOTE The five basic joint types are butt, corner, edge, lap, and T-joints.

3.1.49
lack of fusion
LOF
See incomplete fusion.

3.1.50
lamellar tear
Subsurface terrace and step-like crack in the base metal with a basic orientation parallel to the wrought surface caused by tensile stresses in the through-thickness direction of the base metals weakened by the presence of small, dispersed, planar-shaped, nonmetallic inclusions parallel to the metal surface.

3.1.51
lamination
Type of discontinuity with separation or weakness generally aligned parallel to the worked surface of a metal.

3.1.52
longitudinal crack
Crack with its major axis orientation approximately parallel to the weld axis.

3.1.53
nondestructive examination
NDE
Act of determining the suitability of a material or component for its intended purpose using methods and techniques that do not affect its serviceability.

3.1.54
nonrelevant indication[12]
NDE indication caused by a condition or type of discontinuity that is not rejectable.

NOTE False indications are nonrelevant. Not all nonrelevant indications are recordable.

3.1.55
overlap
Protrusion of weld metal beyond the weld toe or weld root.

NOTE The term also refers to the portion of the preceding weld nugget remelted by the succeeding weld in resistance seam welding.

3.1.56
oxyacetylene cutting
OFC-A
Oxygen-fuel gas cutting process variation employing acetylene as the fuel gas.

[12] Term not defined in AWS A3.0M/A3.0:2010; definition is from ASME V (2017), Article 1, I-121.

NOTE This is considered a thermal process and is an essential variable for some processes. It is not listed in ASME Section IX.

3.1.57
peening
Mechanical working of metals using impact blows.

3.1.58
porosity
Cavity-type discontinuities formed by gas entrapment during solidification or in a thermal spray deposit.

3.1.59
positive material identification
PMI
Physical evaluation or test of a material to confirm that the material that has been or will be placed into service is consistent with the selected or specified alloy material designated by the owner–user.

3.1.60
preheat
Metal temperature value achieved in a base metal or substrate prior to initiating thermal operations.

NOTE Also equal to the minimum interpass temperature.

3.1.61
procedure qualification record
PQR
Record of welding variables used to produce an acceptable test weldment, and the results of tests conducted on the weldment to qualify a welding procedure specification.

3.1.62
recordable indication
Recording on a datasheet of an indication or condition that does not necessarily exceed the rejection criteria in terms of code or contract, but is documented.

3.1.63
reportable indication
Recording on a datasheet of an indication that exceeds the reject flaw size criteria and requires not only documentation, but also notification to the appropriate authority for correction.

NOTE All reportable indications are recordable indications but not vice versa.

3.1.64
relevant indication[13]
NDE indication caused by a condition or type of discontinuity that requires evaluation.

NOTE All relevant indications are recordable.

3.1.65
reverse polarity
See direct current electrode positive.

[13] Term not defined in AWS A3.0M/A3.0:2010; definition is based on ASME V (2017), Article 1, I-121.

3.1.66
root face
Portion of the groove face within the joint root.

3.1.67
root opening
root spacing
Separation at the joint root between the workpieces.

3.1.68
shielding gas
backing gas
Gases used to produce a protective atmosphere.

3.1.69
slag
Nonmetallic product resulting from the mutual dissolution of flux and nonmetallic impurities in some welding and brazing processes.

3.1.70
slag inclusion
Discontinuity consisting of slag entrapped in weld metal or at the weld interface.

3.1.71
spatter
Metal particles expelled during fusion welding that do not form part of the weld.

NOTE This is a deleterious surface condition that can interfere with subsequent operations such as inspection or coating.

3.1.72
tack weld
Weld made to hold the parts of a weldment in proper alignment until the final welds are made.

3.1.73
temper bead welding
See controlled deposition welding.

3.1.74
throat, theoretical
Distance from the beginning of the joint root perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the cross-section of a fillet weld.

NOTE This dimension is based on the assumption that the root opening is equal to zero.

3.1.75
transverse crack
Crack with its major axis oriented approximately perpendicular to the weld axis.

3.1.76
travel angle
drag angle
push angle
work angle
Angle that is less than 90° between the electrode axis and a line perpendicular to the weld axis, in a plane determined by the electrode axis and the weld axis.

NOTE This angle can also be used to partially define the position of guns, torches, rods, and beams.

3.1.77
tungsten inclusion
Discontinuity consisting of tungsten entrapped in weld metal.

3.1.78
undercut
Groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.

3.1.79
underfill
Groove weld condition in which the weld face or root surface is below the adjacent surface of the base metal.

3.1.80
welder
Person who performs manual or semiautomatic welding.

3.1.81
welder certification
Written verification that a welder has produced welds meeting a prescribed standard of welder performance.

3.1.82
welder performance qualification
WPQ
Demonstration of a welder's or welding operator's ability to produce welds meeting prescribed standards.

3.1.83
welding
Joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal.

3.1.84
welding engineer
Person who holds an engineering degree and is knowledgeable and experienced in the engineering disciplines associated with welding.

3.1.85
welding operator
Person who operates adaptive control, automatic, mechanized, or robotic welding equipment.

3.1.86
welding procedure specification
WPS
Document that provides the required welding variables for a specific application to ensure repeatability by properly trained welders and welding operators.

3.1.87
weldment
Assembly joined by welding.

3.1.88
weld interface
fusion line (nonstandard)
Boundary between weld metal and base metal in a fusion weld, between base metals in a solid-state weld without filler metal, or between filler metal and base metal in a solid-state weld with filler metal.

3.1.89
weld joint
Junction of members or edges of members that are to be joined or have been joined by welding.

3.1.90
weld metal zone
WMZ
Portion of the weld area consisting of weld metal.

NOTE See also base metal zone and heat-affected zone.

3.1.91
weld reinforcement
convexity
face reinforcement
root reinforcement
Weld metal in excess of the quantity required to fill a weld groove.

3.1.92
weld toe
Junction of the weld face and the base metal.

3.1.93
wet fluorescent magnetic-particle examination technique
WFMT
Inspection method suitable only for ferromagnetic materials.

3.2 Acronyms

LT	leak testing/examination method
MT	magnetic particle examination method
NDE	nondestructive examination
PT	dye penetrant examination method
RT	radiographic examination method
VT	visual examination method

4 Welding Processes

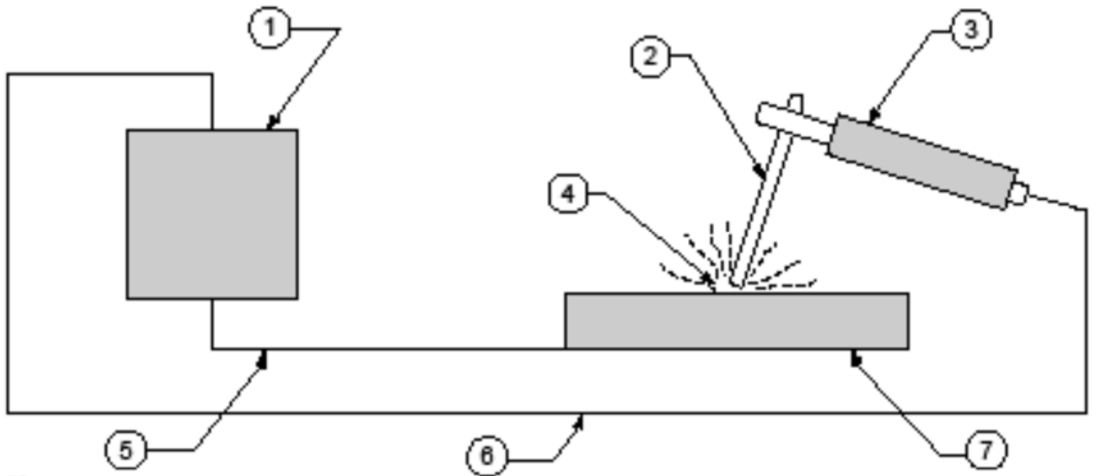
4.1 General

The inspector should understand the basic arc welding processes most frequently used in the fabrication and repair of refinery and chemical process equipment. These processes include shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), flux-cored arc welding (FCAW), submerged arc welding (SAW), stud welding (SW), plasma arc welding (PAW), and electrogas welding (EGW). Descriptions of less frequently used welding process are available in the bibliography. Each process has advantages and limitations depending upon the application and can be prone to specific types of discontinuities.

4.2 Shielded Metal Arc Welding (SMAW)

4.2.1 General

SMAW is the most widely used of the various arc welding processes. SMAW creates an arc between a covered electrode and the weld pool. It employs the heat of the arc, originating from the tip of a consumable covered electrode, to melt the base metal. Shielding is provided by the decomposition of the electrode coating, without the application of pressure, and with filler metal from the electrode. Either alternating current (AC) or direct current (DC) may be employed, depending on the required mechanical properties, welding power supply, and specific electrode selected. A constant-current (CC) power supply is preferred. SMAW is a manual welding process. See Figure 1 and Figure 2 for schematics of the SMAW welding process and electrode deposition, respectively.



Key
1 AC or DC power source and controls
2 electrode
3 electrode holder
4 arc
5 workpiece lead
6 electrode lead
7 workpiece

From Jefferson's Welding Encyclopedia, 18th Edition, Reprinted Courtesy of AWS.

Figure 1—SMAW Welding Process

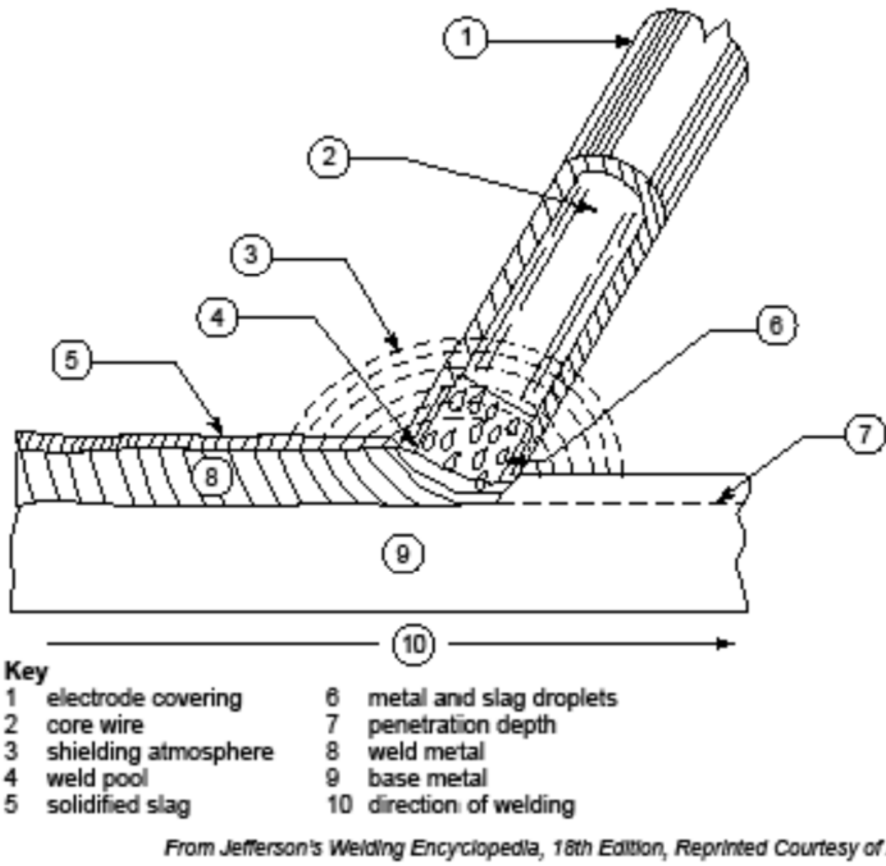


Figure 2—SMAW Welding Electrode Deposition

4.2.2 Electrode Covering

Depending on the type of electrode being used, the covering performs one or more of the following functions:

a) provides a gas to shield the arc and prevent excessive atmospheric contamination of the molten filler metal;

b) provides scavengers, deoxidizers, and fluxing agents to cleanse the weld and prevent excessive grain growth in the weld metal;

c) establishes the electrical characteristics of the electrode, stabilizes the welding arc, and influences operability in various welding positions;

d) provides a slag blanket to protect the molten weld metal from the atmosphere and enhances the mechanical properties, bead shape, and surface cleanliness of the weld metal;

e) provides a means of adding alloying elements to produce appropriate weld metal chemistry and mechanical properties and to increase deposition efficiency.

4.2.3 Advantages of SMAW

Following are some commonly accepted advantages of the SMAW process.

a) The equipment is relatively simple, inexpensive, and portable.

b) The process can be used in areas of limited access.

c) The process is less sensitive to wind and draft than other welding processes.

d) The process is suitable for most of the commonly used metals and alloys.

e) The level of training and experience required is lower than for other welding processes.

4.2.4 Limitations of SMAW

Limitations associated with SMAW include the following.

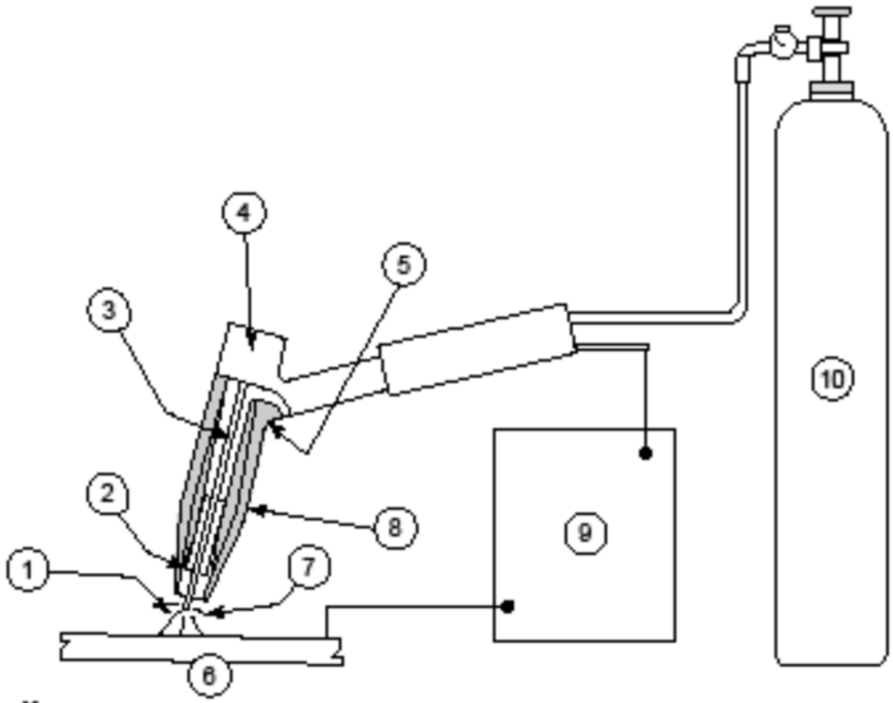
a) Deposition rates are lower than for other processes such as GMAW.

b) Slag must be removed from every deposited weld pass, at stops and starts, and before depositing a weld bead adjacent to or onto a previously deposited weld bead.

4.3 Gas Tungsten Arc Welding (GTAW)

4.3.1 General

GTAW is an arc welding process that generates an arc between a nonconsumable tungsten electrode and the weld pool. The process is commonly, and somewhat incorrectly, referred to as tungsten inert gas (TIG) or heliarc welding, and is used with a shielding gas and without the application of pressure. GTAW can be used with or without the addition of filler metal. The CC-type power supply can be either DC or AC, and depends largely on the metal to be welded. Direct current welding is typically performed with the electrode negative (DCEN) polarity. DCEN welding offers the advantages of deeper penetration and faster welding speeds. Alternating current provides a cathodic cleaning (sputtering) that removes refractory oxides from the surfaces of the weld joint, which is necessary for the welding of nonferrous materials such as aluminum and magnesium. The cleaning action occurs during the portion of the AC wave, when the electrode is positive with respect to the work piece. See Figure 3 and Figure 4 for schematics of the GTAW equipment and welding process.



Key

1	arc	6	workpiece
2	gas passages	7	shielding gas
3	tungsten electrode	8	insulating sheath
4	torch	9	power source
5	electrical conductor	10	inert gas supply

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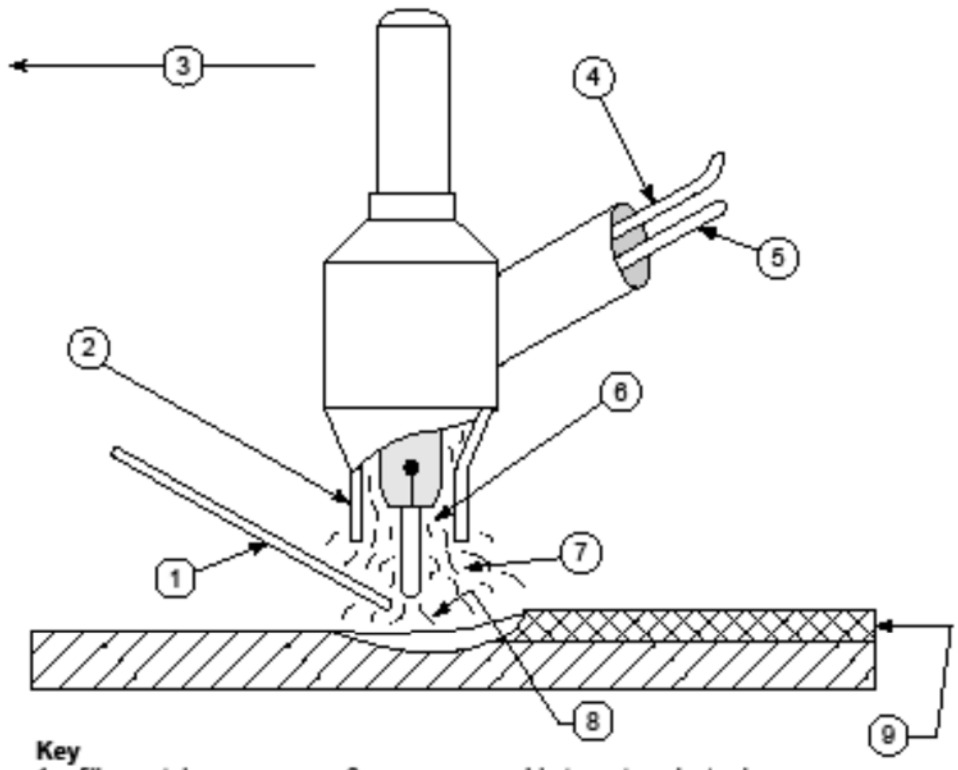
Figure 3—GTAW Welding Equipment



Key

1	filler metal	6	nonconsumable tungsten electrode
2	gas nozzle	7	gas shield
3	direction of welding	8	arc
4	current conductor	9	solidified weld metal
5	shielding gas in		

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Figure 4—GTAW Welding Process

4.3.2 Advantages of GTAW

Some commonly accepted advantages of the GTAW process include the following:

a) produces high purity welds, generally free from defects;

b) requires little postweld cleaning;

c) allows for excellent control of root pass weld penetration;

d) can be used with or without filler metal, dependent on the application;

e) produces a relatively defect- and contaminant-free root pass for those process services that may be more aggressive toward contaminated root passes.

4.3.3 Limitations of GTAW

Limitations associated with GTAW process are:

a) lower deposition rates than the rates possible with consumable electrode arc welding processes,

b) low tolerance for contaminants on filler or base metals,

c) difficulty in shielding the weld zone properly in drafty environments, and

d) greater operator skill is required than that for other methods such as SMAW.

4.4 Gas Metal Arc Welding (GMAW)

4.4.1 General

GMAW is an arc welding process that produces an arc between a continuously fed filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas without the application of pressure. GMAW may be operated in semiautomatic, machine, or automated modes. It employs a constant-voltage (CV) power supply, and uses either the short-circuiting, globular, spray, or pulsed transfer modes to transfer filler metal from the electrode to the work. The transfer mode is determined by several factors. The most influential are:

a) magnitude and type of welding current;

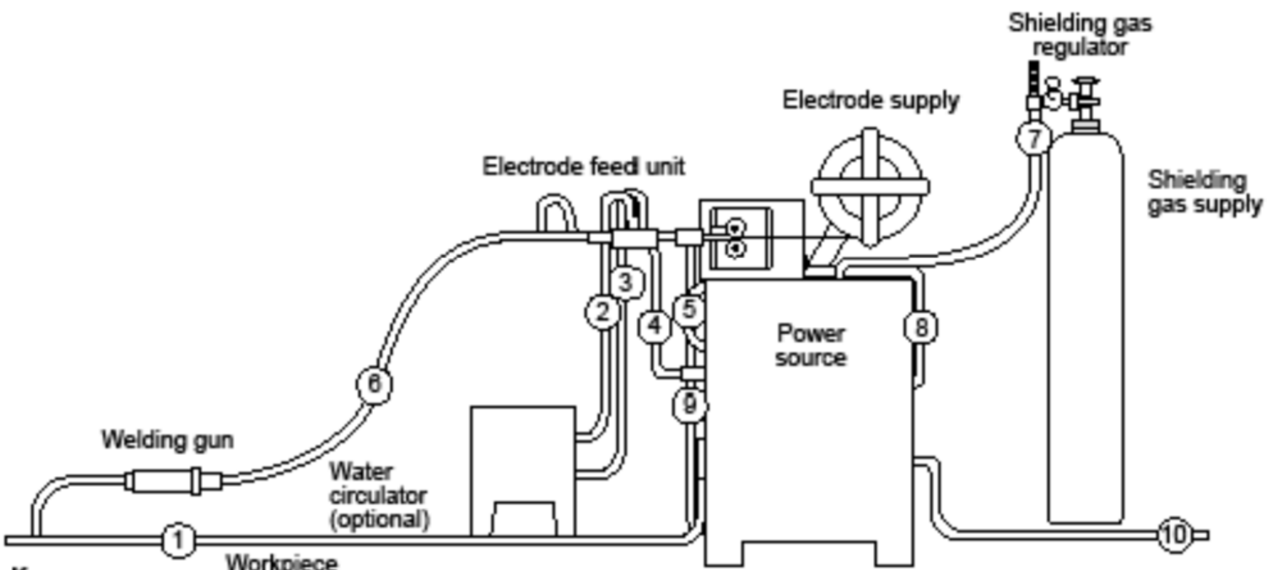
b) electrode diameter;

c) electrode composition;

d) electrode extension or contact tube-to-work distance (often referred to as “stick out”);

e) shielding gas.

See Figure 5 and Figure 6 for schematics of the GMAW equipment and welding process.



Key

1 work lead
2 water to gun
3 water from gun
4 gun switch circuit
5 shielding gas to gun
6 cable assembly
7 shielding gas from cylinder
8 welding contactor control
9 power cable
10 primary input power

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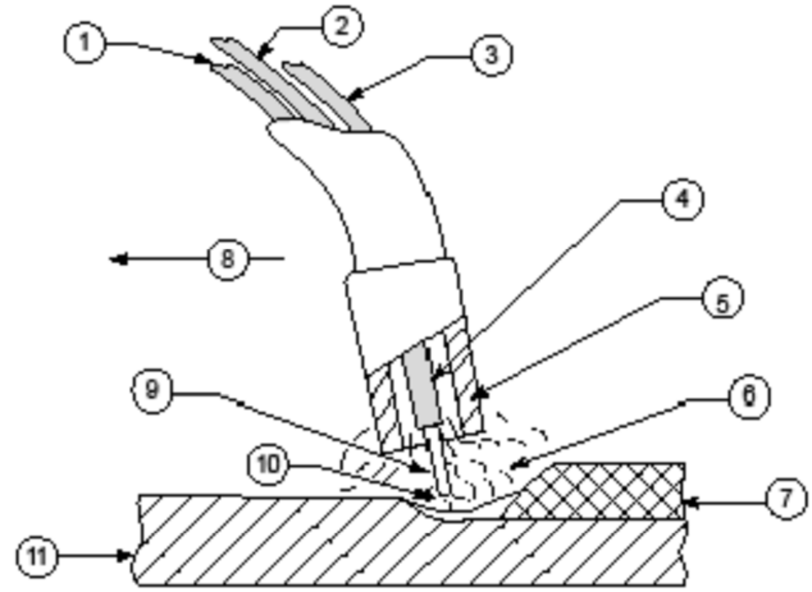
Figure 5—GMAW Equipment



Key

1	shielding gas in	7	weld metal
2	solid electrode wire	8	direction of travel
3	current conductor	9	consumable electrode
4	wire guide and contact tube	10	arc
5	gas nozzle	11	base metal
6	gaseous shield		

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Figure 6—GMAW Welding Process

4.4.2 Short Circuiting Transfer Mode (GMAW-S)

4.4.2.1 General

GMAW-S encompasses the lowest range of both welding current and electrode diameters associated with the GMAW process. This process produces a fast freezing weld pool that is generally suited for joining thin sections, out-of-position welding, or root passes. Due to the fast-freezing nature of this process, there is high potential for lack of sidewall and interpass fusion when welding thick-wall equipment or a nozzle attachment. The shielding gas for this transfer mode is typically 75 % argon with 25 % CO_2.

4.4.2.2 GMAW-MSC Transfer Mode (Modified Short Circuit)

The modified short-circuit GMAW mode, designated the GMAW-MSC process, has several proprietary derivatives of the short-circuiting transfer mode that use a modified waveform to reduce some problems associated with short-circuiting—mainly, spatter and a turbulent weld pool. These systems typically sense the progression of the short circuit as it occurs and modulate the current to limit the amount of force behind spatter and turbulence-producing events. GMAW-MSC power sources are software-driven to maintain optimum arc characteristics by closely monitoring and controlling the electrode current during all phases of the short circuit. There are a limited number of companies that manufacture welding power supplies that employ this technology.

The GMAW-MSC transfer mode minimizes the disadvantages of GMAW-S while maintaining comparable weld metal deposition rates and achieving X-ray quality welds. The welding process has the capability to complete open root welds more rapidly than GTAW, with low heat input and no resulting lack of fusion (LOF). The lower heat input results in smaller heat-affected zones (HAZ) as well as reduced distortion and lesser chance of burn-through. The process appears to be more tolerant of inexperienced welders because GMAW-MSC is tolerant of gaps and capable of automatically maintaining the optimum wire feed speed and contact tip-to-work distance, while allowing the use of larger diameter GMAW consumables.

4.4.3 Globular Transfer Mode

The advantages of this transfer method are its relative low cost when carbon dioxide is used as a shielding gas, along with a high deposition rate. The maximum deposition rate for the globular arc transfer mode is about 6350 mm/min (250 in./min).

The globular arc transfer mode is often considered the least desirable of the GMAW transfer modes due to its tendency to produce high heat, a poor weld surface, and weld spatter, as well as cold lap. This transfer mode uses relatively low current (less than 250 A). During welding, a ball of molten metal from the electrode tends to build up on the end of the electrode, often in irregular shapes, with a diameter up to twice that of the electrode. When the droplet detaches (i.e. by gravity or short circuiting) and is forced onto the work piece, it produces an uneven surface as well as excessive weld spatter. This transfer mode produces a high amount of heat and forces the welder to use a larger electrode wire to maintain a stable arc, which increases the size of the weld pool and causes greater residual stresses and distortion in the weld area. This welding process uses 100 % carbon dioxide as the shielding gas, and is limited to the flat and horizontal positions.

4.4.4 Spray Transfer Mode

The spray transfer mode results in a highly directed stream of discrete drops that are accelerated by arc forces. Since these drops are smaller than the arc length, short circuits do not occur and the amount of spatter generated is negligible. The inert gas shield allows the spray arc transfer mode to weld most metals. However, using this process on materials thinner than 0.250 in. (6 mm) may be difficult because of the high currents needed to produce the spray arc. The spray transfer mode allows for high weld metal deposition rates. At high deposition rates, the welding process may produce a weld metal pool that is too weak to be supported by surface tension alone (primarily dependent upon electrode diameter), which limits the use of the welding process in the vertical and overhead positions. Specialized power supplies have been developed to address the work thickness and welding position limitations. The maximum deposition rate for the spray arc transfer mode is about 150 in./min (3810 mm/min). This transfer mode is typically 98 % argon, 2 % oxygen. Depending upon the wire diameter and amperage, the shielding gas may have composition 80 % argon, 20 % oxygen.

4.4.5 Pulsed Transfer Mode

Pulsed arc GMAW was developed to overcome the thickness and welding position limitations of the Globular, Spray, and Short Circuit modes. This transfer mode provides:

a) a low background/constant current to sustain the arc without providing enough energy to produce drops at the tip of the wire; and

b) a superimposed/pulsing current with an amplitude greater than the transition current necessary for spray transfer.

During the pulsing portion of the current cycle, one or more drops are formed and transferred to the workpiece. The frequency and amplitude of the pulses control the rate at which the wire melts. Pulsing provides the desirable features of spray arc transfer for joining sheet metals and welding in all positions. The maximum deposition rate for the pulsed arc transfer mode is about 5080 mm/min (200 in./min). The pulsed arc GMAW method requires a power source capable of providing current pulses with a frequency between 30 pulses/s and 400 pulses/s, and requires that the shielding gas be primarily argon with a low carbon dioxide concentration. The same shielding gas used for the spray transfer mode is typically used for the pulsed transfer mode as well.

4.4.6 Advantages of GMAW

Some commonly accepted advantages of the GMAW process include the following.

a) It is the only consumable electrode process that can be used to weld most commercial ferrous and nonferrous metals and alloys.

b) Its deposition rates are significantly higher than those obtained with SMAW and GTAW.

c) Minimal postweld cleaning is required due to the absence of slag.

4.4.7 Limitations of GMAW

Limitations associated with GMAW include the following.

a) The welding equipment is more complex, more costly, and less portable than that for SMAW.

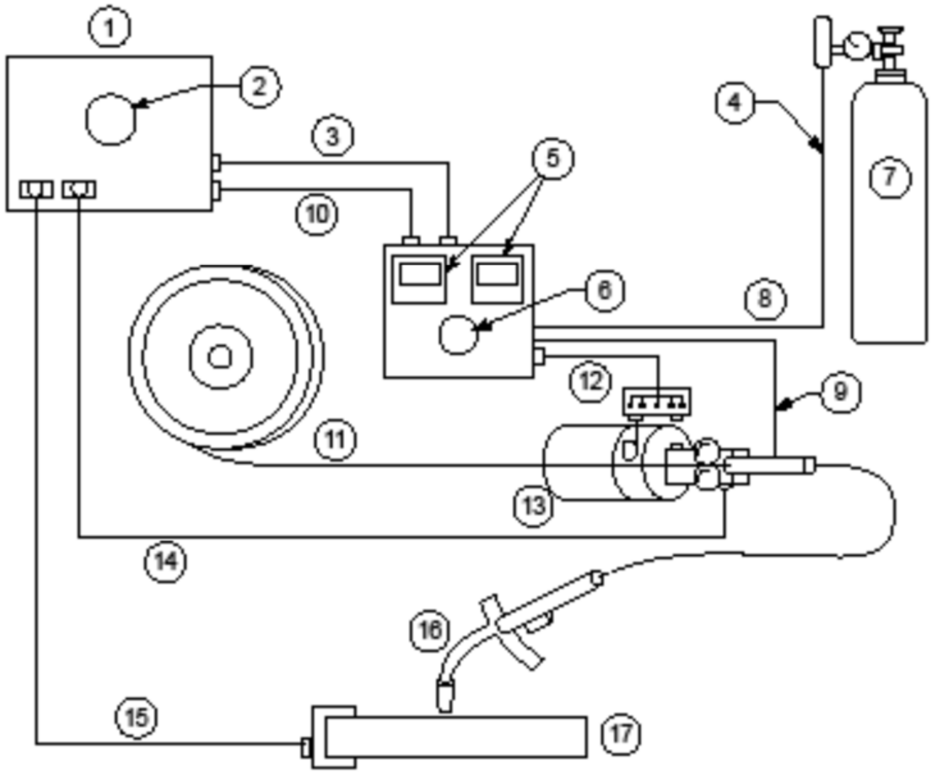
b) The welding arc must be protected from air drafts that can disperse the shielding gas.

c) When using the GMAW-S process, the weld is more susceptible to lack of adequate fusion (see Section 11.3). As a result, ultrasonic examination (UT) is generally employed as the inspection method because the probability of detecting LOF is rather low using radiographic examination (RT) (see Sections 8.8 and 8.9).

4.5 Flux-Cored Arc Welding (FCAW)

4.5.1 General

FCAW is an arc welding process that produces an arc between a continuously fed tubular electrode and the weld pool. The process is used with shielding gas evolved from a flux contained within the tubular electrode itself, with or without additional shielding from an externally supplied gas, and without the application of pressure. Normally a semiautomatic process, the use of FCAW depends on the type of electrodes available, the mechanical property requirements of the welded joints, and the joint designs and fit-up. The recommended power source is the DC CV type, similar to power sources used for GMAW. Figure 7 shows a schematic of FCAW equipment, and Figure 8 shows the welding process with additional gas shielding. Figure 9 shows a schematic of the self-shielded FCAW process where no additional gas is used.



Key

1 direct current constant voltage power source
2 voltage control
3 contactor control
4 to solenoid valve
5 voltmeter and ammeter
6 wire feed (current control)
7 shielding gas source
8 gas in
9 gas out
10 115 V supply
11 wire reel
12 control leads
13 wire drive motor
14 electrode power cable
15 workpiece cable
16 welding gun
17 work

Note Gas shielding is used only with flux cored electrodes that require it.

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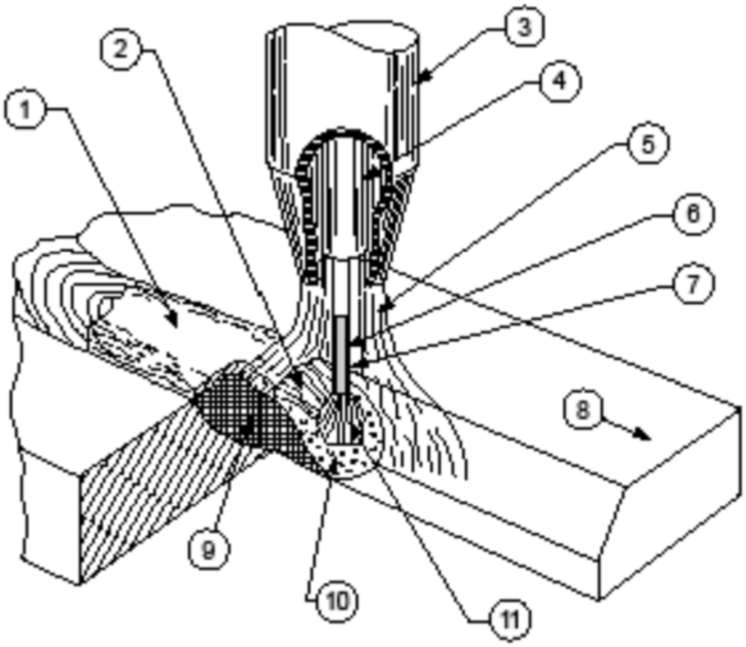
Figure 7—FCAW Equipment



Key
1 solidified slag
2 molten slag
3 gas nozzle
4 wire guide and contact tube
5 shielding gas
6 tubular electrode
7 powdered metal, flux and slag forming materials
8 direction of welding
9 solidified weld metal
10 weld pool
11 arc and metal transfer

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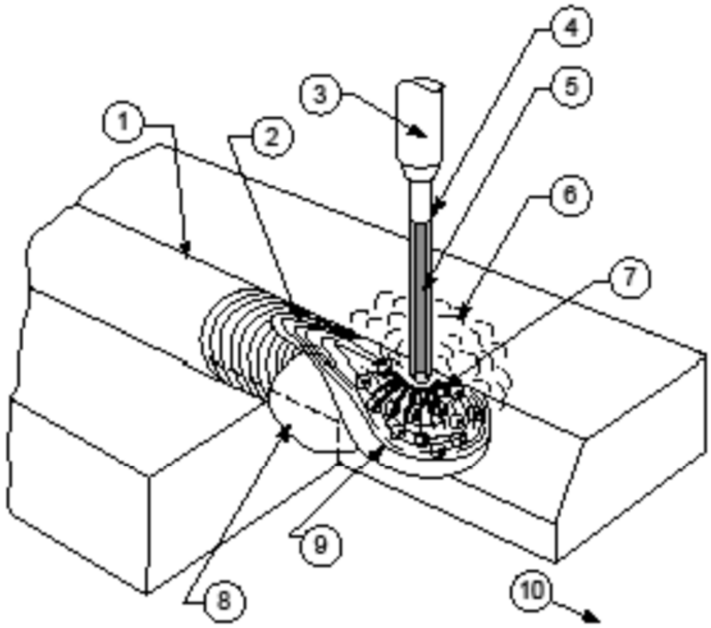
Figure 8—FCAW Welding Process



Key
1 solidified slag
2 molten slag
3 wire guide and contact tube
4 tubular electrode
5 powdered metal, vapor forming materials, deoxidizers, and scavengers
6 arc shield composed of vaporized and slag forming compounds
7 arc and metal transfer
8 weld metal
9 weld pool
10 direction of welding

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Figure 9—FCAW Welding Process, Self-shielded

4.5.2 Advantages of FCAW

Some commonly accepted advantages of the FCAW process include:

a) metallurgical benefits that can be derived from alloying elements contained within the flux;

b) slag that supports and shapes the weld bead, allowing for a slower cooling rate;

c) higher deposition and productivity rates compared to other processes such as SMAW and GTAW;

d) shielding produced at the surface of the weld that makes it more tolerant of stronger air currents than GMAW.

4.5.3 Limitations of FCAW

The following limitations are associated with the FCAW process.

a) The equipment is more complex, more costly, and less portable than that for SMAW.

b) Self-shielding FCAW generates large volumes of welding fumes and requires suitable exhaust equipment.

c) Slag must be removed between weld passes and removed from surfaces planned for inspection. If a weld is being placed in corrosive service, failure to remove slag from the weld cap or root can create sites for corrosion to initiate.

d) Backing material is required for root pass welding.

e) Self-shielded FCAW is typically not recommended for pressure-containing welds.

4.6 Submerged Arc Welding (SAW)

4.6.1 General

SAW is an arc welding process that uses an arc or arcs between a flux-covered bare metal electrode(s) and the weld pool. The arc and molten metal are shielded by a blanket of granular flux, supplied through the welding nozzle from a hopper. The process is used without pressure, and with filler metal from the electrode itself and sometimes from a supplemental source (welding electrode, flux, or metal granules). SAW can be applied in three different modes: semiautomatic, automatic, and machine. It can utilize either a CV or CC power supply. SAW is used extensively in shop pressure vessel fabrication and pipe manufacturing. Figure 10 shows a schematic of the SAW process.

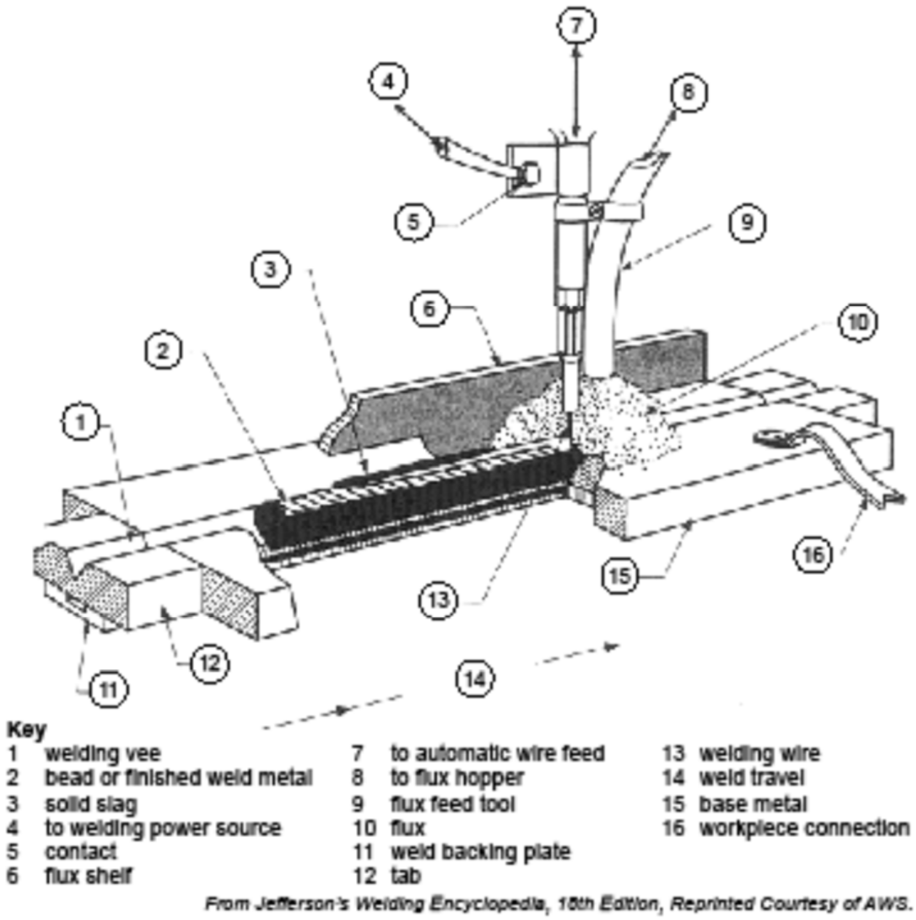


Figure 10—SAW Welding Process

4.6.2 Advantages of SAW

Some commonly accepted advantages of the SAW process are the following.

a) It provides very high metal deposition rates.

b) It produces repeatable high-quality welds for large weldments and repetitive short welds.

4.6.3 Limitations of SAW

The following limitations are associated with SAW.

a) A power supply capable of providing high amperage at 100 % duty cycle is recommended.

b) The weld is not visible during the welding process.

c) Equipment required is more costly and extensive and less portable;

d) The process is generally limited to shop applications and flat position.

4.7 Stud Arc Welding (SW)

4.7.1 General

SW is an arc welding process that generates an arc between a metal stud or similar part and the work piece. A stud gun holds the tip of the stud against the work. Once the surfaces of the parts are properly heated (i.e. when the end of the stud is molten and the work has an equal area of molten pool), they are brought into contact by the application of pressure. Shielding gas or flux may or may not be employed. The process may be fully automatic or semiautomatic. Direct current is typically used for SW with the stud gun connected to the negative terminal (DCEN). The power source is a CC type.

SW is a specialized process predominantly limited to welding insulation and refractory support pins to tanks, pressure vessels and heater casings.

4.7.2 Advantages of SW

Some commonly accepted advantages of the SW process include:

a) high productivity rates compared to manually welding studs to base metal;

b) it is considered to be an all-position process.

4.7.3 Limitations of SW

Limitations of SW are the following:

a) the process is primarily suitable for only carbon steel and low-alloy steels;

b) the process is specialized to a few applications.

4.8 Plasma Arc Welding (PAW)

4.8.1 General

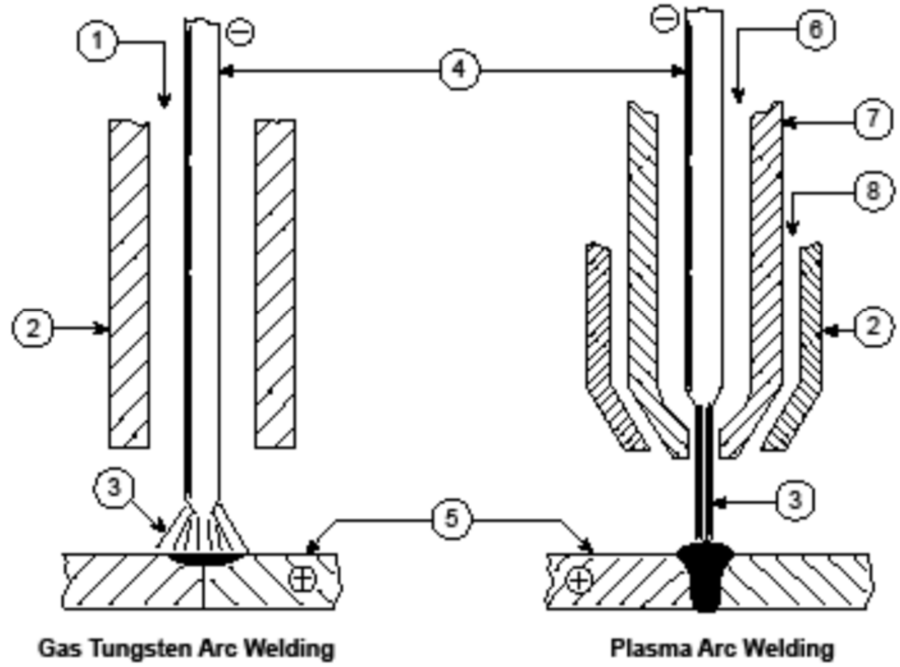
PAW is a variation of the GTAW process except that the tungsten electrode is positioned within the body of the torch. This process is rarely used in the fabrication and repair of pressure equipment. There are two types of plasma arc welding, specifically the transferred arc process and nontransferred arc process.

4.8.2 Plasma Transferred Arc (PTA)

In the PTA process, similar to GTAW, the workpiece is part of the electrical circuit, and the arc is struck between the tungsten electrode and the workpiece. By constricting the arc, the plasma or ionized gas is forced through a fine-bore copper nozzle which constricts the arc, and exits the orifice at high velocities (approaching the speed of sound). The process produces a collimated arc which focuses the arc on a relatively small area of the workpiece with an arc temperature in excess of 20,000 °F (11,100 °C).

4.8.3 Nontransferred Arc or Plasma Spray (PS)

In the PS process, the arc is struck between the tungsten electrode and the constricting nozzle rather than with the workpiece. The plasma spray process is solely used for the deposition of surface coatings. It is not used for making strength welds. A comparison of the GTAW and PAW circuits and welding processes is shown in Figure 11.



Key
1 shielding gas
2 shielding gas nozzle
3 arc plasma
4 electrode
5 workpiece
6 orifice gas shielding
7 constricting nozzle
8 shielding gas

Figure 11—Comparison of the Gas Tungsten Arc and Plasma Arc Welding Processes

4.8.4 Advantages of PAW

Some commonly accepted advantages of the PAW process include:

a) high tolerance for misalignment in the arc;

b) high welding rate;

c) high penetrating capability (keyhole effect);

d) less distortion resulting from lower total heat input due to focused arc;

e) the weld itself and the HAZ are narrower than in traditional GTAW due to the constricted arc.

4.8.5 Limitations of PAW

The limitations of PAW include:

a) expensive equipment;

b) larger torch than GTAW making access more difficult in narrow weld joints;

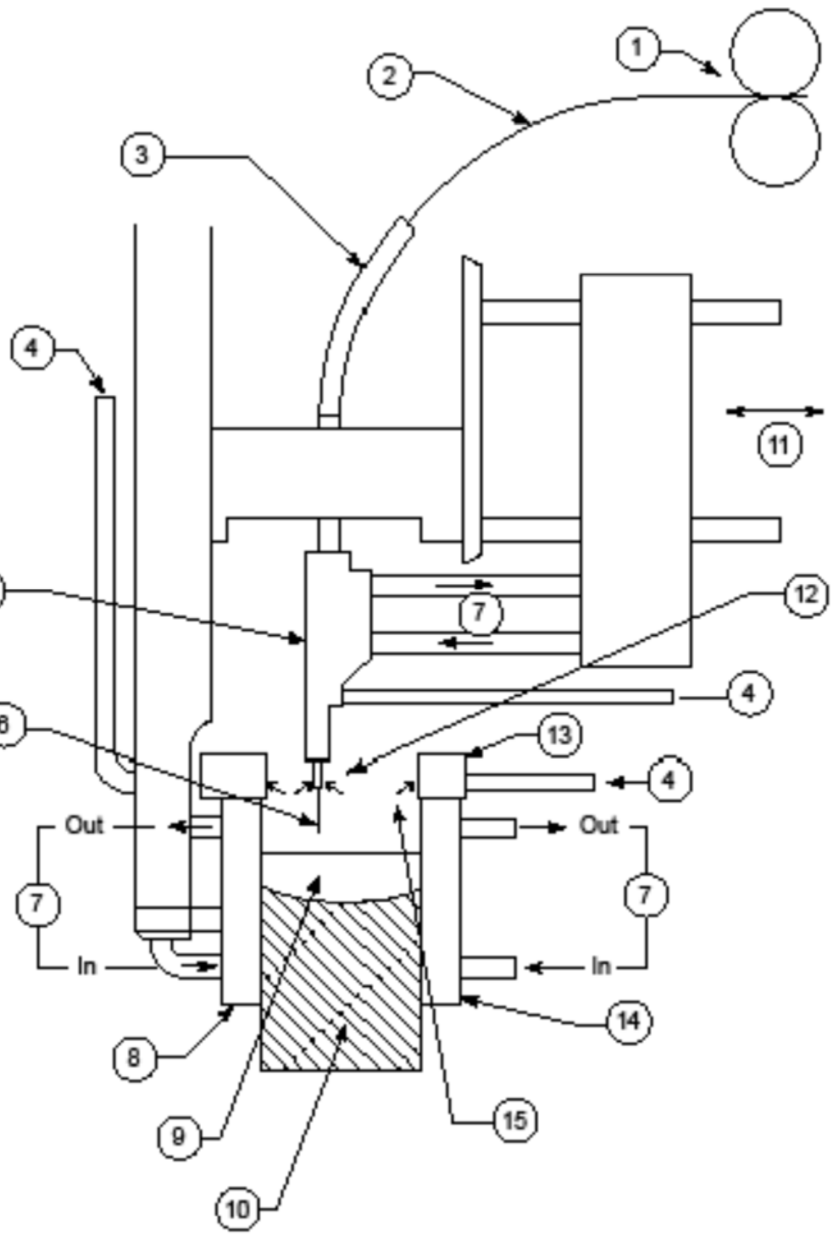
c) focused arc requiring better control by the welder.

4.9 Electrogas Welding (EGW)

4.9.1 General

EGW is similar to the GMAW process in that a solid electrode can be fed into the joint. Alternately, it is similar to the FCAW process in that a flux cored tubular electrode can be used. The weld is deposited in the flat position with the molten metal continually being deposited at the bottom of the moving cavity. In EGW, fixed or moving metal (usually copper) or ceramic shoes (or dams), water cooled if needed, are set up before starting, to bridge the gap between abutting plates and contain the molten metal until solidification is completed. The welding process utilizes either a solid wire or flux-cored electrode. The weld area is protected from atmospheric contamination by an externally supplied shielding gas, or by the gas produced by the disintegration of the flux-cored electrode wire. EGW is used to make square-groove welds for butt and T-joints in the construction of storage tanks, ship hulls, and pressure vessels with plate thicknesses from $^{3}/_{8}$ in. to 4 in. (9 mm to 100 mm). The workpiece should be at least 0.4 in. (10 mm) thick, while the maximum thickness for one electrode is approximately 0.8 in. (20 mm). Additional electrodes make it possible to weld thicker workpieces. The height of the weld is limited only by the mechanism used to lift the welding head. In general, the height ranges from 4 in. to 50 ft (100 mm to 15 m).

Low and medium carbon steels, low-alloy high-strength steels, and some stainless steels can be welded using the electrogas process. Quenched and tempered steels may also be welded by the process, provided adequate heat is applied. Figure 12 shows an EGW setup using a solid electrode.



Key

1 drive rolls
2 welding wire
3 electrode conduit
4 gas
5 electrode guide
6 welding wire
7 water
8 fixed shoe
9 weld pool
10 solidified weld metal
11 oscillator
12 primary shielding gas
13 gas box
14 adjustable shoe
15 supplementary shielding gas

Figure 12—Electrogas Welding With a Solid Electrode

4.9.2 Advantages of EGW

Some commonly accepted advantages of the EGW process include the following:

a) welding usually done in one pass;

b) very high deposition rates;

c) minimum distortion;

d) ability to add beneficial alloying elements to the weldment.

4.9.3 Limitations of EGW

Some limitations of EGW include:

a) low toughness;

b) massive, expensive welding equipment and guidance systems required;

c) lengthy set-up times needed;

d) can only be used with vertically positioned joints;

e) can require external source of shielding gas.

5 Welding Materials

5.1 General

Welding materials refers to the many materials involved in welding, including the base metal, filler metal, fluxes, and gases, if any, as each of these has an impact on the welding procedure specification (WPS) and the weldment mechanical properties. An understanding of the conventions used by the ASME Section IX is necessary to adequately review a qualified welding procedure.

5.2 P-Number Assignment to Base Metals

Base metals are assigned P-numbers in ASME Section IX to reduce the number of welding procedure qualifications required. For ferrous base metals having specified impact test requirements, group numbers within P-numbers are assigned, which may become essential variables under certain circumstances. These assignments are based on comparable base metal characteristics such as composition, weldability, and mechanical properties. Table 1 lists the assignments of base metals to P-numbers.

A complete listing of P-number, S-number, and group number assignments are provided in QW/QB-422 of ASME Section IX. This list is an ascending sort based on specification numbers. Specification numbers grouped by P-number and group number are also listed in ASME Section IX nonmandatory Annex D. Within each list of the same P-number and group number, the specifications are listed in an ascending sort.

Table 1—P-Number Assignments

Base Metal	Welding	Brazing
Steel and alloys	P-No.1 through P-No. 11, including P-No. 5A, 5B, 5C, and 15E	P-No. 101 through P-No. 103
Aluminum and aluminum-base alloys	P-No. 21 through P-No. 25	P-No. 104 and P-No. 105
Copper and copper-base alloys	P-No. 31 through P-No. 35	P-No. 107 and P-No. 108
Nickel and nickel-base alloys	P-No. 41 through P-No. 47	P-No. 110 through P-No. 112
Titanium and titanium-base alloys	P-No. 51 through P-No. 53	P-No. 115
Zirconium and zirconium-base alloys	P-No. 61 through P-No. 62	P-No. 117

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5.3 F-Number Assignment to Filler Metals

Electrodes and welding rods are assigned F-numbers to reduce the number of welding procedure and performance qualifications. The F-number groupings are based primarily upon their usability characteristics, which fundamentally determines the ability of welders to make satisfactory welds for a given process and filler metal.

Welders who qualify with one filler metal are qualified to weld with all filler metals having the same F-number, and in the case of carbon steel SMAW electrodes, may additionally qualify to weld with electrodes having lower F-numbers. For example, a welder who qualified with an E7018 (an F-4 electrode) is qualified to weld with all F-4 electrodes, plus all F-1, F-2, and F-3 electrodes (with backing limitations). However, other F-numbers, such as F-6, qualify for that F-number alone. The grouping does not imply that base metals or filler metals within a group may be indiscriminately substituted for a metal that was used in the qualification test. Consideration should be given to the compatibility of the base and filler metals from the standpoint of metallurgical properties, postweld heat treatment, design and service requirements, and mechanical properties.

A complete list of F-numbers for electrodes and welding rods is addressed in ASME Section IX, Table QW-432.

5.4 AWS Classification of Filler Metals

An AWS classification number identifies welding electrodes and rods. The AWS classification numbers are specified in ASME Section IIC under their appropriate SFA specification number. ASME Section IX, Table QW-432, lists the AWS classification numbers and SFA specification numbers included under each of the F-numbers. Note that the Xs in the AWS classification numbers represent numerals, i.e. the AWS classifications E6010, E7010, E8010, E9010, and E10010 are incorporated under F-number 3 (EXX10). Annex A contains additional details on the conventions used in identification of filler metals for welding processes.

5.5 A-Number

To minimize the number of welding procedure qualifications, steel and steel-alloy filler metals are also grouped according to their A-number. The A-number grouping in ASME Section IX, Table QW-442, is based on the chemical composition of the deposited weld metal. This grouping does not imply that filler metals may be indiscriminately substituted without consideration for the compatibility with the base metal and the service requirements.

5.6 Filler Metal Selection

Inspectors should verify the filler metal selection is appropriate for the base metal being welded. Some considerations in selection include:

a) chemical composition of filler metal;

b) tensile strength of filler metal and base metal;

c) dilution of alloying elements from base metal;

d) hardenability of filler metal;

e) susceptibility to hot cracking;

f) corrosion resistance of filler metal;

g) toughness.

Annex D provides a guide of common filler metals for base metals most often used in petrochemical plants. In addition, Table D.4 compares the current AWS filler metal classifications to the previous ones for low-alloy steels. AWS has modified the classifications for several common low-alloy filler metals.

5.7 Consumable Storage and Handling

Welding consumable storage and handling guidelines should be in accordance with the consumable manufacturer's instructions and guidelines and as given in the AWS A5.XX series of filler metal specifications. Covered electrodes exposed to moisture can become unstable due to moisture pickup by the coating. Particularly susceptible to moisture pickup are coatings on low-hydrogen electrodes and stainless-steel electrodes. Moisture can be a source of hydrogen, which can cause weldment cracking.

To reduce exposure to moisture, certain welding consumables should be stored in heated holding ovens after they have been removed from the manufacturer's packaging. Low-hydrogen SMAW electrodes are characterized by a final identification digit of 5, 6, or 8 (e.g. E7016, E8018) and are supplied in non-hermetically sealed containers. Some manufacturers recommend that these electrodes be warmed according to specific temperature requirements prior to use. The electrodes should be stored separately from other types of electrodes with higher hydrogen content, such as cellulose-based electrodes (E6010, E8010), as these can be a primary source of hydrogen pickup. Some welding consumables that are slightly damp can be reconditioned by baking in separate special ovens; however, this is not a universally accepted practice. Electrode ovens should be heated by electrical means and have automatic heat controls and visible temperature indicators. These ovens should only be used for electrode storage, as using them for food storage or cooking could cause the electrode coatings to absorb moisture. Any electrodes or fluxes that have become wet should be discarded.

6 Welding Procedure

6.1 General

Qualified welding procedures are required for welding fabrication and repair of pressure vessels, piping, tanks, and other items. These procedures detail the steps necessary to make a specific weld and generally consist of a written description, details of the weld joint and welding process variables, and test data to demonstrate that the procedure produces weldments meeting design requirements.

While various codes and standards exist for the development of welding procedures, this section reflects criteria described in ASME BPVC Section IX. Welding procedures qualified to ASME Section IX are required by API inspection codes for both fabrication and repair welding. However, construction codes and proprietary company specifications may have additional requirements or allow specific additions or exceptions, so they should be reviewed for each weld application.

Welding procedures required by ASME Section IX include a written WPS and an attendant document called a procedure qualification record (PQR). The purpose of the WPS is to provide specific direction to the person applying the material during the welding process. As well as defining parameters for the welder or welding operator, the WPS also provides information to the welding inspector to measure a weld against the relevant WPS.

The PQR is a record of the welding data and variables used to weld a test coupon and the test results used to qualify the WPS. The purpose of PQR is to demonstrate that the joining process proposed for construction is capable of producing joints having the required mechanical properties for the intended application.

It is important to differentiate the PQR from the welder performance qualification (WPQ), detailed in Section 7. The purpose of the WPQ is to provide a record of the welding variables and results of tests conducted on a weldment to establish that the welder is capable of making an acceptable quality weld using an appropriate WPS.

6.2 Welding Procedure Specification (WPS)

6.2.1 General

ASME Section IX requires each organization to develop welding procedures to be used in the fabrication or repair of components. While this requirement may appear repetitious, qualified WPSs are an important aspect of fabrication quality control. They help each organization recognize the significance of changes in welding variables that may be required on the job and the effects of the changes on weldment properties. The WPS is only one step for welding fabrication quality assurance. Some codes and standards allow welding procedure qualification by others, provided the qualification is acceptable to the inspector and meets other conditions imposed by the referencing code or standard.

The complete WPS for a welding process addresses all essential, supplementary essential, and nonessential variables when impact testing is required, or when specified by the end user (see ASME Section IX QG-101). Essential variables affect the mechanical properties of the weld. If they are changed beyond what the reference code paragraph allows for the process, the WPS shall be requalified. Nonessential variables do not affect the mechanical properties of the weld. They may be changed on the WPS without requalifying the welding procedure. When supplementary essential variables apply, or when specified by the end user, they are treated as essential variables.

6.2.2 Types of Variables (Refer to C.4.1)

6.2.2.1 Essential, Supplementary Essential, and Nonessential Variables for Shielded Metal Arc Welding (SMAW)

Article IV Paragraph		Process Variable	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Joints QW-402	.1	Change in groove design					X	
	.5	The deletion of backing					X	
	.10	Change in root spacing					X	
	.11	The addition or deletion of retainers					X	
Base Metals QW-403	.5	Change in the group number			X	X		
	.6	Base metal thickness (T) limits toughness			X	X		
	.8	Base metal thickness (T) qualified	X	X				
	.11	The change in P-number qualified	X	X				
Filler Metals QW-404	.3	A change in the size of filler metal					X	
	.4	A change in the F-number	X	X				
	.5	A change in the A-number	X	X				
	.12	A change in the filler metal classification			X	X		
	.14	The addition or deletion of filler metal	X	X				
	.22	The addition or deletion of a consumable insert					X	
	.23	A change in the filler metal product form	X	X				
	.30	Change in the deposited weld thickness (t)	X	X				
	.33	A change in the classification					X	
Positions QW-405	.1	The addition of a position					X	
	.2	A change of position			X	X		
	.3	A change from vertical up to vertical down progression					X	
Preheat QW-406	.1	Decrease > 100 °F preheat temperature	X	X				
	.3	Increase > 100 °F interpass temperature			X	X		
PWHT QW-407	.1	A change in PWHT	X	X				
	.2	A change in PWHT (time and temperature range)			X	X		
Gas QW-408	.1	The addition or deletion of trail gas and/or change in composition					X	
	.2	A change from a single gas, mixture, or percentage	X	X				
	.3	A change in the shielding gas flow rate or mixture					X	
	.5	The addition or deletion of backing gas or flow					X	
	.9	The deletion of backing gas or a change in composition	X	X				
	.10	The deletion of trail gas or a change in composition	X	X				

Article IV Paragraph		Process Variable	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Electrical Characteristics QW-409	.1	Heat input increase			X	X		
	.3	The addition or deletion of a pulsing current					X	
	.4	A change in current type (AC, DC) and polarity			X	X	X	
	.8	A change in the amperage range					X	
	.12	A change in tungsten electrode type and size					X	
Technique QW-410	.1	A change in string or weave bead					X	
	.3	A change in orifice, cup, or nozzle size					X	
	.5	A change in the method of cleaning					X	
	.6	A change in the method of back gouging					X	
	.7	A change in oscillation technique					X	
	.9	A change from multiple to single pass welding per side			X	X	X	
	.10	A change from single to multiple electrodes			X	X	X	
	.11	A change from closed to out of chamber	X	X				
	.15	A change in electrode spacing					X	
	.25	A change from manual to automatic					X	
	.26	The addition or deletion of peening					X	
	.64	The use of a thermal process	X	X				

NOTE 1 WPS Contents: See QW-200.1(b).
NOTE 2 PQR Contents: See QW-200.2(b).
NOTE 3 ASME Section IX must be utilized in conjunction with this table; see Article IV, *Weld Data*.
NOTE 4 Nonessential variables may be included on the PQR but are not required.

Reference: ASME Section IX, Table QW-256, *Welding Variables—Gas Tungsten—Arc Welding (GTAW).*

6.2.2.2 Essential, Supplementary Essential, and Nonessential Variables for Gas Tungsten Arc Welding (GTAW)

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Joints QW-402	.1	Change in groove design					X	
	.5	The deletion of backing					X	
	.10	Change in root spacing					X	
	.11	The addition or deletion of retainers					X	

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Base Metals QW-403	.5	Change in the group number			X	X		
	.6	Base metal thickness (T) limits toughness			X	X		
	.8	Base metal thickness (T) qualified	X	X				
	.11	The change in P-number qualified	X	X				
Filler Metals QW-404	.3	A change in the size of filler metal					X	
	.4	A change in the F-number	X	X				
	.5	A change in the A-number	X	X				
	.12	A change in the filler metal classification			X	X		
	.14	The addition or deletion of filler metal	X	X				
	.22	The addition or deletion of a consumable insert					X	
	.23	A change in the filler metal product form	X	X				
	.30	Change in the deposited weld thickness (t)	X	X				
	.33	A change in the classification					X	
Positions QW-405	.1	The addition of a position					X	
	.2	A change of position			X	X		
	.3	A change from vertical up to vertical down progression					X	
Preheat QW-406	.1	Decrease > 100 °F preheat temperature	X	X				
	.3	Increase > 100 °F Interpass temperature			X	X		
PWHT QW-407	.1	A change in the PWHT	X	X				
	.2	A change in PWHT (time and temperature range)			X	X		
Gas QW-408	.1	The addition or deletion of trail gas and/or change in composition					X	
	.2	A change from a single gas, mixture, or percentage	X	X				
	.3	A change in the shielding gas flow rate or mixture					X	
	.5	The addition or deletion of backing gas or flow					X	
	.9	The deletion of backing gas or a change in composition	X	X				
	.10	The deletion of trail gas or a change in composition	X	X				
Electrical Characteristics QW-409	.1	Heat input increase			X	X		
	.3	The addition or deletion of a pulsing current					X	
	.4	A change in current type (AC, DC) and polarity			X	X	X	
	.8	A change in the amperage range					X	
	.12	A change in tungsten electrode type and size					X	

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Technique QW-410	.1	A change in string or weave bead					X	
	.3	A change in orifice, cup, or nozzle size					X	
	.5	A change in the method of cleaning					X	
	.6	A change in the method of back gouging					X	
	.7	A change in oscillation technique					X	
	.9	A change from multiple to single pass welding per side			X	X	X	
	.10	A change from single to multiple electrodes			X	X	X	
	.11	A change from closed to out of chamber	X	X				
	.15	A change in electrode spacing					X	
	.25	A change from manual to automatic					X	
	.26	The addition or deletion of peening					X	
	.64	The use of a thermal process	X	X				
NOTE 1 WPS Contents: See QW-200.1(b). NOTE 2 PQR Contents: See QW-200.2(b). NOTE 3 ASME Section IX must be utilized in conjunction with this table; see Article IV, *Weld Data.* NOTE 4 Nonessential variables may be included on the PQR but are not required.								

Reference: ASME Section IX, Table QW-256, *Welding Variables—Gas Tungsten—Arc Welding (GTAW).*

6.2.2.3 Essential, Supplementary Essential, and Nonessential Variables for Gas Metal Arc Welding (GMAW) and Flux-Cored Arc Welding (FCAW)

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Joints QW-402	.1	Change in groove design					X	
	.5	The deletion of backing					X	
	.10	Change in root spacing					X	
	.11	The addition or deletion of retainers					X	
Base Metals QW-403	.5	Change in the group number			X	X		
	.6	Base metal thickness (T) limits toughness			X	X		
	.8	Base metal thickness (T) qualified	X	X				
	.9	t pass > ½ in. (13 mm)	X	X				
	.10	T limits (S. cir. Arc)	X	X				
	.11	Change in P-number qualified	X	X				

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Filler Metals QW-404	.4	A change in the F-number	X	X				
	.5	A change in the A-number	X	X				
	.6	Change in filler metal diameter					X	
	.12	A change in the filler metal Classification			X	X		
	.23	Change in filler metal product form	X	X				
	.24	Addition/deletion or change in supplemental filler metal	X	X				
	.27	Change in alloy elements	X	X				
	.30	Change in the deposited weld thickness (t)	X	X				
	.32	T limits (S. cir. Arc)	X	X				
	.33	A change in the classification					X	
Positions QW-405	.1	The addition of a position					X	
	.2	A change of position			X	X		
	.3	A change from vertical up to vertical down progression					X	
Preheat QW-406	.1	Decrease > 100 °F preheat temperature	X	X				
	.3	Increase > 100 °F interpass temperature			X	X		
PWHT QW-407	.1	A change in the PWHT	X	X				
	.2	A change in PWHT (time and temperature range)			X	X		
Gas QW-408	.1	The addition or deletion of trail gas and/or change in composition					X	
	.2	A change from a single gas, mixture, or percentage	X	X				
	.3	A change in the shielding gas flow rate or mixture					X	
	.5	The addition/deletion or change of backing gas or flow					X	
	.9	The deletion of backing gas or a change in composition	X	X				
	.10	Change of shielding or trailing gas	X	X				
Electrical Characteristics QW-409	.1	Heat input increase			X	X		
	.2	Change in transfer mode	X	X				
	.4	A change in current type (AC, DC) and polarity			X	X	X	
	.8	A change in the amperage range					X	

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Technique QW-410	.1	A change in string or weave bead					X	
	.3	A change in orifice, cup, or nozzle size					X	
	.5	A change in the method of cleaning					X	
	.6	A change in the method of back gouging					X	
	.7	A change in oscillation technique					X	
	.9	A change from multiple to single pass welding per side			X	X	X	
	.10	A change from single to multiple electrodes			X	X	X	
	.11	A change from closed to out of chamber	X	X				
	.15	A change in electrode spacing					X	
	.25	A change from manual to automatic					X	
	.26	The addition or deletion of peening					X	
	.64	The use of a thermal process	X	X				
NOTE 1 WPS Contents: See QW-200.1(b). NOTE 2 PQR Contents: See QW-200.2(b). NOTE 3 ASME Section IX must be utilized in conjunction with this table; see Article IV, *Weld Data*. NOTE 4 Nonessential variables may be included on the PQR but are not required.								

Reference: ASME Section IX, Table QW-255, *Welding Variables—GMAW and FCAW.*

6.2.2.4 Essential, Supplementary Essential, and Nonessential Variables for Submerged Arc Welding (SAW)

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Joints QW-402	.1	Change in groove design					X	
	.4	The deletion of backing					X	
	.10	Change in root spacing					X	
	.11	The addition or deletion of retainers					X	
Base Metals QW-403	.5	Change in the group number			X	X		
	.6	Base metal thickness (T) limits toughness			X	X		
	.8	Base metal thickness (T) qualified	X	X				
	.9	Deposited weld thickness (t) pass > ½ inch	X	X				
	.11	The change in P-number qualified	X	X				

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Filler Metals QW-404	.4	A change in the F-number	X	X				
	.5	A change in the A-number	X	X				
	.6	A change in the diameter of the electrode					X	
	.9	Change in flux-wire classification	X	X				
	.10	A change in composition of the flux	X	X				
	.24	The addition/deletion/change in supplemental	X	X				
	.27	The change in composition of supplemental filler metal	X	X				
	.29	A change in the flux trade name and designation					X	
	.30	Change in the deposited weld thickness (t)	X	X				
	.33	A change in filler metal classification	X	X			X	
	.34	Change in the flux type	X	X				
	.35	Change in flux-wire classification			X	X	X	
	.36	Use of recrushed slag	X	X				
Positions QW-405	.1	The addition of a position					X	
Preheat QW-406	.1	Decrease > 100 °F preheat temperature	X	X				
	.2	A change in preheat maintenance					X	
	.3	Increase > 100 °F interpass temperature			X	X		
PWHT QW-407	.1	A change in the PWHT	X	X				
	.2	A change in PWHT (time and temperature range)			X	X		
Electrical Characteristics QW-409	.1	Heat input increase			X	X		
	.4	A change in current and polarity			X	X	X	
	.8	A change in the amperage and voltage range					X	
Technique QW-410	.1	A change in string or weave bead					X	
	.5	A change in the method of cleaning					X	
	.6	A change in method of back gouging					X	
	.7	A change in oscillation technique					X	
	.8	A change in the tube–work distance					X	
	.9	A change from multiple to single pass welding per side			X	X	X	
	.10	A change from single to multiple electrodes			X	X	X	
	.15	A change in the electrode spacing					X	
	.25	A change from manual to automatic					X	
	.26	The addition or deletion of peening					X	
	.64	The use of a thermal process	X	X				

NOTE 1 WPS Contents: See QW-200.1(b).
NOTE 2 PQR Contents: See QW-200.2(b).
NOTE 3 ASME Section IX must be utilized in conjunction with this table, see Article IV, *Weld Data*.
NOTE 4 Nonessential variables may be included on the PQR but are not required.

Reference: ASME Section IX, Table QW-254, *Welding Variables—Submerged—Arc Welding (SAW).*

6.2.2.5 Essential, Supplementary Essential, and Nonessential Variables for Stud Arc Welding (SW)

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Joints QW-402	.8	Change in stud shape size	X	X				
	.9	Deletion of flux or ferrule	X	X				
Base Metals QW-403	.17	Change in the base metal or stud metal P-number	X	X				
Positions QW-405	.1	The addition of a position	X	X				
Preheat QW-406	.1	Decrease > 100 °F preheat temperature	X	X				
PWHT QW-407	.1	A change in the PWHT	X	X				
Gas QW-408	.2	A change in single mixture, or percent	X	X				
Electrical Characteristics QW-409	.4	A change in current and polarity	X	X				
	.9	A change in arc timing	X	X				
	10	A change in the amperage	X	X				
	.11	A change in the power source	X	X				
Technique QW-410	.22	A change in gun model or lift	X	X				
	.64	The use of a thermal process	X	X				
NOTE 1 WPS Contents: See QW-200.1(b). NOTE 2 PQR Contents: See QW-200.2(b). NOTE 3 ASME Section IX must be utilized in conjunction with this table; see Article IV, *Weld Data.* NOTE 4 Nonessential variables may be included on the PQR but are not required.								

Reference: ASME Section IX, Table QW-261, *Welding Variables—Stud Welding (SW).*

6.2.2.6 Essential, Supplementary Essential, and Nonessential Variables for Plasma Arc Welding (PAW)

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Joints QW-402	.1	Change in groove design			X	X		
	.5	The deletion of backing					X	
	.10	Change in root spacing					X	
	.11	The addition or deletion of retainers					X	
Base Metals QW-403	.5	Change in the group number			X	X		
	.6	Base metal thickness (T) limits toughness			X	X		
	.8	Base metal thickness (T) qualified	X	X				
	.12	The change in P-number or melt-in	X	X				
Filler Metals QW-404	.3	A change in size					X	
	.4	A change in the F-number	X	X				
	.5	A change in the A-number	X	X				
	.12	A change in the classification related to toughness			X	X		
	.14	The addition or deletion of filler metal	X	X				
	.22	The addition or deletion of consum. insert					X	
	.23	Change in filler metal product form	X	X				
	.27	Change in alloy elements	X	X				
	.30	Change in the deposited weld thickness (t)	X	X				
	.33	A change in the classification					X	
Positions QW-405	.1	The addition of a position					X	
	.2	A change of position			X	X		
	.3	A change from vertical up to vertical down progression					X	
Preheat QW-406	.1	Decrease > 100 °F preheat temperature	X	X				
	.3	Increase > 100 °F interpass temperature			X	X		
PWHT QW-407	.1	A change in the PWHT	X	X				
	.2	A change in PWHT (time and temperature range)			X	X		

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Gas QW-408	.1	The addition or deletion of trail gas and/or change in composition					X	
	.4	A change in composition	X	X				
	.5	The addition or deletion of backing gas or flow					X	
	.9	The deletion of backing gas or a change in composition	X	X				
	.10	The deletion of trail gas or a change in composition	X	X				
	.21	A change in flow rate					X	
Electrical Characteristics QW-409	.1	Heat input increase			X	X		
	.4	A change in current and polarity			X	X	X	
	.8	A change in the amperage and voltage range					X	
	.12	A change in tungsten electrode					X	
Technique QW-410	.1	A change in string or weave bead					X	
	.3	A change in orifice, cup or nozzle size					X	
	.5	A change in the method of cleaning					X	
	.6	A change in the method of back gouging					X	
	.7	A change in oscillation technique					X	
	.9	A change from multiple to single pass welding per side			X	X	X	
	.10	A change from single to multiple electrodes			X	X	X	
	.11	A change from closed to out of chamber	X	X				
	.12	A change in melt into keyhole			X	X		
	.15	A change in electrode spacing					X	
	.26	The addition or deletion of peening					X	
	.64	The use of a thermal process	X	X				

NOTE 1 WPS Contents: See QW-200.1(b).
NOTE 2 PQR Contents: See QW-200.2(b).
NOTE 3 ASME Section IX must be utilized in conjunction with this table, see Article IV, *Weld Data*.
NOTE 4 Nonessential variables may be included on the PQR but are not required.

Reference: ASME Section IX, Table QW-257, *Welding Variables—Plasma Arc Welding (PAW)*

6.2.2.7 Essential, Supplementary Essential, and Nonessential Variables for Electrogas Welding (EGW)

Article IV Paragraph		Process Variables	Essential		Supplementary Essential		Nonessential	
			WPS	PQR	WPS	PQR	WPS	PQR
Joints QW-402	.1	Change in groove design					X	
	.10	Change in root spacing					X	
	.11	Addition/deletion of retainers	X	X				
Base Metal QW-403	.1	Change in P-number qualified	X	X				
	.5	Change in group number			X	X		
	.6	Change base metal minimum thickness T qualified			X	X		
	.8	Change in thickness T beyond range qualified	X	X				
	.9	t pass > ½ in. (13 mm)	X	X				
Filler Metals QW-404	.4	Change in F-number	X	X				
	.5	Change in A-number	X	X				
	.6	Change in diameter of electrode					X	
	.12	Change in classification as related to toughness			X	X		
	.23	Change in filler metal product form	X	X				
	.33	Change in the classification	X	X			X	
Preheat QW-406	.1	Decrease > 100 °F (38 °C) preheat temperature					X	
PWHT QW-407	.1	A change in the PWHT	X	X				
	.2	Change in PWHT time and temperature range			X	X		
Gas QW-408	.2	Change in single, mixture, or percentage	X	X				
	.3	Change in shielding flow rate					X	
Electrical Characteristics QW-409	.1	Increase in heat input	X	X				
	.4	Change in current or polarity			X	X	X	
	.8	Change in I & E range					X	
Technique QW-410	.5	A change in the method of cleaning					X	
	.7	A change in oscillation technique					X	
	.9	Change in multiple to single pass/side			X	X	X	
	.10	Change from single to multiple electrodes	X	X				
	.15	Change in electrode spacing					X	
	.26	Addition or deletion of peening					X	
	.64	The use of a thermal process	X	X				

NOTE 1 WPS Contents: See QW-200.1(b).
NOTE 2 PQR Contents: See QW-200.2(b).
NOTE 3 ASME Section IX must be utilized in conjunction with this table; see Article IV, *Weld Data*.
NOTE 4 Nonessential variables may be included on the PQR but are not required.

Reference: ASME Section IX, Table QW-259, *Welding Variables—Electrogas Welding (EGW).*

The format of the WPS is not fixed, provided it addresses all essential and nonessential variables (and supplementary essential variables when applicable). An example form is available in ASME Section IX, Annex B.

The WPS is issued to the welder to read and follow. The WPS gives the welder specific guidelines to successfully complete production welds. The WPS shall be available to the inspector for review and approval; the PQR shall be available to the inspector upon request.

6.3 Procedure Qualification Record (PQR)

The PQR records the essential and, when impact qualification is required, supplementary essential variables used to weld a test coupon, the coupon test results, and the manufacturer's certification of accuracy in the qualification of a WPS. Record of the nonessential variables used during the welding of the test coupon is optional; however, it is an excellent quality practice to record all process-dependent parameters. Nonessential variables addressed in the PQR must also be addressed in, and be within the ranges allowed in, the corresponding WPS.

ASME Section IX requires that the manufacturer supervise the production of the test weldments and certify that the PQR properly qualifies the welding procedure; however, other groups may perform specimen preparation and testing. Mechanical tests are required to qualify a welding procedure to document that the properties of the weldment meet the minimum established acceptance criteria. Test sample selection and testing requirements are defined in Section IX. Typically, they include a tension test to determine the yield and ultimate strength of a groove weld, guided bend tests to determine the degree of soundness and ductility of a groove weld, notch toughness testing when toughness requirements are imposed, and hardness measurements when hardness restrictions are defined. Yield strength may also be reported. If any test specimen fails, the test coupon fails, and a new weld must be made and tested.

The format of the PQR is not fixed, provided it addresses all essential variables (and supplementary essential variables when necessary). An example form is available in ASME Section IX, Annex B.

The PQR should accompany the WPS and be available for review by the inspector upon request. It does not need to be available to the welder. One PQR may support several WPSs. One WPS may be qualified by more than one PQR within the limitations of the fabrication code.

6.4 Reviewing the WPS and PQR

Inspectors should review the WPS and PQR to verify that they are acceptable from a code perspective and applicable to the welding to be performed. While there are many ways to review a welding procedure, the most effective utilizes a systematic approach that ensures a complete and thorough review of the WPS and PQR to verify that all ASME Section IX (and construction and repair code) requirements have been addressed.

The initial step is to verify that the WPS has been properly documented and addresses the requirements of Section IX and the construction/repair code. The second step is to verify that the PQR has been properly performed and documented, and addresses all the requirements of Section IX and the construction and repair code. The third step is to confirm the PQR essential variable values properly support the range specified in the WPS.

The review shall document that the PQR variables represent and support the range specified in the WPS for the production application. Annex C provides an example of using a checklist for the review of WPSs and PQRs.

6.5 Tube-to-Tubesheet Welding Procedures

6.5.1 General

Tube-to-tubesheet welds have many factors affecting weld quality that are different than those for conventional groove and fillet welds. These factors result mainly from the unique geometry of the welds. Therefore, a demonstration mockup in accordance with ASME IX, QW-193, may be required by the construction code or proprietary company specifications.

6.5.2 Essential Variables

The types of essential variables listed in ASME IX QW-288 include:

a) joint configuration;

b) tube and tubesheet thickness;

c) ligament thickness;

d) multiple versus single pass;

e) welding position;

f) interpass temperature;

g) tube expansion;

h) cleaning method;

i) electrode or filler metal diameter;

j) inserts;

k) specific requirements for explosive welding;

l) weld process and type;

m) vertical position progression;

n) P-number and A-number;

o) preheat;

p) postweld heat treatment (PWHT);

q) weld current level;

r) polarity or current type;

s) welding type;

t) F-number;

u) shielding gas;

v) gas flow rate.

6.5.3 Procedure Qualification Test

The procedure qualification test requirements for tube-to-tubesheet welds are specified in ASME IX QW-193. The tests include:

a) visual;

b) dye penetrant;

c) macro examination of weld cross-sections.

Other testing that may be specified by the construction code or proprietary company specifications include:

1) hardness testing;

2) shear load test in accordance with ASME VIII, Div. 1, Annex A.

7 Welder Qualification

7.1 General

ASME Section IX, Article III, lists welding processes separately with essential variables that apply to welder and welding operator performance qualifications. Unlike the WPS and PQR, the welding performance qualification (WPQ) is only limited by essential variables. See ASME Section IX, QW-350. It should be acknowledged that the essential variables for the WPS are separate from the essential variables for the WPQ. The welder is required to weld to perform production welding within the limits of the welder's WPQ. ASME Section IX, QW-423, provides the range of base metal qualification P-numbers based on the P-numbers used for the welder qualification.

Filler metal F-numbers fundamentally determine the welder's ability to make satisfactory welds with a given filler metal. The F-numbers are provided in ASME Section IX, Table QW-432. It is important to note that the WPQ is used to document the welder's or welding operator's ability to make a sound weld per a qualified WPS. See ASME Section IX, QW-301.2.

7.2 Welders and Welding Operators

Welders and welding operators who are qualified to weld in accordance with one qualified WPS are also qualified to weld in accordance with other qualified WPSs using the same welding process, within the limits of the essential variables of QW-350 for welders and QW-360 for welding operators.

7.3 Examination Failure of a Production Weld

If a welder is to be qualified per a production weld and fails to meet the standards, the welder is considered to have failed the WPQ. The rejected weld will be examined in its entirety and repaired by a qualified welder or welding operator.

7.4 Retest for Qualification

An immediate retest may be granted if the conditions of ASME Section IX, QW-320, are met.

7.5 Expiration, Revocation, and Renewal of Welder or Welding Operator Qualification

A performance qualification will expire or be revoked if:

a) a welder or welding operator has not welded with a specific process during a period of six months or more, or

b) there is a specific reason to question the ability of the welder or welding operator to produce a production weld that meets the specifications of the WPS.

7.6 Welder Performance Qualification

The WPQ addresses all essential variables listed in QW-350 of ASME Section IX. A welder may perform a qualification test that may incorporate more than one welding process. The performance qualification test coupon is to be welded according to the appropriate, qualified WPS, and the welding is to be supervised and controlled by the welder‘s employer. The qualification is specific to the welding process(es) used, and each different welding process, or combination of welding processes, requires a specific, separate qualification. A change in any essential variable listed for the welding process will require the WPS to be requalified and the welder to qualify for that WPS.

ASME Section IX QW-352 through QW-357 and Table QW-416 list the essential variables and referencing code paragraphs for different welding processes. The variable groups addressed are joints, base metals, filler metals, positions, gas, and electrical characteristics. Section IX QW-423 covers alternate base materials for welder performance qualification, and QW-433 covers alternate F-numbers.

The record of the WPQ test includes all the essential variables, the type of test and test results, and the ranges qualified. The format of the WPQ is not fixed, provided it addresses all the required parameters. An example form is available in ASME Section IX, Form QW-484A, in Annex B.

The required mechanical tests performed on welder and welding operator qualification test coupons are defined in ASME Section IX, QW-452. If radiographic examination is used for welder or welding operator qualification of coupons, the minimum length of coupon to be examined is 6 in. (150 mm) and includes the entire weld circumference for pipe coupons. Coupons are required to pass visual examination and mechanical testing, if used. Alternately, welders and welding operators making a groove weld using SMAW, SAW, GTAW, and GMAW (except short-circuit mode) may be qualified using radiography of the first production weld. For welders, a minimum of 6 in. (150 mm) length of the first production weld must be examined for performance qualification, while a minimum of 36 in. (900 mm) length must be examined for welding operators.

There are rules (e.g. ASME Section IX) for the immediate retesting of welders or welding operators who fail a qualification test; this is commonly referred to as the “two for one rule” whereby the welder/operator must be tested on, and successfully complete, twice the original number of tests. Welders or welding operators who fail any part of the second test typically have to be retrained; however, no clear guidance is provided to inspectors regarding what constitutes retraining. Documented evidence of retraining and production of acceptable practice welds are presented to the inspector for approval before allowing a further test.

Welder performance qualification expires if the welding process is not used during any six-month period. The welder’s qualification can be revoked if there is a reason to question the welder’s ability to make sound, code-compliant welds. A welder’s log or continuity report can be used to verify that a welder’s qualifications have remained current.

A welder’s qualification is approved via signature; this cannot be delegated to another organization.

7.7 Reviewing a WPQ

7.7.1 Review Prior to Welding

Prior to any welding, inspectors should review welders’ WPQ to verify that they are qualified to perform the welding given its position, process, and other limitations. When reviewing a WPQ, items to check include:

a) welder’s name and stamp number;

b) welding process and type;

c) identification of WPS used for welding test coupon;

d) backing (if used)—if qualified without backing, then welder is qualified to weld with backing;

e) P-number(s) of base metals joined—see ASME Section IX, QW-423, for alternate base materials for WPQ;

f) thickness of base metals and diameter of pipe;

g) filler metal SFA number;

h) filler metal F-number—see ASME Section IX, QW-433, for alternate F-numbers for WPQ;

i) consumable insert (if used)—this is an essential variable only for PAW;

NOTE This is an essential variable only for PAW and GTAW.

j) deposited thickness (for each welding process used);

k) welding position of the coupon;

l) vertical weld progression;

m) backing, shielding, and trailing gas used (could be a change of gas or deletion of gas, depending on the process);

n) metal transfer mode (if GMAW);

o) weld current type/polarity (if GTAW);

p) if machine welded, refer to QW-484 for additional values required;

q) guided bend test type and results, if used;

r) visual examination results;

s) additional requirements of the construction code;

t) testing organization identification, acceptance via signature, and date;

u) radiographic results (if used).

7.7.2 Verifying the Qualification Range

The following ASME Section IX references should be used to verify the qualification range:

a) base metal qualification—QW- 423.1 and QW-403.15;

b) backing—QW-350 and QW-402.4;

c) deposited weld metal thickness qualification—QW-452.1 (if transverse bend tests) and QW-404.30;

d) groove weld small diameter limits—QW-452.3 and QW-403.16;

e) position and diameter limits—QW-461.9, QW-405.3, and QW-403.16;

f) F-number—QW-433 and QW-404.15.

7.7.3 Welder Qualifications for Tube-to-Tubesheet Welding

When a demonstration mockup in accordance with ASME IX, QW-193, is required by the construction code or proprietary company specifications, the welder qualification requirements have the same essential variables and acceptable ranges as in the PQR used to support the WPS.

7.8 Limitations for Welder Qualifications

Limitations for welders or welding operators are discussed in ASME Section IX, QW-305.

8 Nondestructive Examination

8.1 Discontinuities/imperfections

NDE is defined as those inspection methods that allow materials to be examined without changing or destroying their future usefulness. NDE is an integral part of an organization's quality assurance program. Several NDE methods are employed to ensure that the weld meets design specifications and does not contain defects.

The inspector should choose an NDE method with the capability and adequate sensitivity to detect discontinuities in the weld joints requiring examination for accept/reject evaluation. Table 2 and Figure 13 (reproduced from AWS B1.10 [4]) list the common types and locations of discontinuities and illustrate their positions within a butt weld. The NDE methods most commonly used during weld inspection are shown in Table 3.

Table 4 lists the various weld joint types and common NDE methods available to inspect their configuration. Table 5 further lists the detection capabilities of the most common NDE methods.

The inspector should be aware of discontinuities common to specific base metals and weld processes to ensure that these discontinuities are detectable. Table 6 is a summary of these discontinuities, potential NDE methods, and possible solutions to the weld process.

Table 2—Common Types of Discontinuities

Type of Discontinuity	Subclause*	Location	Remarks
1) Porosity	4.3	WMZ	Porosity could also be found in the base metal and HAZ if the base metal is a casting.
a) Uniformly scattered	4.3.1		
b) Cluster	4.3.2		
c) Piping	4.3.3		
d) Aligned	4.3.4		
e) Elongated	4.3.5		
2) Inclusion	4.4	WMZ/WI	
a) Slag	4.4.1		
b) Tungsten	4.4.2		
3) Incomplete fusion	4.5	WMZ/WI	WM between passes.
4) Incomplete joint penetration	4.6	BMZ	Weld root in a groove weld.
5) Undercut	4.7	WI/HAZ	Adjacent to weld toe or weld root in base metal.
6) Underfill	4.8	WMZ	Weld face or root surface of a groove weld.
7) Overlap	4.9	WMZ	Weld toe or root surface.
8) Lamination	4.10	BMZ	Base metal, generally near mid-thickness of section.
9) Delamination	4.11	BMZ	Base metal, generally near mid-thickness of section.
10) Seam and lap	4.12	BMZ	Base metal surface generally aligned with rolling direction.
11) Lamellar tear	4.13	BMZ	Base metal.
12) Crack (includes hot cracks and cold cracks described in text)	4.14 4.14.1		
a) Longitudinal	4.14.2, 4.14.3	WMZ, HAZ, BMZ	Weld metal or base metal adjacent to WI.
b) Transverse	4.14.2, 4.14.4	WMZ, HAZ, BMZ	Weld metal (may propagate into HAZ and base metal).
c) Crater	4.14.5	WMZ	Weld metal at point where arc is terminated.
d) Throat	4.14.6	WMZ	Parallel to weld axis. Through the throat of a fillet weld.
e) Toe	4.14.7	WI, HAZ	Root surface or weld root.
f) Face and root	4.14.8	WMZ	Face or root of their surfaces.
g) Underbead and HAZ	4.14.9	HAZ	HAZ (may propagate into base metal).
13) Concavity	4.15	WMZ	Weld face or fillet weld.
14) Convexity	4.16	WMZ	Weld face or fillet weld.
15) Weld reinforcement	4.17	WMZ	Weld face or root surface of a groove weld.
16) Spatter		WMZ, BMZ	Weld face or base metal surface.
17) Arc strike		WMZ, BMZ	Weld face or base metal surface.

WMZ—weld metal zone; BMZ—base metal zone; HAZ—heat-affected zone; WI—weld interface.

* Subclause references refer to sections of AWS B1.10, 2016 Edition.

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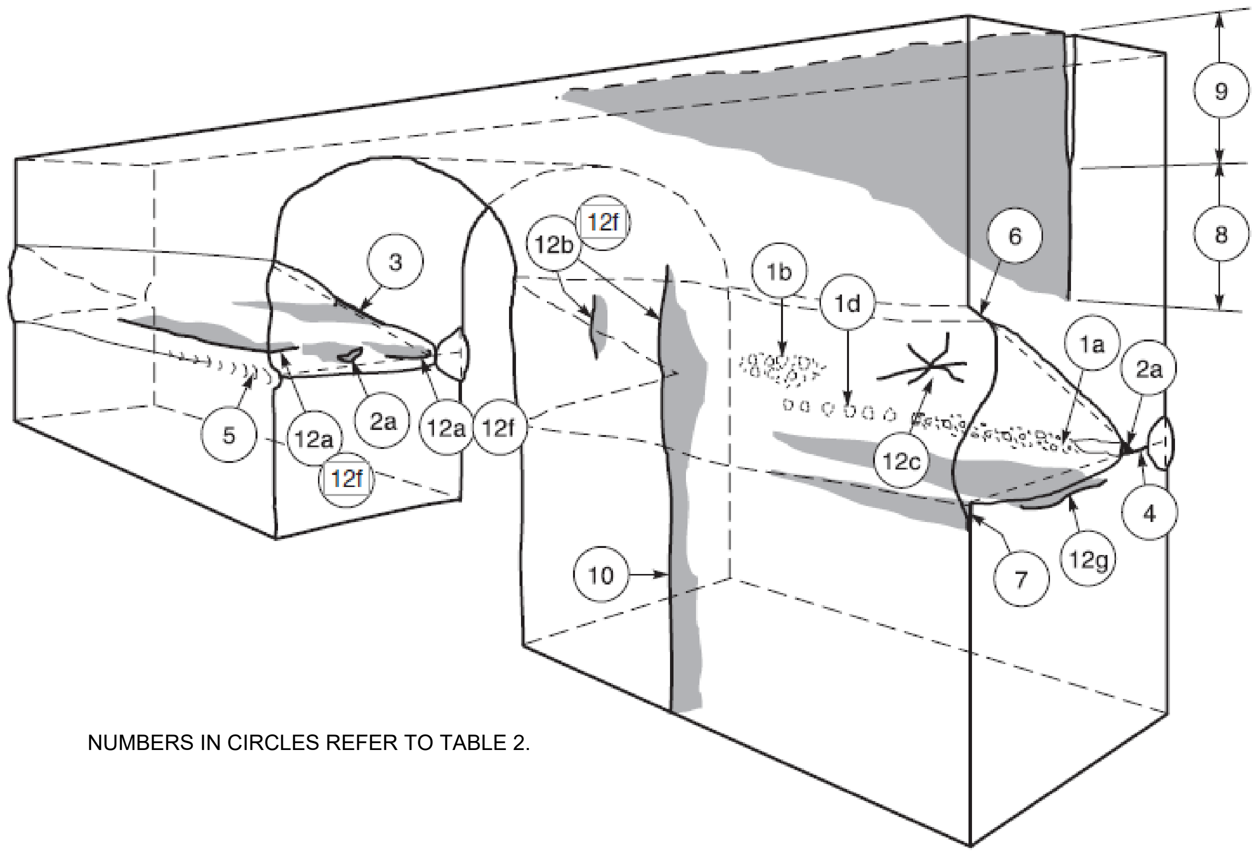

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Figure 13—Typical Discontinuities Present in a Single Bevel Groove Weld in a Butt Joint

Table 3—Commonly Used NDE Methods

NDE Method	Symbols
Visual Examination	VT
Magnetic Particle Examination	MT
Wet Fluorescent Magnetic Particle Examination	WFMT
Liquid Penetrant Examination	PT
Leak Testing/Examination	LT
Eddy Current Examination	ET
Radiographic Examination	RT
Ultrasonic Examination	UT
Alternating Current Field Measurement	ACFM

Table 4—Capability of the Applicable Examination Method for Weld-Type Joints

Joints	Inspection Methods							
	Volumetric			Surface				
	RT	UT	ET	PT	MT	VT	LT	ACFM
Butt	A	A	A	A	A	A	A	A
Corner	M	A	M	A	A	A	A	A
Tee	M	A	M	A	A	A	A	A
Lap	M	M	M	A	A	A	A	M
Edge	M	M	M	A	A	A	A	A

Volumetric	RT: radiographic examination (volumetric) UT: ultrasonic examination (volumetric)
	ET: eddy current examination (shown in both volumetric and surface as it can detect near-surface flaws)
Surface	PT: penetrant examination including color contrast penetrant and fluorescent penetrant (surface) MT: magnetic particle examination (surface) VT: visual examination (surface) LT: leak examination (surface) ACFM: alternating current field measurement (surface)
	A: applicable method M: marginal applicability (depends on other factors, such as material thickness, discontinuity size, orientation, and location

Table 5—Capability of the Applicable Method vs. Discontinuity

	Inspection Methods						
Discontinuities	RT	UT	PT [a,c]	MT [b,c,d]	VT [a]	ET	LT [e]
Porosity	A	O	A	O	A	O	A
Slag inclusions	A	O	A	O	A	O	U
Incomplete fusion	O	A	U	O	O	O	O
Incomplete joint penetration	A	A	U	O	O	O	U
Undercut	A	O	A	O	A	O	U
Overlap	U	O	A	A	O	O	U
Cracks	O	A	A	A	A	A	A
Laminations	U	A	A	A	A	U	U

RT—Radiographic examination
UT—Ultrasonic examination
PT—Penetrant examination including both DPT (dye penetrant examination) and FPT (fluorescent penetrant examination)
MT—Magnetic particle examination
VT—Visual examination
ET—Electromagnetic examination
LT—Leak testing/examination
A—Applicable method
O—Marginal applicability (depending on other factors such as material thickness, discontinuity size, orientation, and location)
U—Usually not used

[a] Surface.
[b] Surface and slightly subsurface.
[c] Weld preparation or edge of base metal.
[d] Magnetic particle examination is applicable only to ferromagnetic materials.
[e] Leak testing/examination is applicable only to enclosed structure which may be sealed and pressurized during testing/examination.

Table 6—Discontinuities Commonly Encountered with Welding Processes

Material	Type of Discontinuity	Welding Processes	Typical NDE Method	Practical Solution
Carbon Steel	Hydrogen cracking	SMAW, FCAW, SAW	VT, PT, MT after cool down	Low-hydrogen electrode, preheat, post heat, clean weld joint.
	Lack of fusion (LOF)	ALL	UT	Proper heat input, proper welding technique.
	Incomplete penetration	ALL	RT, UT, VT[a]	Proper heat input, proper joint design.
	Undercut	SAW, SMAW, FCAW, GMAW	VT	Reduce current, travel speed.
	Slag inclusion	SMAW, FCAW, SAW	RT, UT	Proper welding technique, cleaning, avoid excessive weaving.
	Porosity	ALL	RT	Low hydrogen, low sulfur environment, proper cleaning and shielding.
	Burn-through	SAW, FCAW, GMAW, SMAW	RT, VT[a]	Proper heat input.
	Arc strike	ALL	VT, MT, PT, Macroetch	Remove by grinding.
	Lack of side wall fusion	GMAW-S	UT	Proper heat input, vertical uphill.
	Tungsten inclusion	GTAW	RT	Arc length control.
Austenitic Stainless Steel	Solidification cracking	ALL	PT	Proper filler, ferrite content, proper joint design.
	Hot cracking	SAW, FCAW, GMAW, SMAW	RT, PT, UT	Low heat input, stringer bead.
	Incomplete penetration	ALL	RT, UT	Proper heat input.
	Undercut	SAW, SMAW, FCAW, GMAW	VT	Reduce travel speed.
	Slag inclusion	SMAW, FCAW, SAW	RT, UT	Proper cleaning.
	Porosity	ALL	RT	Low hydrogen, low sulfur environment, proper shielding.
	Arc strike	ALL	VT, PT, Macroetch	Remove by grinding.
	Tungsten inclusion	GTAW	RT	Arc length control.

[a] When root is accessible.

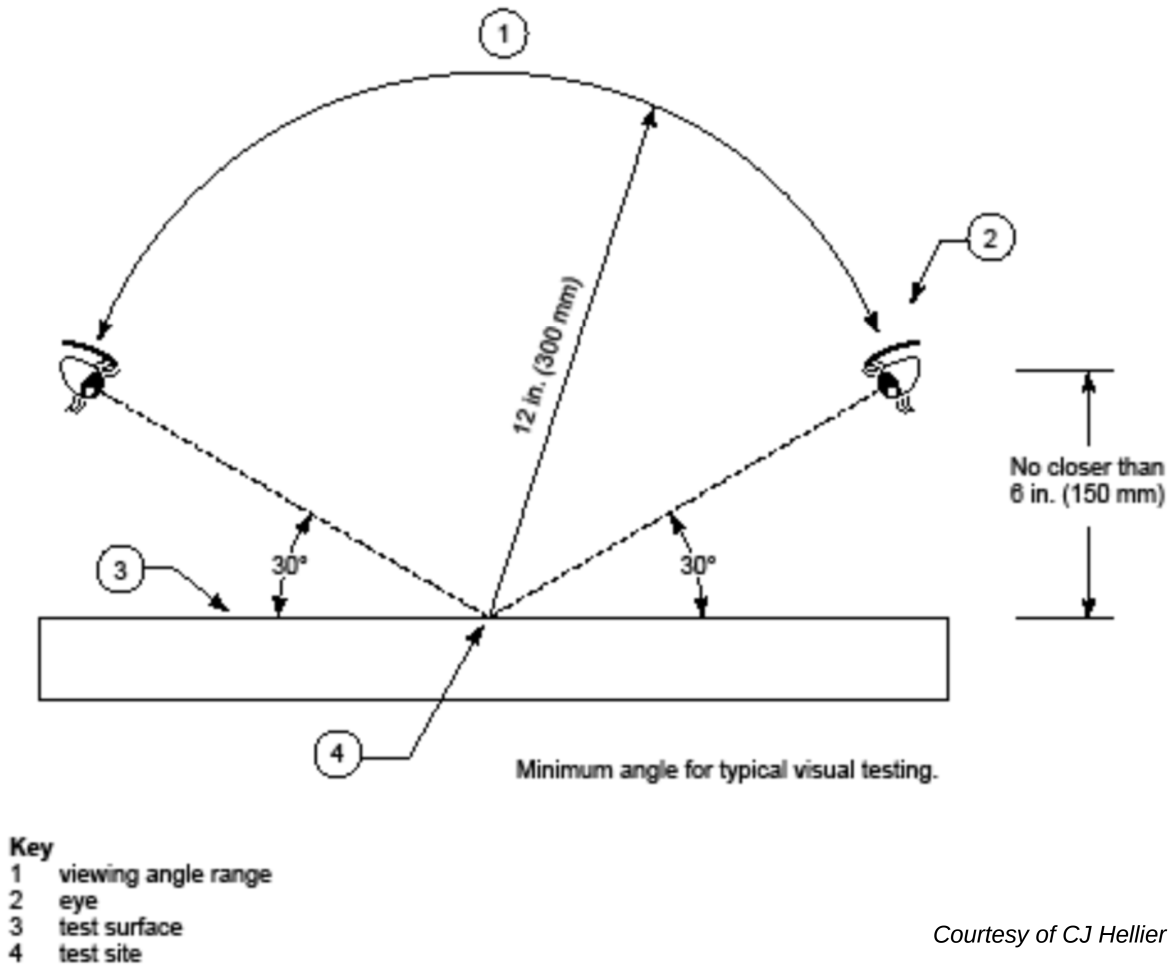
8.2 Materials Identification

During welding inspection, the inspector should verify the conformance of the base material and filler metal chemistries for the selected or specified alloyed materials as required by the relevant WPS. This should include reviewing the certified mill test report, reviewing stamps or markings on the components, or require positive metal identification (PMI) testing. It is the responsibility of the owner–user to establish a written material verification program indicating the extent and type of PMI to be as outlined in API 578.

8.3 Visual Examination (VT)

8.3.1 General

VT is the most extensively used NDE method for welds. It includes either direct or indirect observation of the exposed surfaces of the weld and base metal. Direct VT is conducted when access is sufficient to place the eye within 6 in. through 24 in. (150 mm through 600 mm) of the surface to be examined and at an angle not less than 30° to the surface, as illustrated in Figure 14. Mirrors may be used to improve the angle of vision.



Courtesy of CJ Hellier

Figure 14—Direct Visual Examination Requirements

Remote VT may be substituted for direct examination. Remote examination may use aids such as telescopes, borescopes, fiberscopes, cameras, or other suitable instruments, provided they have a resolution at least equivalent to that which is attained by direct visual examination. In either case, the illumination should be sufficient to allow resolution of fine detail. These illumination requirements are to be addressed in a written procedure.

ASME Section V, Article 9, lists requirements for VT. Codes and specifications may list compliance with these requirements as mandatory. Some requirements listed in this article include the following:

a) a written, qualified procedure;

b) the minimum amount of information that is to be included in the written procedure;

c) demonstration of the adequacy of the inspection procedure;

d) inspection personnel must be certified by their employer for the specific method;

e) personnel are required to document annual completion of a J-1 Jaeger-type eye vision test (with or without correction);

f) direct VT requires access to permit the eye to be within 6 in. through 24 in. (150 mm through 600 mm) of the surface, at an angle not less than 30°;

g) the minimum required illumination of the part under examination;

h) indirect VT permits the use of remote visual examination and devices be employed;

i) evaluation of indications in terms of the acceptance standards of the referencing code;

j) a form adequately documenting the results per the relevant code section.

8.3.2 Visual Inspection Tools

8.3.2.1 General

To visually inspect and evaluate welds, adequate illumination and good eyesight are the basic requirements. In addition, a basic set of optical aids and measuring tools, specifically designed for weld inspection, can assist the inspector. In the following subsections are some commonly used tools and methods for VT of welds.

8.3.2.2 Optical Aids

Optical aids used in visual inspection include the following:

a) Lighting: Inspection surface illumination is of extreme importance. Adequate illumination levels should be established in order to ensure an effective visual inspection. Standards such as ASME Section V, Article 9, specify minimum lighting levels of 100 foot-candles (1000 lux) at the examination surface. This is not always easy to achieve, so inspectors have to be aware of the need to measure lighting conditions using a light meter.

b) Mirrors; Valuable to the inspector, allowing them to look inside piping, threaded and bored holes, and castings, and around corners if necessary.

c) Magnifiers; Helpful in bringing out small details and imperfections.

d) Borescopes and fiberscopes: Widely used for examining tubes, deep holes, long bores, and pipe bends that have internal surfaces not accessible to direct viewing.

8.3.2.3 Mechanical Aids

Mechanical aids used in visual inspection include the following:

a) Steel ruler: Available in a wide selection of sizes and graduations to suit the needs of the inspection (considered a nonprecision measuring instrument).

b) Vernier scale: a precision instrument, capable of measuring with a precision factor of 0.0001 in. The Vernier system is used on various precision measuring instruments, such as calipers, micrometers, height and depth gauges, the gear tooth, and protractors.

c) Combination square set: Consisting of a blade and a set of three heads: square, center, and protractor, used universally in mechanical work for assembly and layout examination.

d) Mechanical thickness gauge: Commonly called a “feeler” gauge, and used to measure the clearance between objects.

e) Levels: Tools designed to prove whether a plane or surface is truly horizontal or vertical.

8.3.2.4 Weld Examination Devices

Typical inspection tools for weld inspection include the following:

a) Inspector’s kit (see Figure 15); Contains some of the basic tools needed to perform an adequate visual examination of a weld during all stages of welding. It includes everything from a lighted magnifier to a Vernier caliper.

b) Bridge cam gauge (see Figure 16): Can be used to determine the weld preparation angle prior to welding. This tool can also be used to measure excess weld metal (reinforcement), depth of undercut or pitting, fillet weld throat size, or weld leg length and misalignment (high–low).

c) Fillet weld gauge: Provides a quick and precise means of measuring the more commonly used fillet weld sizes. The types of fillet weld gauges include:

  1) Adjustable fillet weld gauge (see Figure 17) measures weld sizes for fit-ups with 45° members and welds with unequal weld leg lengths;

  2) Skew-T fillet weld gauge (see Figure 18) measures the angle of the vertical member;

  3) Weld fillet gauge (see Figure 19) is a quick go/no-go gauge used to measure the fillet weld leg size. Gauges normally come in sets with weld leg sizes from 3 mm ($^{1}/_{8}$ in.) to 25 mm (1 in.). Figure 20 shows a weld fillet gauge being used to determine if the crown has acceptable concavity or convexity.

d) Weld size gauge (see Figure 21): Measures the size of fillet welds, the actual throat size of convex and concave fillet welds, the reinforcement of butt welds, and root openings.

e) Hi-lo welding gauge (see Figure 22): Measures internal misalignment after fit-up, pipe wall thickness after alignment, length between scribe lines, root opening, $37^{1}/_{2}$° bevel, fillet weld leg size, and reinforcement on butt welds. The hi-lo gauge provides the ability to ensure proper alignment of the pieces to be welded. It also measures internal mismatch, weld crown height, and root weld spacing.

f) Digital or infrared pyrometer or temperature sensitive crayons: Measures preheat and interpass temperatures.

Courtesy of GA.I., Gage Co.

Figure 15—Inspector's Kit

Courtesy of GA.I., Gage Co.

Figure 16—Bridge Cam Gauge

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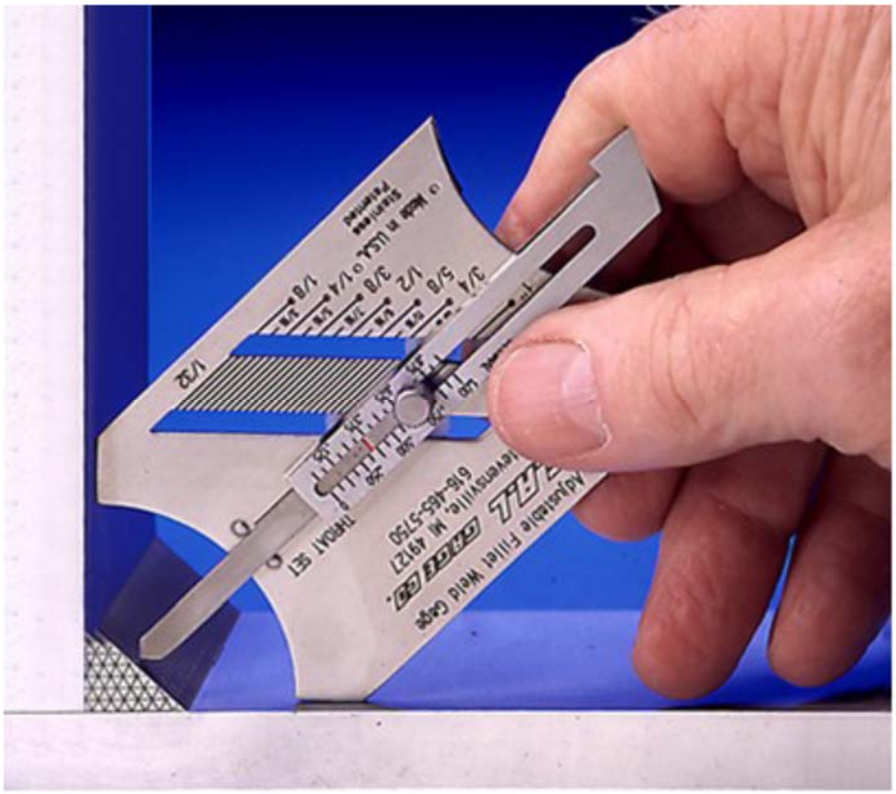
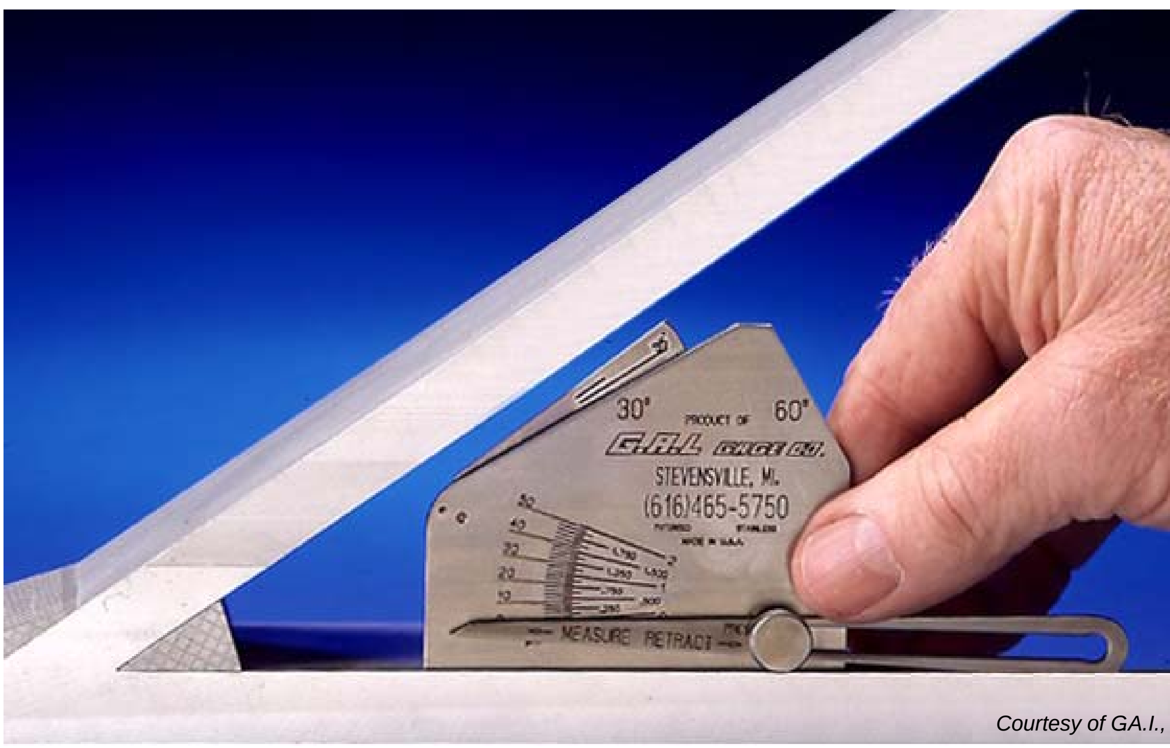


Courtesy of G.A.I. Gage Co.

Figure 17—Adjustable Fillet Weld Gauge



Courtesy of GA.I., Gage Co.

Figure 18—Skew-T Fillet Weld Gauge

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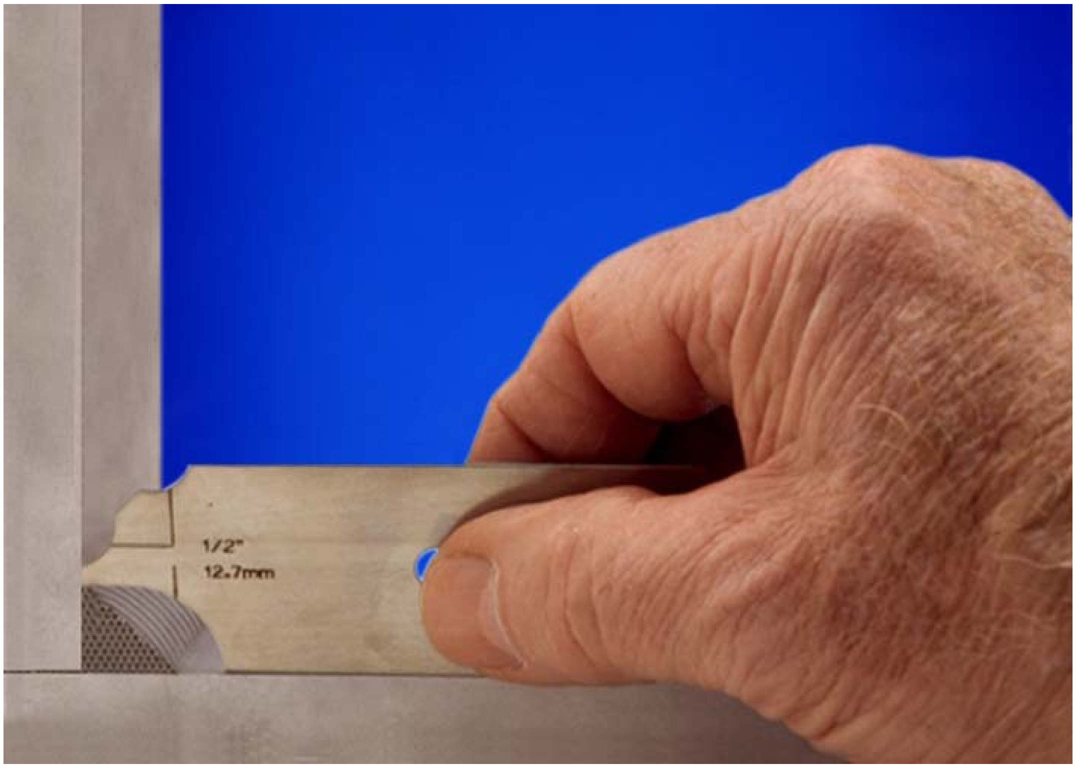

Courtesy of GA.I., Gage Co.

Figure 19—Weld Fillet Gauge

Courtesy of GA.I., Gage Co.

Figure 20—Weld Fillet Gauge

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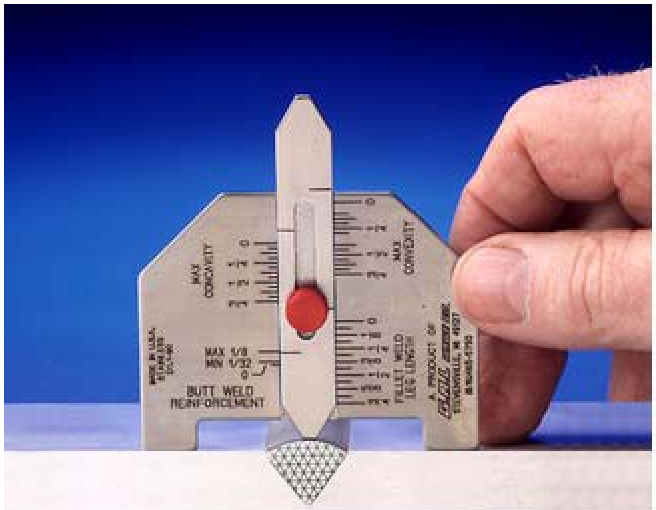
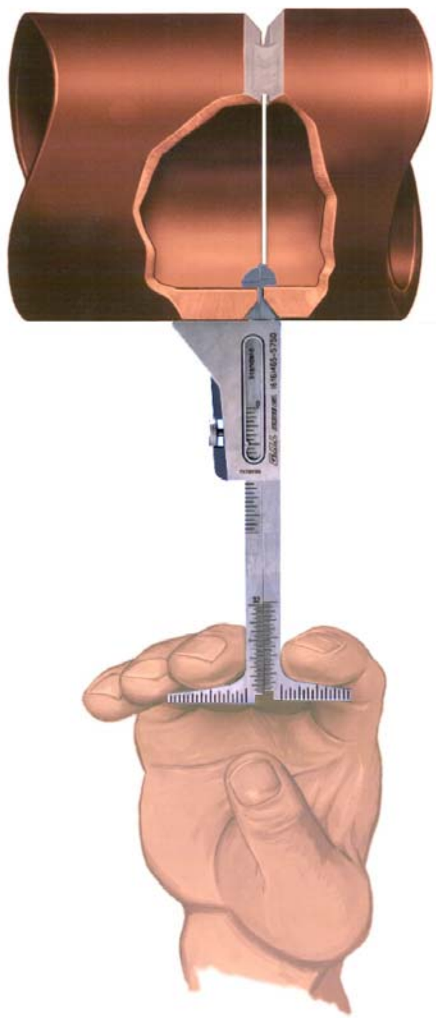


Courtesy of GA.I., Gage Co.

Figure 21—Weld Size Gauge



Courtesy of GA.I., Gage Co.

Figure 22—Hi-Lo Gauge

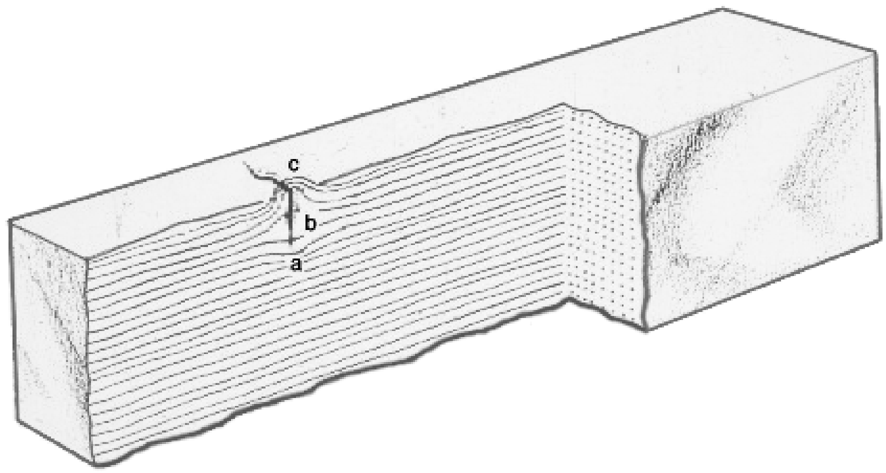
The products in the photographs on this page are used as examples only, and do not constitute an endorsement of these products by API or a requirement of their use for compliance with the standard.

8.4 Magnetic Particle Examination (MT)

8.4.1 General

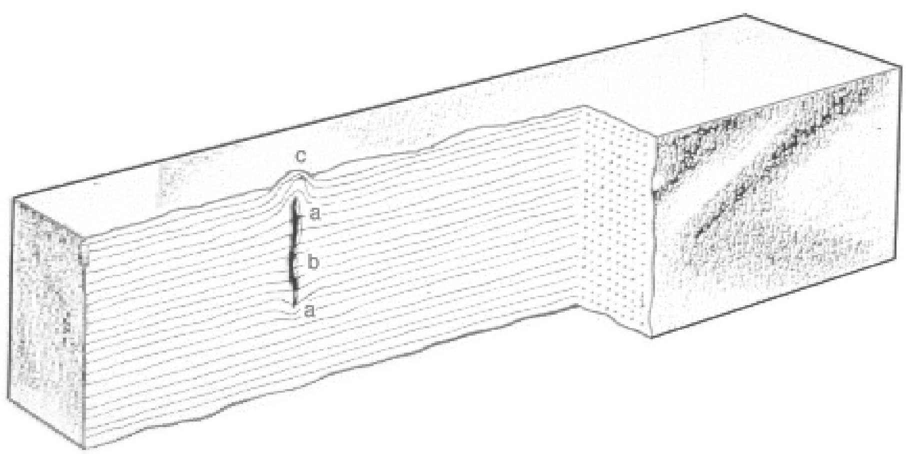
MT is effective in locating surface or near-surface discontinuities of ferromagnetic materials. It is most commonly used to evaluate weld joint surfaces, intermediate checks of weld layers, and back-gouged surfaces of completed welds. Typical types of discontinuities that can be detected using MT, with adequate accessibility, include cracks, lamination, laps, and seams.

In this method, the weld (and HAZ) is locally magnetized, creating a magnetic field in the material. Finely divided ferromagnetic particles are then applied to the magnetized surface and are drawn to breaks in the magnetic field (causing the formation of north and south poles at the imperfection) resulting from discontinuities, as shown in Figure 23 and Figure 24.



Courtesy of CJ Hellier

Figure 23—Surface-Breaking Discontinuity



Courtesy of CJ Hellier

Figure 24—Subsurface Discontinuity

Figure 23 shows the disruption to the magnetic field caused by a defect open to the surface. Ferromagnetic particles are drawn to the break in the flux field, creating north and south poles. The pattern of the particles may be very sharp and distinct, or diffuse, depending upon several factors including field strength, type of imperfection, and indicator medium. Figure 24 illustrates how a subsurface defect would also disrupt the magnetic lines of flux. The observed indication would not be as clearly defined as would a defect open to the surface. The pattern formed by the particles represents the shape and size of any existing discontinuities, as seen in Figure 25. The particles used during the exam can be either dry or wet, depending upon the type of imperfection being examined and the level of sensitivity required. If the examination is performed in normal lighting, the color of the particles (known as the color-contrast method) should provide adequate contrast to the exam surface. The best results are achieved when the lines of flux are perpendicular to the discontinuity. The inspections should overlap by at least 50 mm (2 in.). Two inspections are typically performed, one parallel to the weld and one perpendicular the weld, to provide the maximum probability of coverage. When a magnetic force is applied to the material, a magnetic flux field is created around and through the material. Discontinuities that are perpendicular to the lines of flux attract the magnetic particles, causing an indication as shown in Figure 26. Figure 27 illustrates the setup for detecting transverse indications. The yoke is placed parallel on the weld to detect discontinuities transverse to the weld. Figure 28 shows the setup for detecting indications that run parallel to the weld. In this case, the yoke is placed across the weld to detect discontinuities parallel to the weld. Imperfections will need to be perpendicular to the magnetic flux field for maximum probability of detection.

For added sensitivity, wet fluorescent magnetic particle (WFMT) techniques may be used. With this technique, a filtered blacklight is used to observe the particles, which requires the examination area to be darkened as specified in ASME Section V, Article 7.

ASME Section V, Article 7, lists requirements for MT. Some codes and specifications may list compliance with these requirements as being mandatory. ASME B31.3 and ASME Section VIII, Division 1, requires MT to be performed in accordance with Article 7. Some of the requirements listed in this article include:

a) examination procedure information;

b) use of a continuous particle-application method;

c) use of one of five magnetization techniques;

d) required calibration of equipment;

e) two examinations perpendicular to each other;

f) maximum surface temperature for examination;

g) magnetization currents;

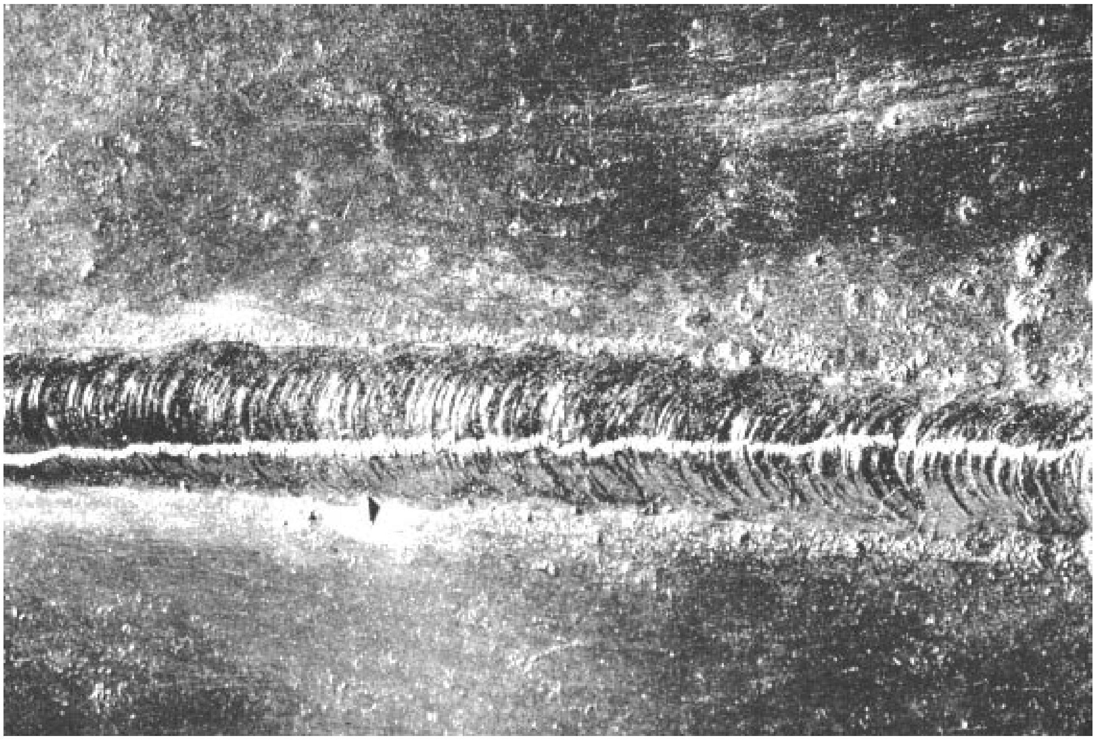
h) evaluation of indications in terms of the acceptance standards of the referencing code;

i) demagnetization;

j) minimum required surface illumination (visible or blacklight) of the part under examination.

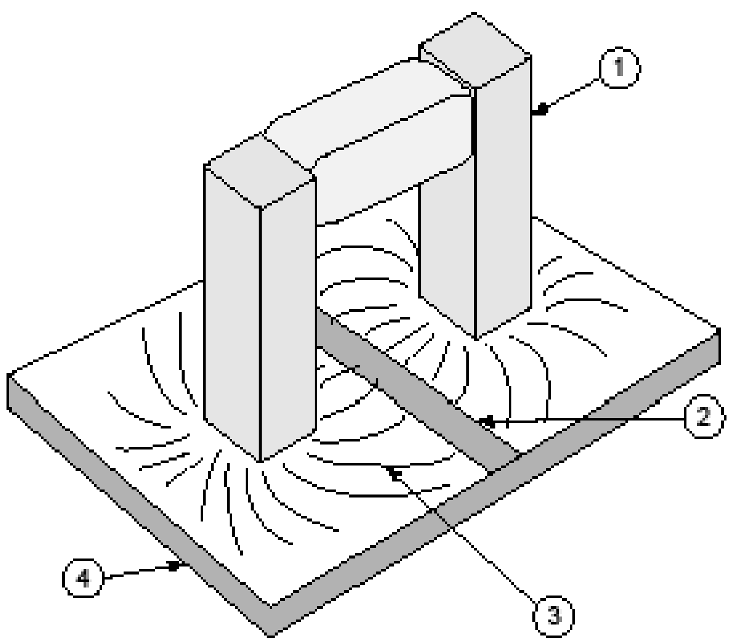
8.4.2 Magnetic Flux Direction Indicator

The direction of the magnetic flux can be confirmed by the use of several indicators. One of the most popular indicators is the pie gauge. It consists of eight low-carbon steel segments, brazed together to form an octagonal plate that is copper plated on one side to hide the joint lines (see Figure 29). The plate is placed on the test specimen, adjacent to the weld, during magnetization with the copper side up. The ferromagnetic particles are applied to the copper face and outline the orientation of the resultant field.



Courtesy of CJ Hellier

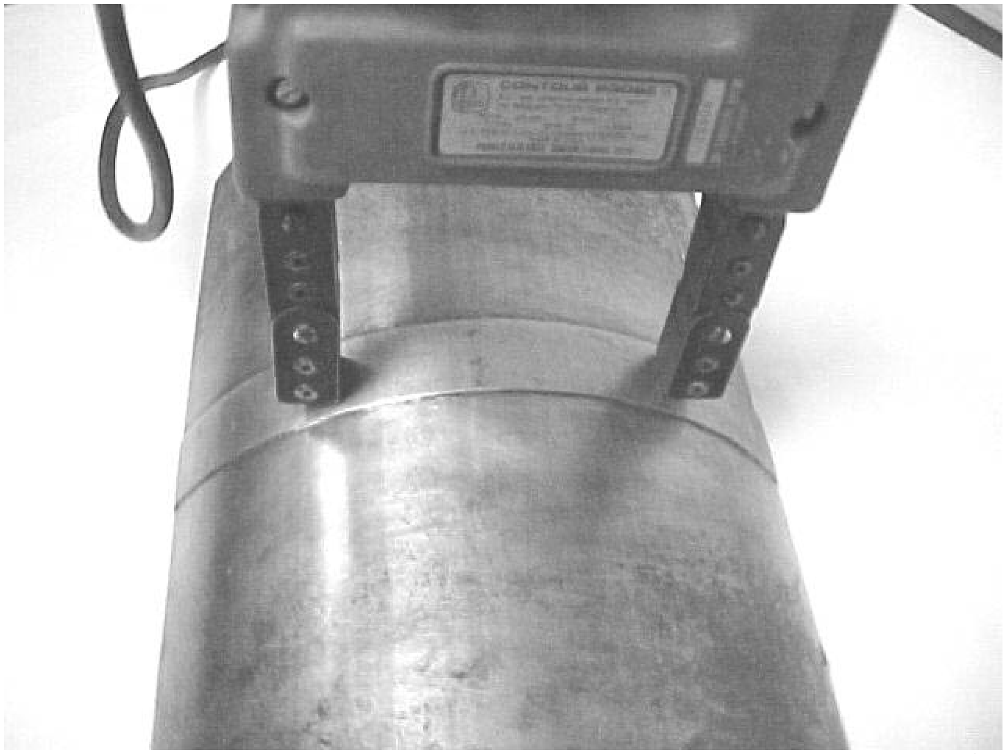
Figure 25—Weld Discontinuity



Key
1 yoke
2 weld
3 flux lines
4 test part

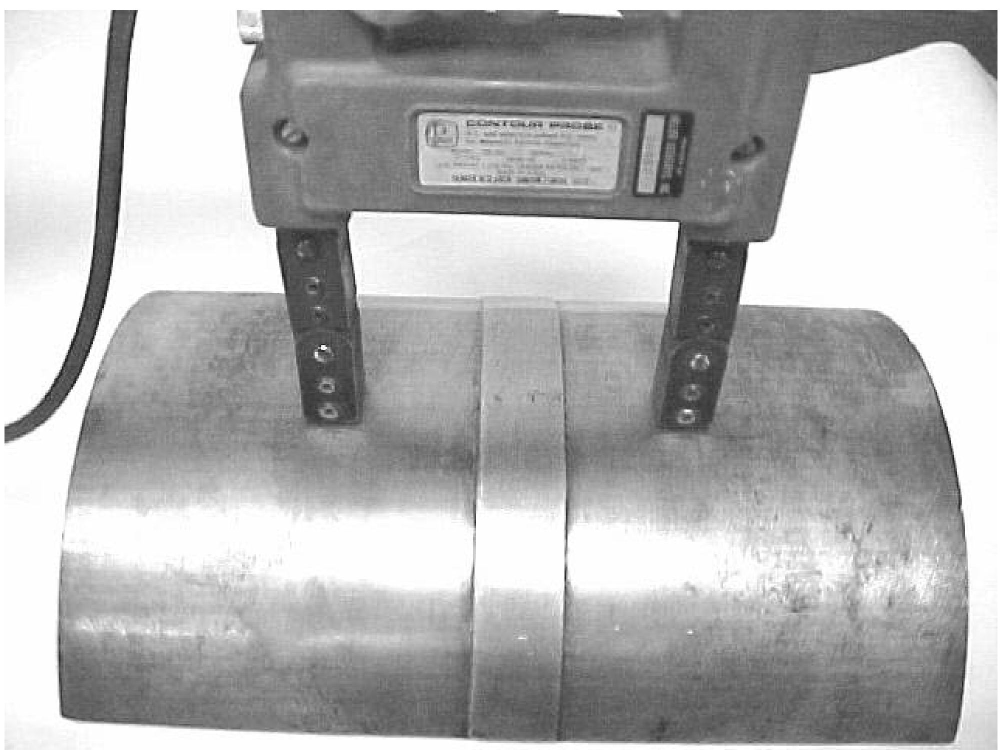
Courtesy of CJ Hellier

Figure 26—Flux Lines



Courtesy of CJ Hellier

Figure 27—Detecting Discontinuities Transverse to Weld



Courtesy of CJ Hellier

Figure 28—Detecting Discontinuities Parallel to the Weld

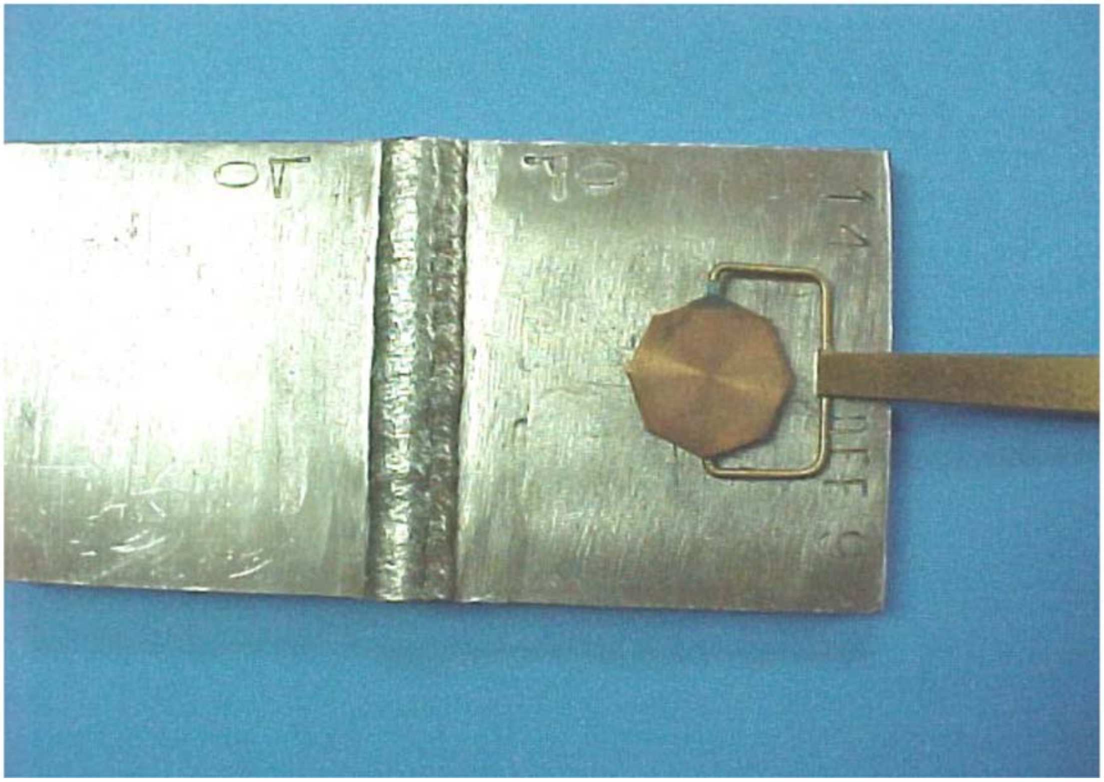


Figure 29—Pie Gauge

8.4.3 Demagnetization

When the residual magnetism in the part could interfere with subsequent processing or usage, demagnetization techniques should be used to reduce the residual magnetic field to within acceptable limits. Care should be taken when performing MT during the welding process. If a residual field is left in a partially completed weld, this field may deflect the weld arc and make it difficult to control the weld deposit.

8.5 Alternating Current Field Measurement

The ACFM technique is an electromagnetic, noncontacting technique that is able to detect and size surface-breaking imperfections in a range of different materials and through coatings of varying thicknesses. This technique can be used for inspecting complex geometries such as nozzles, ring-grooves, and grind-out areas. It requires minimal surface preparation and can be used at elevated temperatures up to 900 °F (480 °C). However, it is less sensitive and more prone to operator errors than WFMT. ACFM is used for the evaluation and monitoring of existing cracks.

ACFM uses a probe similar to an eddy current probe and introduces an alternating current in a thin skin near the surface of any conductor. When a uniform current is introduced into the area under test, if it is free of imperfections, the current is undisturbed. If the area has a crack, the current flows around the ends and the faces of the crack. A magnetic field exists above the surface associated with this uniform alternating current and becomes disturbed if a surface-breaking crack is present.

The probe is scanned longitudinally along the weld with the front of the probe parallel and adjacent to the weld toe. Two components of the magnetic field are measured: B_x along the length of the defect, which responds to changes in surface current density and gives an indication of depth when the reduction is the greatest; and B_z, which gives a negative and positive response at either end of the defect caused by current-generated poles, providing an indication of length. A physical measurement of defect length indicated by the probe position is then used together with a software program to accurately determine the length and depth of the imperfection.

During the application of the ACFM technique, actual values of the magnetic field are being measured in real time. These are used with mathematical model look-up tables to eliminate the need for calibration of the ACFM instrument using a calibration piece with artificial defects such as slots.

8.6 Liquid Penetrant Examination (PT)

8.6.1 General

PT is capable of detecting surface-connecting discontinuities in ferrous and nonferrous alloys, as well as nonmetal objects. PT can be used to examine weld joint surfaces, completed welds, and perform intermediate checks of individual weld passes. This technique is commonly employed on austenitic stainless steels where MT is not possible. The examiner should recognize that many specifications limit contaminants in the penetrant materials that could adversely affect the weld or parent materials. Most penetrant manufacturers provide material certifications on the amounts of contaminants (e.g. chlorine, fluorine, sulfur, and halogens).

Capillary action (a force resulting from adhesion, cohesion, and surface tension in liquids that are in contact with solids, as in a capillary tube) is the basis for the penetrant to be drawn into a material. Reverse capillary action is the principle behind the visualization of indications after the application of developer.

A limitation of PT is that standard penetrant systems are restricted to a maximum of 125 °F (52 °C), so the weld or material to be inspected must be below this temperature, which significantly slows down the welding operation. Additionally, this method requires extensive clean-up so as not to contaminate the weld surface. High-temperature penetrant systems can be qualified to extend the temperature envelope.

During PT, the test surface is generally solvent cleaned and coated with a penetrating liquid that seeks surface-connected discontinuities. The length of time the penetrant remains on the surface, also known as dwell time, is based upon several factors, primarily the type of imperfection that can be expected to be present. After the excess surface liquid penetrant is carefully removed, a solvent-based powder suspension (developer) is normally applied by spraying. The liquid in any discontinuity bleeds out to stain the powder coating. An indication of depth is possible if the inspector observes and compares the indication bleed-out to the opening size visible at the surface. The greater the bleed-out to surface-opening ratio, the greater the volume of the discontinuity.

8.6.2 Liquid Penetrant Techniques

The two general penetrant techniques approved for use include the color-contrast penetrant technique (normally red in color to contrast with a white background) and the fluorescent penetrant technique, which uses a fluorescing dye that is visible using ultraviolet light, as shown in Figure 30. Fluorescent penetrant techniques are generally used to detect fine linear-type indications. The examination is performed in a darkened area using a filtered ultraviolet light source, commonly referred to as a blacklight.

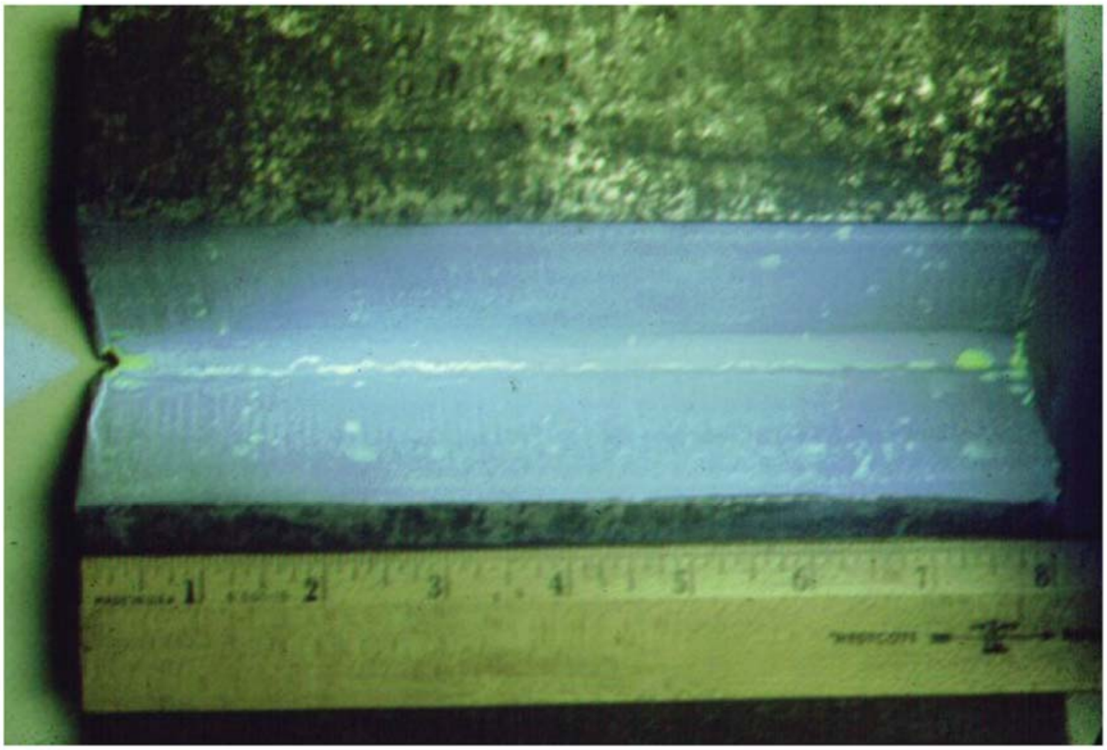


Figure 30—Fluorescent Penetrant Technique

Three penetrant systems are available for use with both techniques. They are:

a) solvent removable,

b) water washable, and

c) post emulsifiable.

Compatibility with base metals, surface profile (welds), and process material should be considered before penetrants are used, since they can be difficult to completely remove.

ASME Section V, Article 6, Paragraph T-620, lists general requirements for PT. Codes and specifications may list compliance with these requirements as mandatory. API Standard 650, ASME B31.3, and ASME Section VIII, Division 1, require PT to be performed in accordance with ASME Section V, Article 6. Some requirements listed in this article include the following:

a) inspection to be performed in accordance with a procedure (as specified by the referencing code section);

b) type of penetrant materials to be used;

c) details for pre-examination cleaning including minimum drying time;

d) dwell time for the penetrant;

e) details for removing excess penetrant, applying the developer, and time before interpretation;

f) evaluation of indications in terms of the acceptance standards of the referencing code;

g) postexamination cleaning requirements;

h) minimum required surface illumination (visible or blacklight) of the part under examination.

8.7 Eddy Current Examination (ET)

8.7.1 General

Eddy current inspection is used to detect surface imperfections, and in some cases, subsurface discontinuities in tubing, pipe, wire, rod, and bar stock. ET has limited use in weld inspection. ET can be used as a quick test to determine that components being joined during welding have the same material properties, and as a quick check for imperfections of the weld joint faces. It can also be used to measure the thickness of protective, nonconductive surface coatings and cladding thickness.

ET uses a magnetic field to create circulating currents in electrically conductive material. Discontinuities in the material alter the magnetically induced fields and present them on the unit's display. Similar to MT, this technique provides the greatest probability of detection when the circulating currents are perpendicular to the discontinuity.

More information can be found in ASME Section V, Article 8, which addresses ET of tubular products.

8.7.2 Tangential Eddy Current Examination (TECA)

TECA uses an eddy current array to introduce alternating currents into the surface of the tested component to detect and size surface-breaking cracks. The method uses a probe to introduce the current and alert the operator to the presence of defects and their magnitude.

The method's use of multiplexed tangential coils and pancake coils allows scans of wide surfaces in a single pass to reduce the inspection time.

8.8 Radiographic Examination (RT)

8.8.1 General

RT is a volumetric examination method capable of examining the entire specimen rather than just the surface. It is the historical approach to examine completed welds for surface and subsurface discontinuities. The method uses the change in absorption of radiation by solid metal and in areas of discontinuity (voids). The transmitted radiation causes a permanent image (radiograph) of the weld to be captured on film. Alternate methods can be used to create the image: computed radiography (CR) or digital radiography (DR). Any of the methods will create a "negative image" of the material being examined, as thicker areas will appear lighter while thinner sections will appear darker. Materials with relatively higher density, such as tungsten, will appear much lighter than the weld/base metal. Due to the hazard of radiation and the licensing requirements, the cost of RT can be higher and trained and certified personnel less available than with other NDE methods.

An NDT examiner interprets and evaluates the radiographs for differences in absorption and transmission results. Radiographic indications display a different density in contrast to the normal background image of the weld or part being inspected. The radiographer also ensures that the film is exposed by the primary source of the radiation and not the undesirable backscatter or secondary radiation exposure.

The NDT examiner who performs the film interpretation, evaluation, and reporting shall be certified at a minimum to ASNT Level II requirements. However, all personnel performing radiography are required to attend radiation-safety training and comply with the applicable regulatory requirements.

ASME Section V, Article 2, Paragraph T-220, lists the general requirements for radiographic examination. There are very specific requirements regarding the quality of the produced radiograph, including the sharpness of the image, the ability to prove adequate film density in the area of interest, and sensitivity to the size and type of expected flaws. Requirements listed in Article 2 include:

a) method to determine if backscatter is present;

b) permanent identification, traceable to the component;

c) film selection in accordance with SE-1815;

d) designations for hole or wire type image quality indicators;

e) suggested radiographic techniques;

f) facilities for viewing radiographs;

g) calibration (certification of source size).

The creation of a radiograph is considered acceptable when it meets the required quality features in general terms of sensitivity and density. These factors are designed to ensure that imperfections of a dimension relative to section thickness are revealed.

8.8.2 Image Quality Indicators (IQIs)

Standards for industrial radiography require the use of one or more IQIs to determine that the required sensitivity has been achieved. The IQI was previously called a penetrameter, but this term is no longer used in most codes. To determine radiographic sensitivity, the required plaque-type hole (and outline) or wire, as specified by the governing code, must be clearly visible on the radiograph. Mistakes with IQI selection can have much greater impact on the interpretation of radiographs of thinner wall pipe where large root pass imperfections can significantly reduce the strength and integrity of a weld.

IQIs are tools used in industrial radiography to establish the quality level of the radiographic technique, but they are not used to determine the size of an imperfection. IQIs are selected based on the following:

a) material being radiographed: the IQI must be made from material that is radiographically similar to that being radiographed;

b) thickness of the base material plus weld reinforcement (internal and external): the thickness of any backing ring or strip is not a consideration in IQI selection.

There are two general types of IQIs.

a) Wire-type IQIs are constructed of an array of (generally) six parallel wires of specified diameters encased in plastic. They are made of material that is radiographically similar to the component being radiographed. Wire-type IQIs are placed on and perpendicular to the weld prior to the exposure of a radiograph. The diameter of the essential wire, based upon code requirements as a function of thickness, visible as a lighter white image on the radiograph, documents that the radiographic technique has the required sensitivity, as a function of contrast and definition. The specific wire that is to be clearly visible on an acceptable radiograph is known as the essential wire and it is specified by the standard. Wire-type IQIs are most often placed perpendicular to the center line of the weld with the required sensitivity based on weld thickness.

b) Hole-type IQIs are plaques (strips of metal) of known thickness with holes of a specified diameter drilled or punched through the sheet. They are made of material that is radiographically similar to the component being radiographed. The thicknesses of hole-type IQIs are specified to represent approximately 2 % or 4 % of the thickness of the object being radiographed. The holes in the IQI are projected on a radiograph as darker (black or gray) spots. The ability to see the plaque outline and the diameter of the required hole visible as a darker image on the radiograph documents the sensitivity of the radiographic technique. The diameters of the holes in hole-type IQIs are a multiple of the thickness of the sheet. Common hole diameters are one, two, and four times the thickness ($1T$, $2T$, and $4T$) of the IQI, as shown in Figure 31. Hole-type IQIs are placed adjacent to the weld either on the parent material or on a shim having a thickness equivalent to the weld combined reinforcement (internal and external).

For a pipe weld thickness of 0.312 in. (7.9 mm), a No. 15 ASTM IQI with a thickness of 0.015 in. (0.38 mm) as shown in Figure 32 would be required. See Table 7 for IQI numbers for other thicknesses. This table illustrates the specified thickness and number of ASTM E94 IQIs for all thickness ranges, and summarizes the essential hole diameter requirements for hole-type IQIs.

The hole that is required to be visible on an acceptable radiograph is called the essential hole. Each size of hole-type IQI is identified by a number that is related to the sheet thickness in inches. For example, a No. 10 IQI is 0.010 in. (0.25 mm) thick while a No. 20 is 0.020 in. (0.51 mm) thick.

Table 7—ASTM E94 IQIs

Pipe Wall or Weld Thickness in. (mm)	No.	Essential Hole Diameter in. (mm)
0 to 0.250 (0 to 5.6)	12	0.025 (0.63)
> 0.250 to 0.375 (5.8 to 9.5)	15	0.030 (0.76)
> 0.375 to 0.500 (9.5 to 12.7)	17	0.035 (0.89)
> 0.500 to 0.750 (12.7 to 19.0)	20	0.040 (1.02)
> 0.750 to 1.000 (19.0 to 25.4)	25	0.050 (1.27)
> 1.000 to 2.000 (25.4 to 50.8)	30	0.060 (1.52)

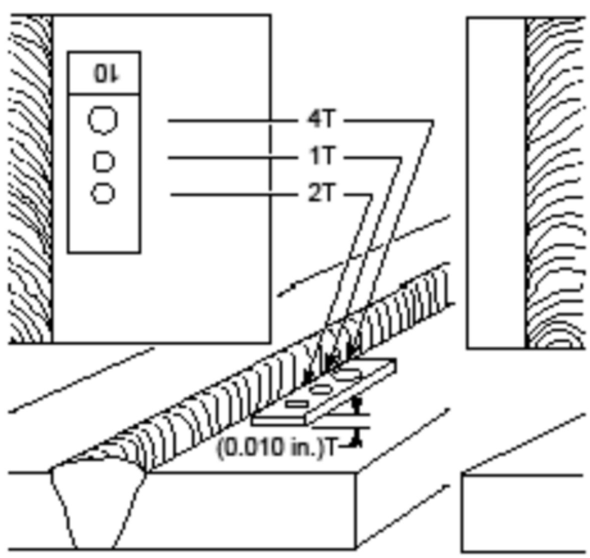


Figure 31—IQI Common Hole Diameters

Figure 32—IQI

8.8.3 Radioactive Source Selection

For weld inspection, iridium 192, cobalt 60, and selenium 75 radioactive isotopes are used. X-ray machines may also be used. Iridium 192 is normally used for performing radiography on steel with a thickness range of 0.25 in. to 3 in. (6 mm to 75 mm). Cobalt 60 is used for steel thickness of 1.5 in. to 7 in. (38 mm to 175 mm). The minimum or maximum thickness that can be radiographed for a given material is determined by demonstrating that the required radiographic sensitivity has been documented.

8.8.4 Radiographic Film

Although digital recording of radiography is sometimes used, radiographic film Class I or II is extensively used for industrial RT. The film is required to be of a sufficient length and width to allow a minimum of 1 in. (25 mm) on consecutive circumferential exposures, and $^3/_4$ in. (19 mm) coverage on either side of the weld. Film should be stored in a cool, dry, clean area away from the exposure area, where the emulsion cannot be affected by heat, moisture, or radiation.

An industry standard is to select a radiographic film capable of providing the required radiographic quality level in the most expedient timeframe. There are several options with respect to industrial radiographic film selection. Radiographic film with an ultrafine (smaller) grained structure is capable of providing very high contrast with excellent definition. This film is generally known as Class I Film. Radiographic film with a larger grain structure has a resultant lower contrast and definition, and is known as Class 2 film. Because the grains in Class 1 film are much smaller than those in Class 2 film, the exposure times for Class 1 film are longer than those of Class 2 film. The tradeoff of increased quality versus reduced exposure time must be evaluated when selecting radiographic film for each specific application.

8.8.5 Film Processing

Exposed film can either be manually processed or the examiner may use an automatic processor. Typical development time is 5 to 8 min at 68 °F (20 °C). When the developer temperature is higher or lower, the developing time is adjusted; however, processing time and temperature must be in accordance with the chemical manufacturer’s recommendations. Automatic processing consistently produces radiographs of desired quality. The chemicals used in processing (developer, stop bath, fixer, and rinse water) are changed on a regular basis to maintain quality requirements.

8.8.6 Surface Preparation

Surface conditions that could mask an imperfection, if visually detected by the radiographer prior to radiography, should be remedied prior to exposure. Weld ripples or other irregularities on the inside, where accessible, or on the outside should be removed so the surface feature cannot be confused with the image of a discontinuity.

8.8.7 Radiographic Identification

The identification information on all radiographs should be plainly and permanently produced, traceable to contract, manufacturer, date, and to component, weld or weld seam, and part numbers as appropriate, and should not obscure any area of interest. This is typically accomplished using lead characters. Location markers should also appear on the film identifying the area of coverage.

8.8.8 Radiographic Techniques

8.8.8.1 General

The most effective technique from both quality and efficiency standpoints is one in which the radiation passes through a single thickness of the material being radiographed and the film is in contact with the surface opposite the source side. Other techniques may be used as the referencing code or situation dictates. Regardless of the technique used, the goal is to achieve the highest possible quality. The IQI should be placed according to the referencing code or specification. Placing the IQI as close to the weld as possible without interfering with the weld image is a basic requirement of all codes and specifications.

A technique should be chosen based upon its ability to produce clear images of discontinuities, especially those that may not be oriented in a favorable direction to the radiation source. Radiography is extremely sensitive to the orientation of tight planar discontinuities such as cracks. If a tight planar discontinuity is expected to be at an angle to the source of the radiation, it may be difficult or impossible to detect. The nature, location, and orientation of discontinuities should always be a major factor in establishing the technique.

8.8.8.2 Single-Wall Exposure, Single-Wall Viewing Technique

A single-wall exposure technique should be used whenever practical. In the single-wall technique, the radiation passes through only one wall of the material or weld, which is viewed for acceptance on the radiograph (see Figure 33). An adequate number of exposures should be made to demonstrate that the minimum required coverage has been obtained.

8.8.8.3 Double-Wall Exposure, Single-Wall Viewing Technique

A technique may be used in which the radiation passes through two walls and only the weld on the film side is evaluated. An adequate number of exposures should be made to demonstrate that the required coverage is met for circumferential welds (materials). A minimum of three exposures taken at 120° to each other should be made.

8.8.8.4 Double-Wall Exposure, Double-Wall Viewing Technique

When it is not practical to use a single-wall technique, a double-wall technique should be used.

For materials and welds in components having a nominal pipe size (NPS) of 3 [outside diameter of 3.5 in. (90 mm) or less], a technique may be used in which the radiation passes through two walls and the weld (material) in both walls is viewed for acceptance on a single radiograph. For double-wall viewing of welds, the radiation beam may be offset from the plane of the weld at an angle sufficient to separate the images of the source-side portions and the film-side portions of the weld so there is no overlap of the areas to be interpreted (see Figure 34). When complete coverage is required, a minimum of two exposures taken at 90° to each other should be made of each weld joint.

Alternatively, the weld may be radiographed with the radiation beam positioned such that both walls are superimposed. When complete coverage is required, a minimum of three exposures taken at either 60° or 120° to each other should be made for each weld joint.

Due to inherent problems including geometric unsharpness, RT of fillet welds is not recommended.

8.8.8.5 Storage of Film and Other Imaging Media

All unexposed films shall be stored in a clean, dry place where the conditions will not detrimentally affect the emulsion. If any question arises about the condition of the unexposed film, sheets from the front and back of each package or a length of film equal to the circumference of each original roll shall be processed in the normal manner without exposure to light or radiation. If the processed film shows fog, the entire box or roll from which the test film was removed shall be discarded, unless additional tests prove that the remaining film in the box or roll is free from pre-exposure fog exceeding 0.30 H&D transmitted density for transparent-based film or 0.05 H&D reflected density for opaque-based film. (H&D refers to the Hurter–Driffield method of defining quantitative blackening of film.)

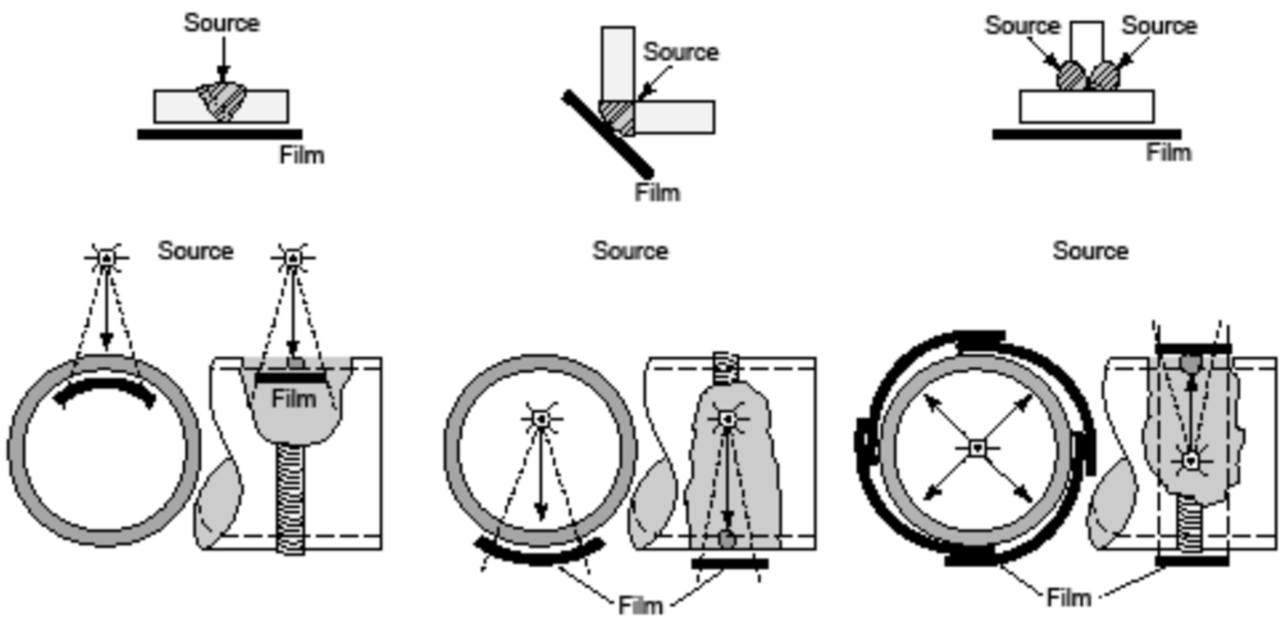
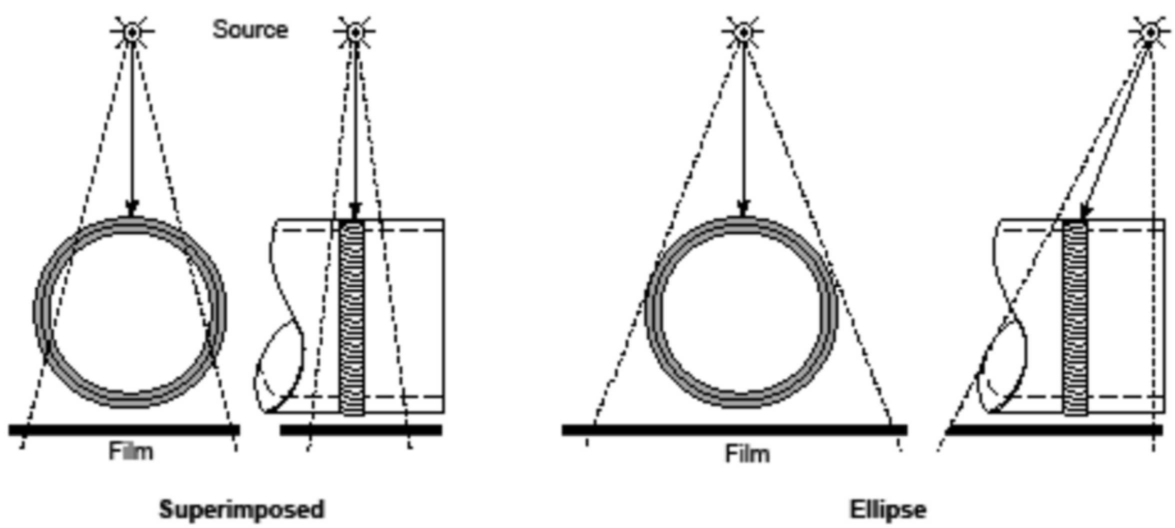


Figure 33—Single-Wall Techniques



Courtesy of Charles J. Heller

Figure 34—Double-Wall Techniques

8.8.9 Evaluation of Radiographs

8.8.9.1 General

The final step in the radiographic process is the evaluation of the radiograph. Accurate film interpretation is the most essential step in the RT process; it requires hours of reviewing and the understanding of principles regarding the nature of ionizing radiation as well as the different types of images and conditions associated in industrial radiography. The interpreter should be aware of different welding processes and the discontinuities associated with those processes. The various discontinuities found in weldments may not always be readily detectable. For example, rounded indications such as porosity, slag, and inclusions have a much greater probability of detection than planar indications such as cracks, LOF, or overlap. A weld crack is generally tight and not always detectable by radiography unless its orientation is in the offset relative to the direction of the radiation. For example, a radiographic source that is offset ±5° from the weld has a lower probability of detecting a crack in a weld where the source is offset 10° from the weld. LOF is typically narrow and linear, and it tends to be straighter than a crack. In many cases, LOF is located at the weld bevel angle or between two subsequent weld bead passes. This may add to the degree of difficulty in identifying this condition.

8.8.9.2 Facilities for Viewing Radiographs

Viewing facilities need to provide subdued background lighting of an intensity sufficient to avoid troublesome reflections, shadows, or glare on the radiograph. Equipment used to view radiographs for interpretation needs to provide a light source sufficient for the weld, base metal, and essential IQI hole or wire to be visible through the specified density range. The viewing conditions should be such that the light from around the outer edge of the radiograph or coming through low-density portions of the radiograph does not interfere with the interpretation. Low-power magnification devices (1.5x to 3x) may also be used to aid in film interpretation and evaluation, but high magnification also enhances the graininess of the film. For example, comparators with scales etched into the glass offer enhanced magnification and measuring capabilities.

8.8.9.3 Quality of Radiographs

Radiographs should be free from mechanical, chemical, or other blemishes to the extent that they do not mask and are not confused with the image of any discontinuity in the area of interest. A radiograph with any blemishes in the area of interest shall be discarded and the area radiographed again.

Definition of the area of interest is often commonly misunderstood and the subject of confusion. Many of the common codes and standards in the hydrocarbon industry do not actually define the area of interest, which leads to misalignment between inspectors and fabricators. ASTM E1316 states "*the specific portion of a radiograph that needs to be evaluated*". This is the approach generally preferred by inspectors, and it gives the inspector the final decision to identify the area of interest. ASME Section XI for the nuclear industry has a more practical guidance of *1t* where *t* is the nominal thickness of the component being joined. This provides a minimum recommended guidance for inspectors reviewing radiographs.

8.8.9.4 Radiographic Density

Film density is the quantitative measure of film blackening as a result of exposure and processing. Clear film has a zero density value. Exposed film that allows 10 % of the incident light to pass through has a 1.0 film density. A film density of 2.0 H&D, 3.0 H&D, and 4.0 H&D allows 1 %, 0.1 %, and 0.01 %, respectively, of the incident light to pass through.

The transmitted film density through the radiographic image through the body of the hole-type IQI, or adjacent to the wire IQI, in the area of interest should be within the range 1.8 H&D to 4.0 for X-rays and 2.0 H&D to 4.0 H&D for gamma rays. Adequate radiographic density is essential; rejectable conditions in a weld may be undetectable if slight density variations in the radiographs are not observed.

A densitometer or step wedge comparison film is used to measure or estimate the darkness (density) of the film, respectively. A densitometer is an electronic instrument calibrated using a step tablet or step wedge calibration film traceable to a national standard. The step wedge comparison film is a step wedge that has been documented to have a specific H&D density by examination using a calibrated densitometer.

The density of the radiograph is measured through the IQI. Several density readings should be taken at random locations in the area of interest (excluding areas having discontinuities). The density range in the area of interest shall not vary more or less than a specified percentage of the base density as defined in the code or specification.

It is a good practice to process an unexposed piece of film daily to determine the pre-exposure condition of the radiographic film.

8.8.9.5 Backscatter Radiation

Radiation that passes through the object and film can be reflected back towards the film (a phenomenon known as backscatter). A lead letter “B” with a minimum dimension of $^{1}/_{2}$ in. (12 mm) and $^{1}/_{16}$ in. (1.5 mm) thickness is typically attached to the back of each film holder/cassette during each exposure to determine if backscatter radiation is exposing the film. If a lighter density image of the letter “B” appears on any radiograph of a darker background, protection from scatter radiation is considered insufficient and the radiograph is considered unacceptable. A darker density image of the “B” on a lighter background is not cause for rejection of the radiograph.

There is a common misconception by those not trained in industrial radiography that the letter “B” always appears on a radiograph. This is in fact not correct, and the opposite is true. Where there is no medium besides free air to cause backscatter, there will be insufficient radiation reflected back to the film or imaging device to produce an image.

8.8.9.6 Interpretation

Radiographic interpretation is the skill of extracting the maximum information from a radiographic image. This requires subjective judgment by the interpreter and is influenced by the interpreter’s knowledge of:

a) the characteristics of the radiation source and energy level(s) with respect to the material being examined;

b) the characteristics of the recording media in response to the selected radiation source and the energy level(s);

c) the processing of the recording media with respect to the image quality;

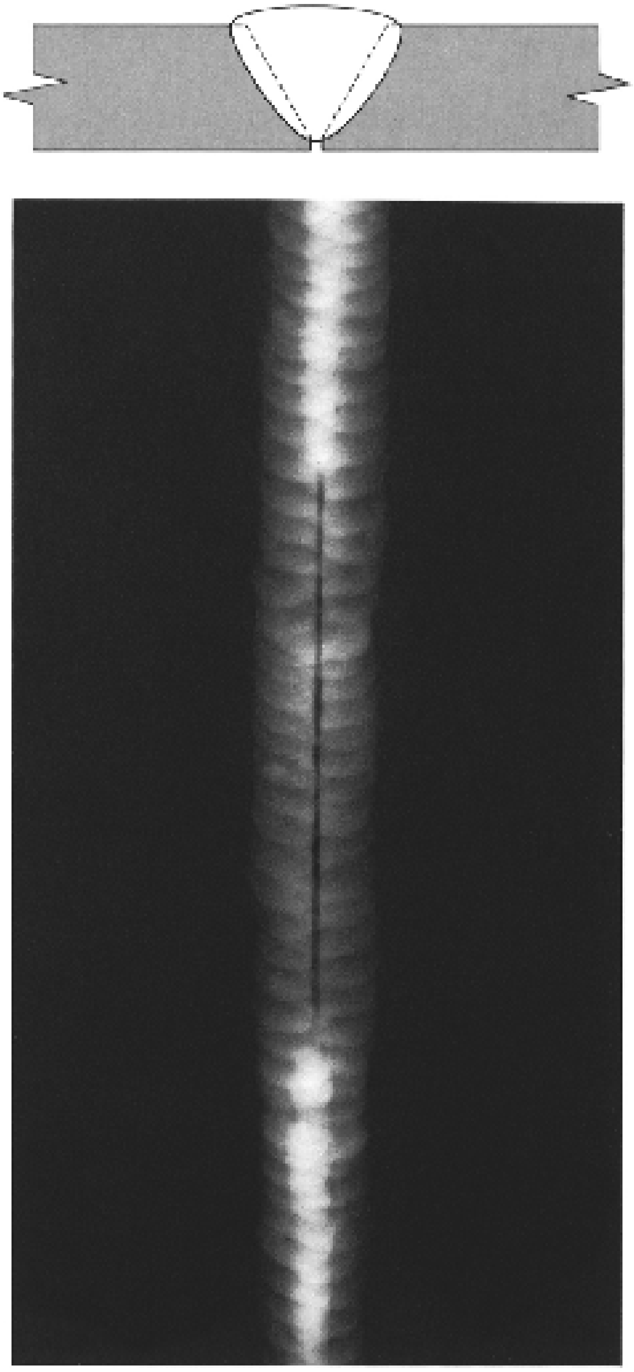
d) the product form, welding process, and geometric configuration of the object being radiographed;

e) the possible and most probable types of discontinuities that may occur in the test object;

f) the possible variations of the images of the discontinuities as a function of radiographic geometry and other factors; and

g) the acceptance criteria that are to be applied for accept/reject determination.

Because radiographic interpreters have varying levels of knowledge and experience, training becomes an important factor for improving the agreement levels between interpreters. In applications where quality of the final product is important for safety or reliability, more than one qualified interpreter should evaluate the radiographs. Figures 35–46 are radiographic weld images illustrating some typical welding discontinuities and defects.

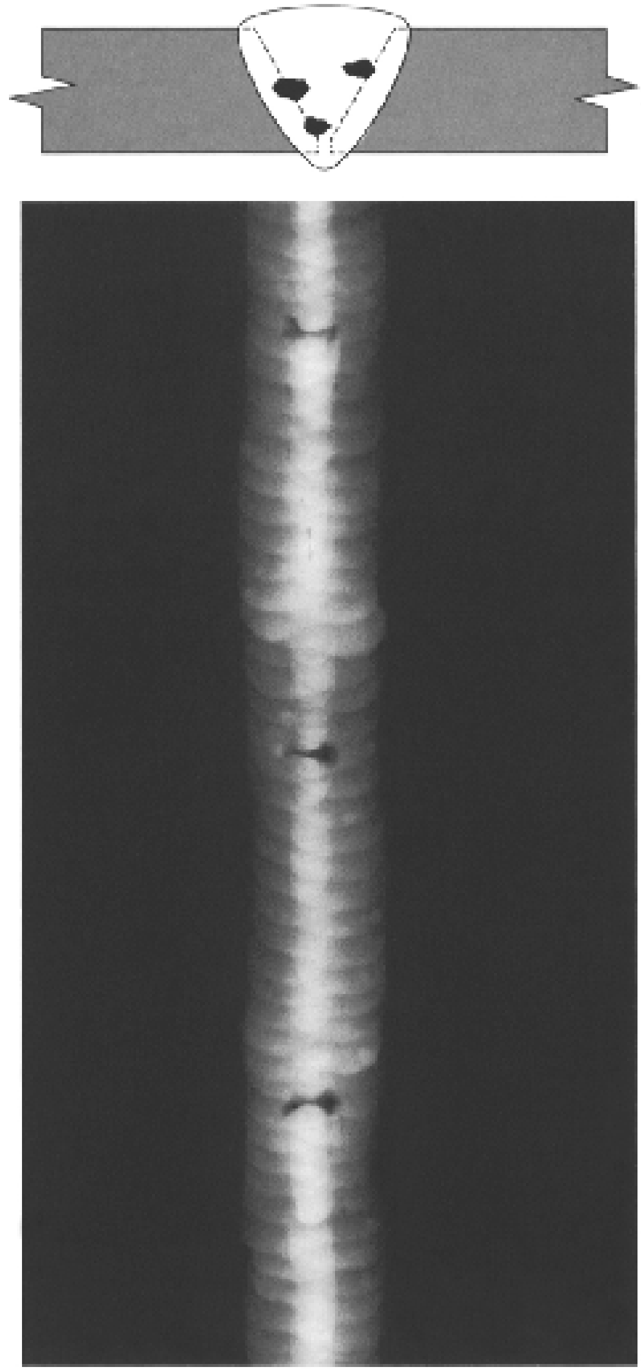


NOTE 1 The edges of the pieces have not been welded together, usually at the bottom of single V-groove welds.

NOTE 2 Radiographic image: A darker density band, with straight parallel edges, in the center of the width of the weld image.

NOTE 3 Welding process: SMAW.

Figure 35—Incomplete or Lack of Penetration (LOP)

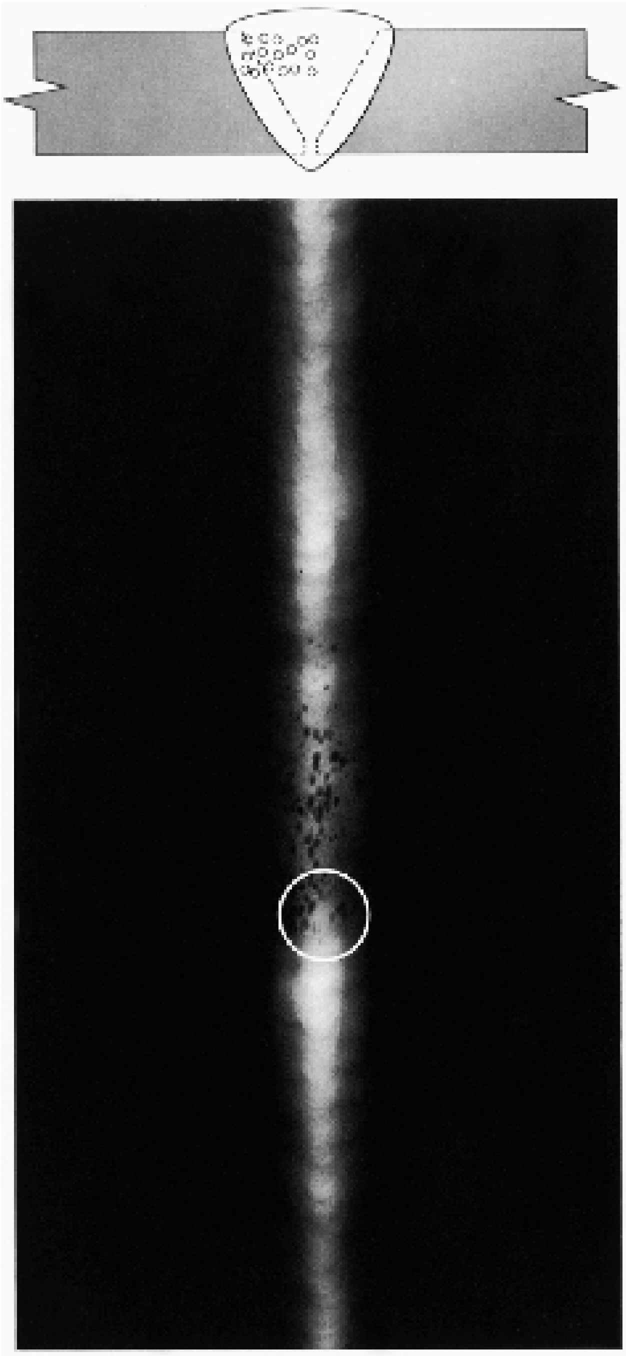


NOTE 1 Usually caused by nonmetallic impurities that solidify on the weld surface and are not removed between weld passes.

NOTE 2 Radiographic image: An irregularly shaped darker density spot usually slightly elongated and randomly spaced.

NOTE 3 Welding process: SMAW.

Figure 36—Interpass Slag Inclusions

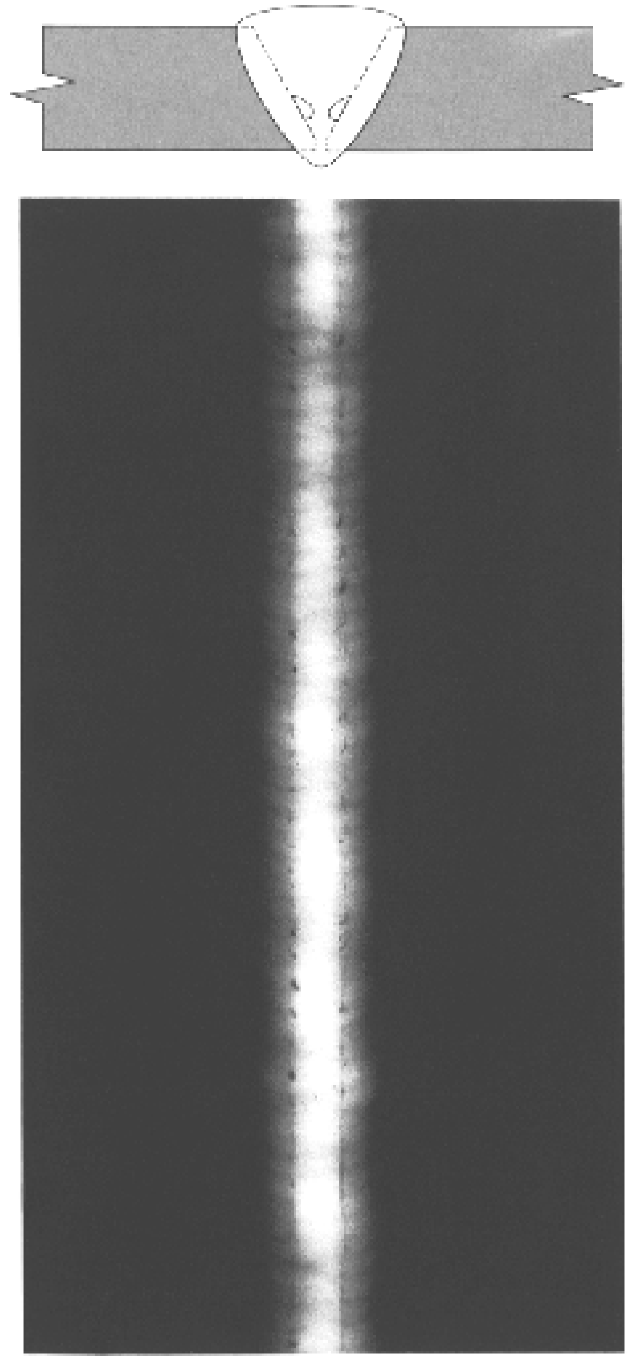


NOTE 1 Rounded or slightly elongated voids grouped together.

NOTE 2 Radiographic image: Rounded or slightly elongated darker density spots in clusters randomly spaced.

NOTE 3 Welding process: SMAW.

Figure 37—Cluster Porosity

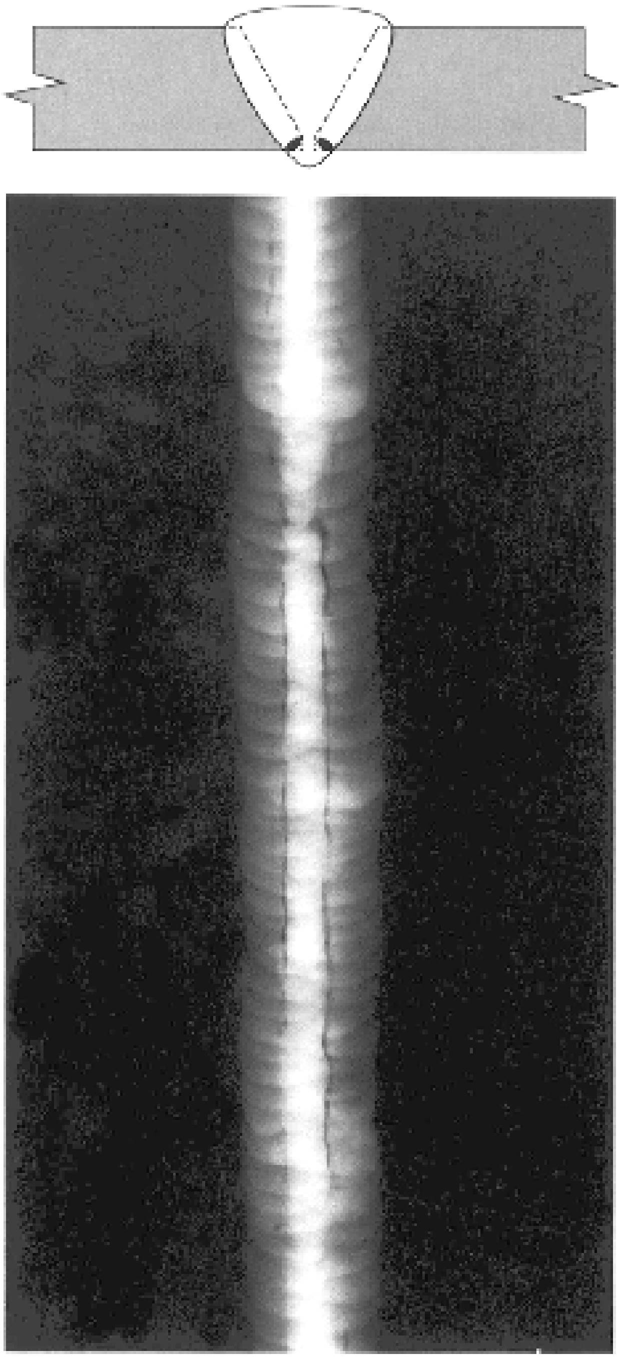


NOTE 1 Elongated voids between the weld beads and the joint surfaces.

NOTE 2 Radiographic image: Elongated parallel, or single, darker density lines sometimes with darker density spots dispersed along the LOF lines which are very straight in the lengthwise direction and not winding like elongated slag lines.

NOTE 3 Welding process: GMAW.

Figure 38—Lack of Side Wall Fusion

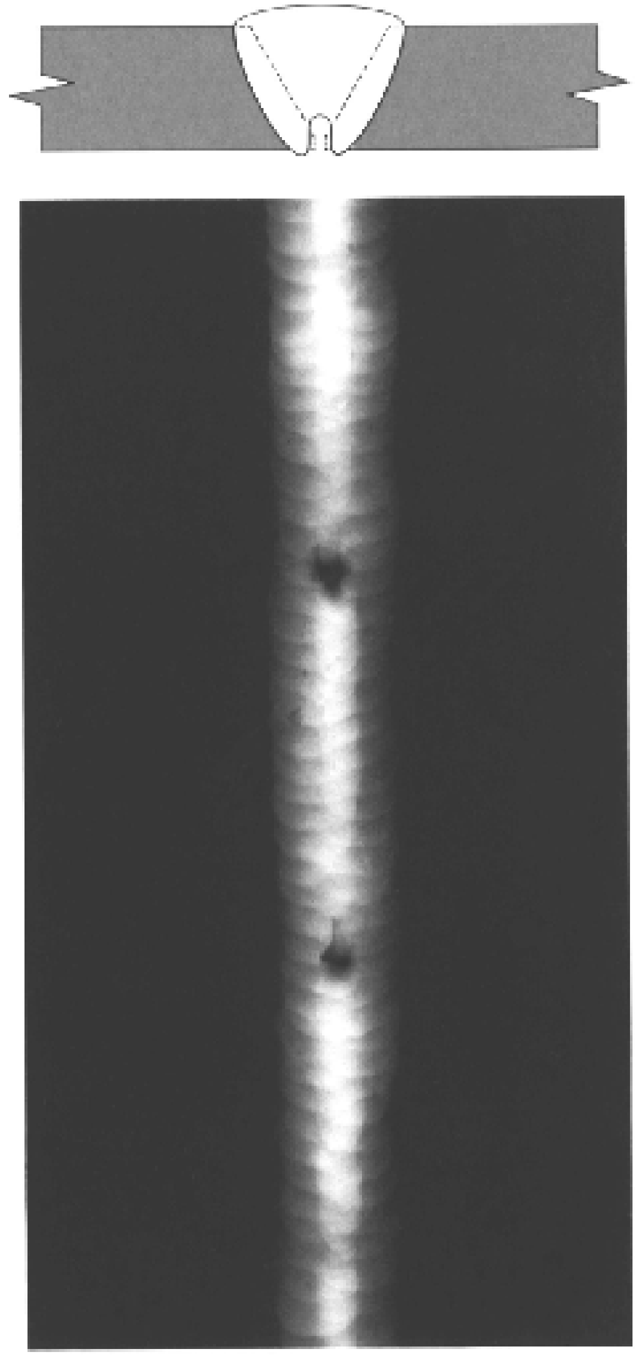


NOTE 1 Impurities that solidify on the surface after welding and were not removed between passes.

NOTE 2 Radiographic image: Elongated, parallel, or single darker density lines, irregular in width and slightly winding in the lengthwise direction.

NOTE 3 Welding process: SMAW.

Figure 39—Elongated Slag (Wagon Tracks)

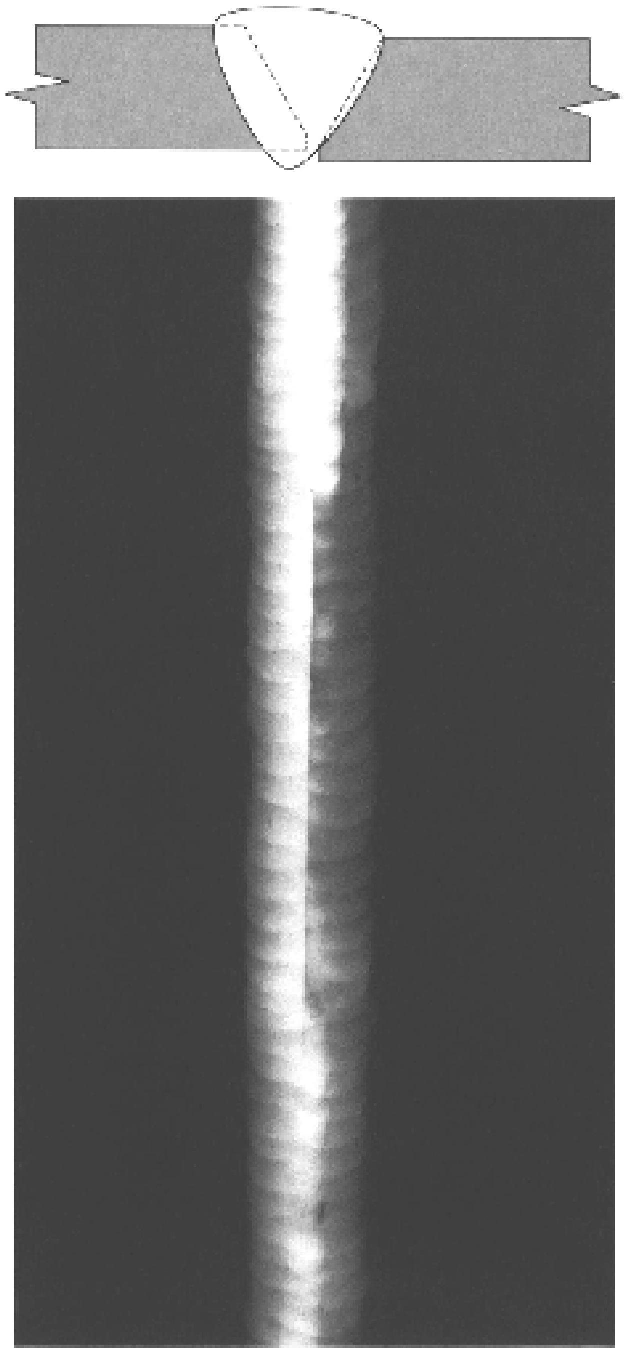


NOTE 1 A severe depression or a crater-type hole at the bottom of the weld, but usually not elongated.

NOTE 2 Radiographic image: A localized darker density with fuzzy edges in the center of the width of the weld image. It may be wider than the width of the root pass image.

NOTE 3 Welding process: SMAW.

Figure 40—Burn-Through

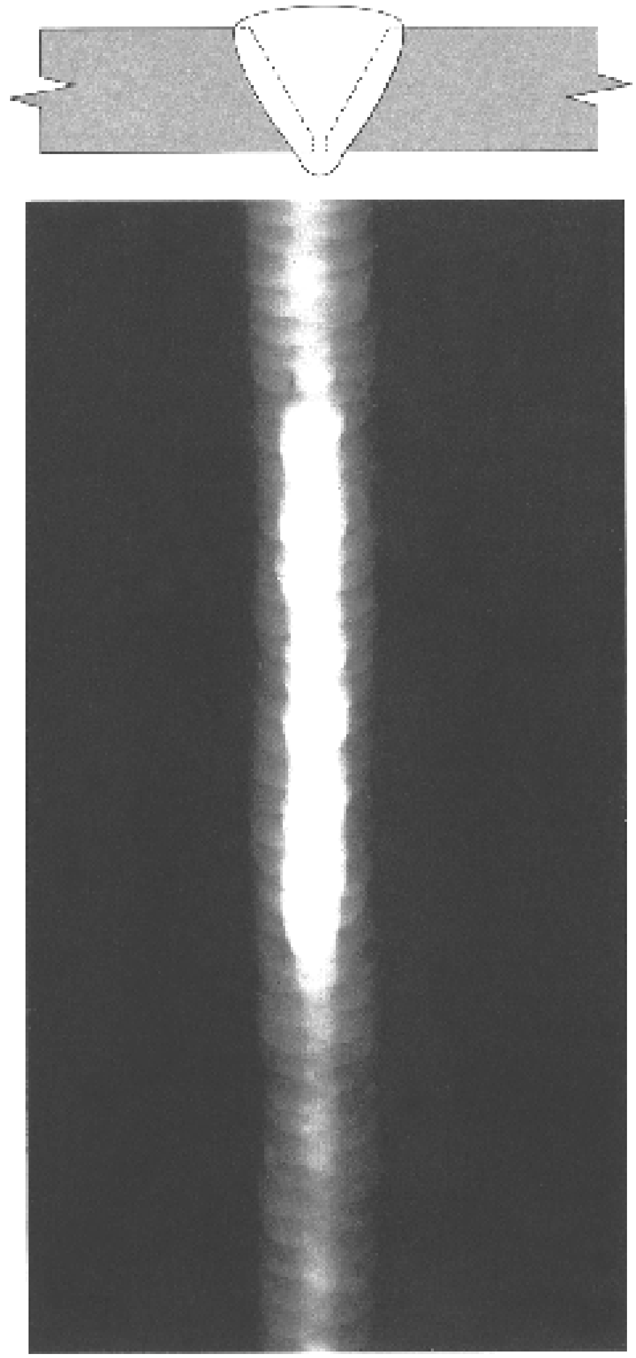


NOTE 1 A misalignment of the pieces to be welded and insufficient filling of the bottom of the weld or "root area".

NOTE 2 Radiographic image: An abrupt density change across the width of the weld image with a straight longitudinal darker density line at the center of the width of the weld image along the edge of the density change.

NOTE 3 Welding process: SMAW.

Figure 41—Offset or Mismatch With Lack of Penetration (LOP)

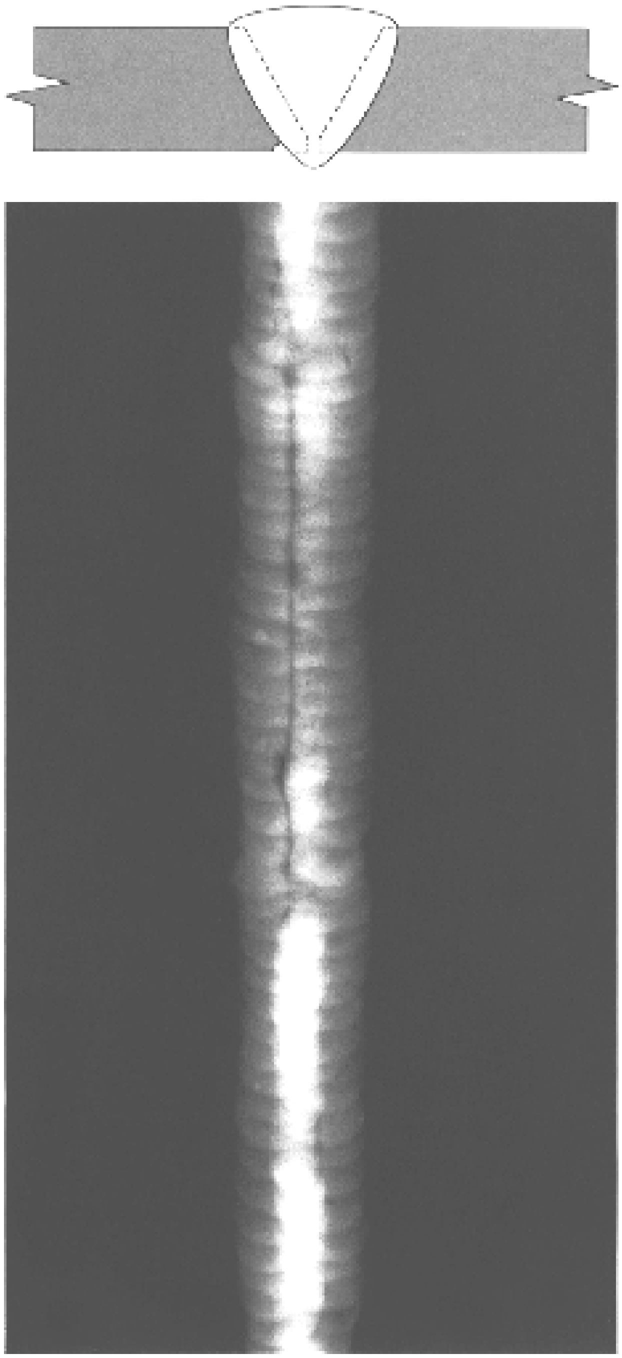


NOTE 1 Extra metal at the bottom (root) of the weld.

NOTE 2 Radiographic image: A lighter density in the center of the width of the weld image, either extended along the weld or in isolated circular "drops".

NOTE 3 Welding process: SMAW.

Figure 42—Excessive Penetration (Icicles, Drop-Through)

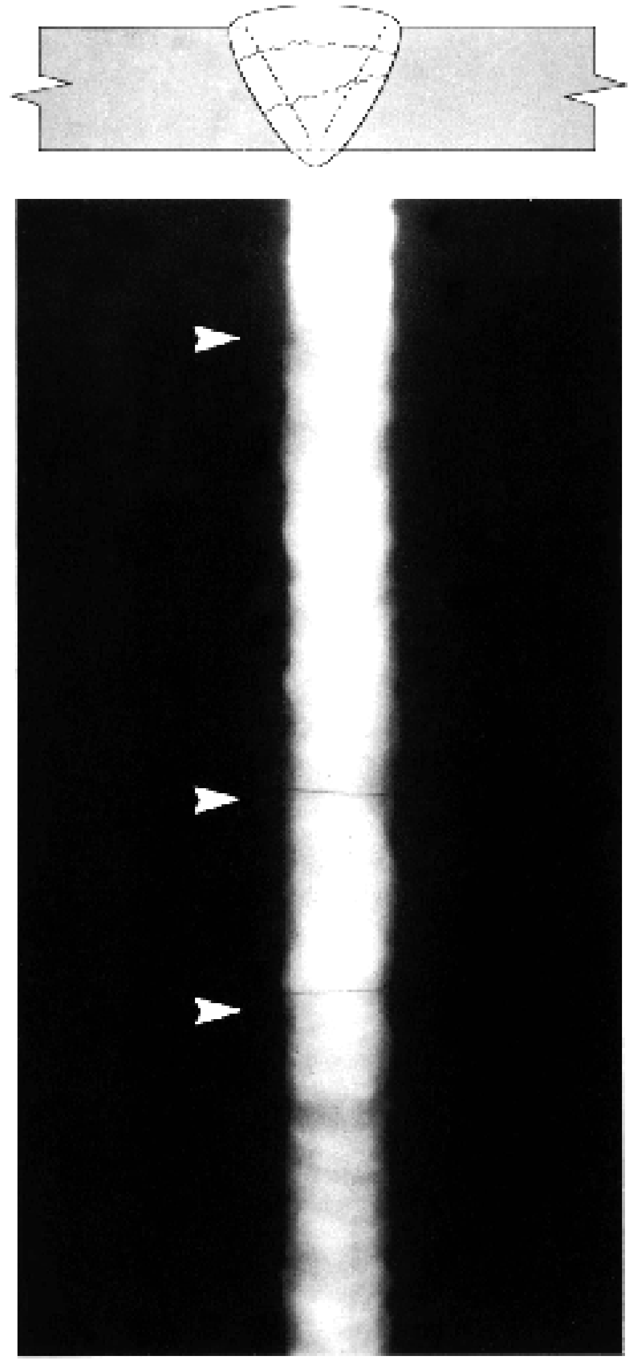


NOTE 1 A gouging out of the parent metal, alongside the edge of the bottom or internal surface of the weld.

NOTE 2 Radiographic image: An irregular darker density near the center of the width of the weld image along the edge of the root pass image.

NOTE 3 Welding process: SMAW.

Figure 43—Internal (Root) Undercut

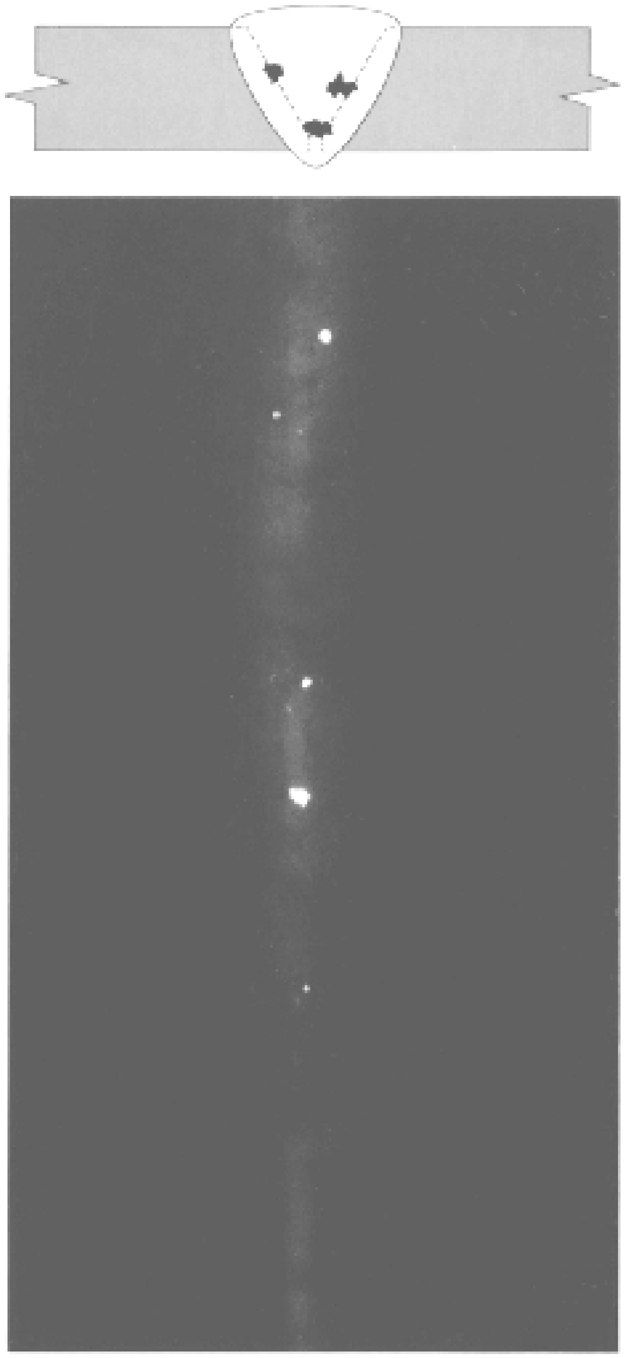


NOTE 1 A fracture in the weld metal running across the weld.

NOTE 2 Radiographic image: feathery, twisted line of darker density running across the width of the weld image.

NOTE 3 Welding process: GIAW.

Figure 44—Transverse Crack

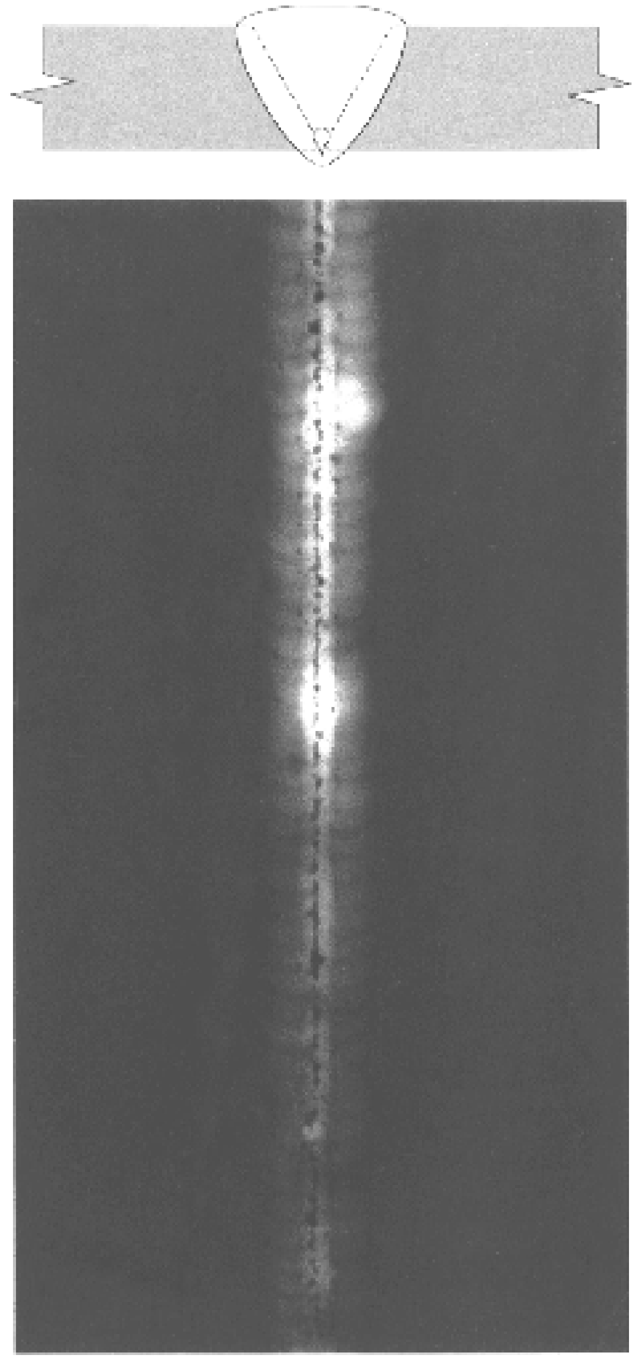


NOTE 1 Random bits of tungsten fused into but not melted into the weld metal.

NOTE 2 Radiographic image: Irregular shaped lower density spots randomly located in the weld image.

NOTE 3 Welding process: GIAW.

Figure 45—Tungsten Inclusions



NOTE 1 Rounded and elongated voids in the bottom of the weld aligned along the weld centerline.

NOTE 2 Radiographic image: Rounded and elongated darker density spots, that may be connected, in a straight line in the center of the width of the weld image.

NOTE 3 Welding process: GMAW.

Figure 46—Root Pass Aligned Porosity

8.8.10 Radiographic Examination Records

The information reported is to include, but not be limited to, the following:

a) job/contract number/identification;

b) location marker placement;

c) number of radiographs (exposures);

d) X-ray voltage or isotope type used;

e) X-ray machine focal spot size or isotope effective focal spot source size;

f) base material type and thickness, weld reinforcement thickness;

g) source-to-object distance;

h) distance from source side of object to film;

i) film manufacturer and type/designation;

j) number of films in each film holder/cassette;

k) single- or double-wall exposure;

l) single- or double-wall viewing;

m) type of IQI and the required hole/wire number designation;

n) procedure and/or code references, examination results;

o) date of examination, name and qualification level of examiners.

Any drawings, component identification, or additional details need to be provided to the customer's representative, along with the examination report. A sample radiography report is provided in Annex E.

8.9 Ultrasonic Examination (UT)

8.9.1 General

UT is capable of detecting surface and subsurface discontinuities. A sound beam in the ultrasonic frequency range (>20,000 cycles per second) travels a straight line through the metal and reflects from an interface. For weld inspection, this high-frequency sound beam is introduced into the weld and HAZ along a predictable path, which, upon reflection or refraction from an imperfection or geometric feature, produces a response that is processed and presented on the display. These images are presented such that they might give the inspector both the size and positional information of the imperfection.

Straight-beam techniques are used for thickness evaluation or to check for lamination, and/or other conditions which may prevent angle beams from examining the weld. Straight-beam (or zero degree) transducers direct a sound beam from an accessible surface of the test piece to a boundary or interface that is parallel or near parallel to the contacted surface. The time it takes for the sound to make a round trip through the piece is displayed on the ultrasonic instrument. There are several different ways that straight-beam ultrasonic information can be displayed, as shown in Figures 47–49, reprinted courtesy of GE Inspection. These displays represent an accurate thickness of the test piece.

Shear wave or angle beam techniques are employed for resolution of discontinuities in welds. The sound beam enters the area of the weld at a known angle. If the sound reflects from a discontinuity, a portion of the sound beam returns to the transducer where it is displayed on the ultrasonic instrument. These images can be displayed in a number of ways to aid in evaluation. From this display, information such as the size, location, and type of discontinuity can be determined.

8.9.2 Types of Ultrasonic Displays

8.9.2.1 A-Scan Display

The A-scan, as shown in Figure 47, is the most common display type. It shows the response along the path of the sound beam for a given position of the probe. It shows the amplitude of the signal coming from the discontinuity as a function of time. The x axis (right) represents the time of flight and indicates the depth of a discontinuity or back wall (thickness). The y axis shows the amplitude of the reflected signals (echoes) and can be used to estimate the size of a discontinuity compared to a known reference reflector used during instrument calibration.

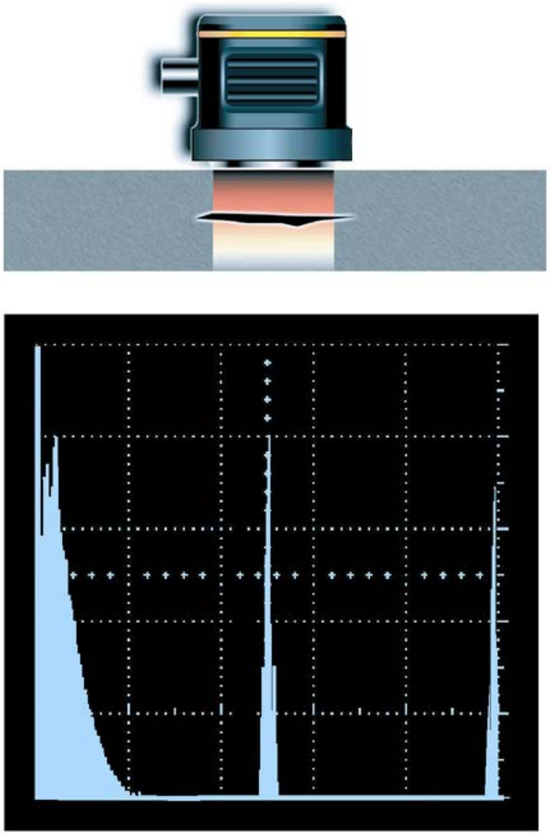


Figure 47—A-Scan

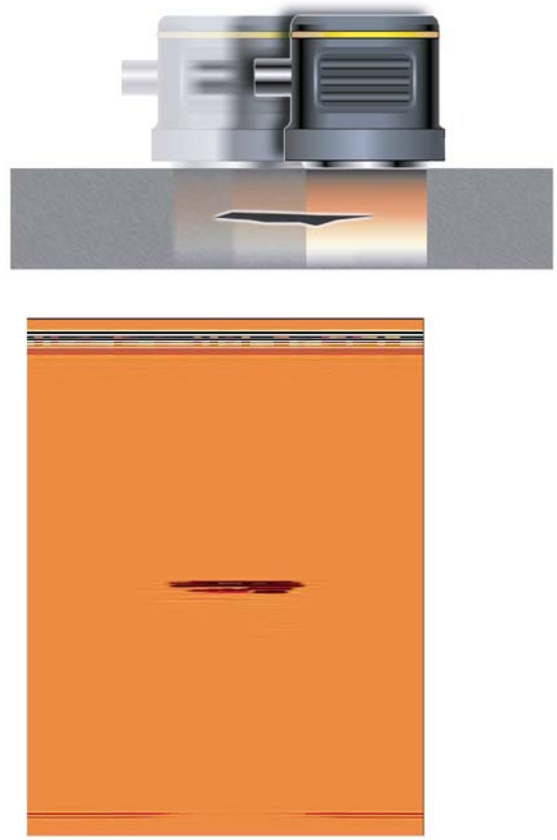
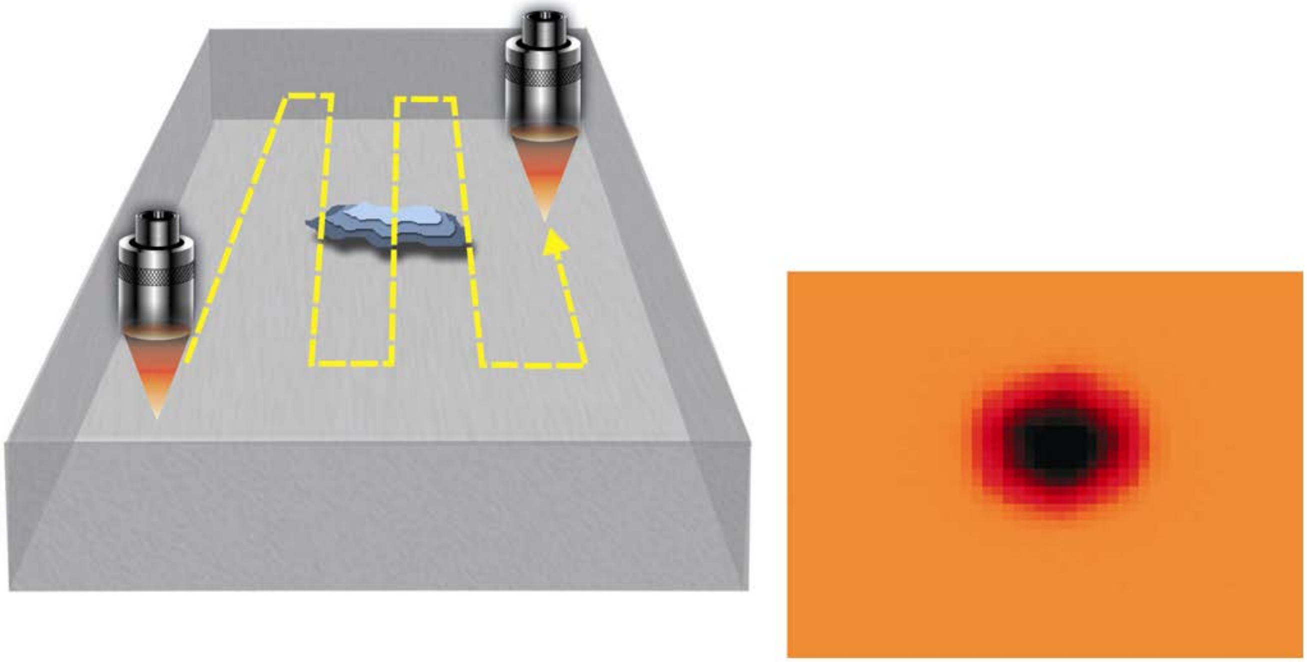


Figure 48—B-Scan



Courtesy of GE Inspection

Figure 49—C-Scan

8.9.2.2 B-Scan Display

The B-scan display (see Figure 48) shows a cross-sectional view of the object under test by scanning the probe along one axis. The horizontal axis (left) relates to the position of the probe as it moves along the surface of the object and provides information as to the lateral location of the discontinuity. Echo amplitude is usually indicated by the color or grayscale intensity of echo indications.

8.9.2.3 C-Scan Display

The C-scan display (see Figure 49) shows a plan view of the test object. The image is produced by mechanically or electronically scanning in an x–y plane. The x and y axes form a coordinate system that indicates probe/discontinuity position. Color or grayscale intensity can be used to represent depth of discontinuity or echo amplitude.

8.9.2.4 D-Scan Display

The D-scan display (see Figure 50) shows a through-thickness view showing a cross-section of the test object perpendicular to the scanning surface and perpendicular to the projection of the beam axis on the scanning surface. The D-scan display is exactly like a B-scan display except that the view is oriented perpendicular to B-scan view in the plane of the plate. The D-scan allows quick discrimination of indications along a weld by presenting their position in depth from the scanning surface. An example of the relationship between all four common ultrasonic displays is shown in Figure 50.

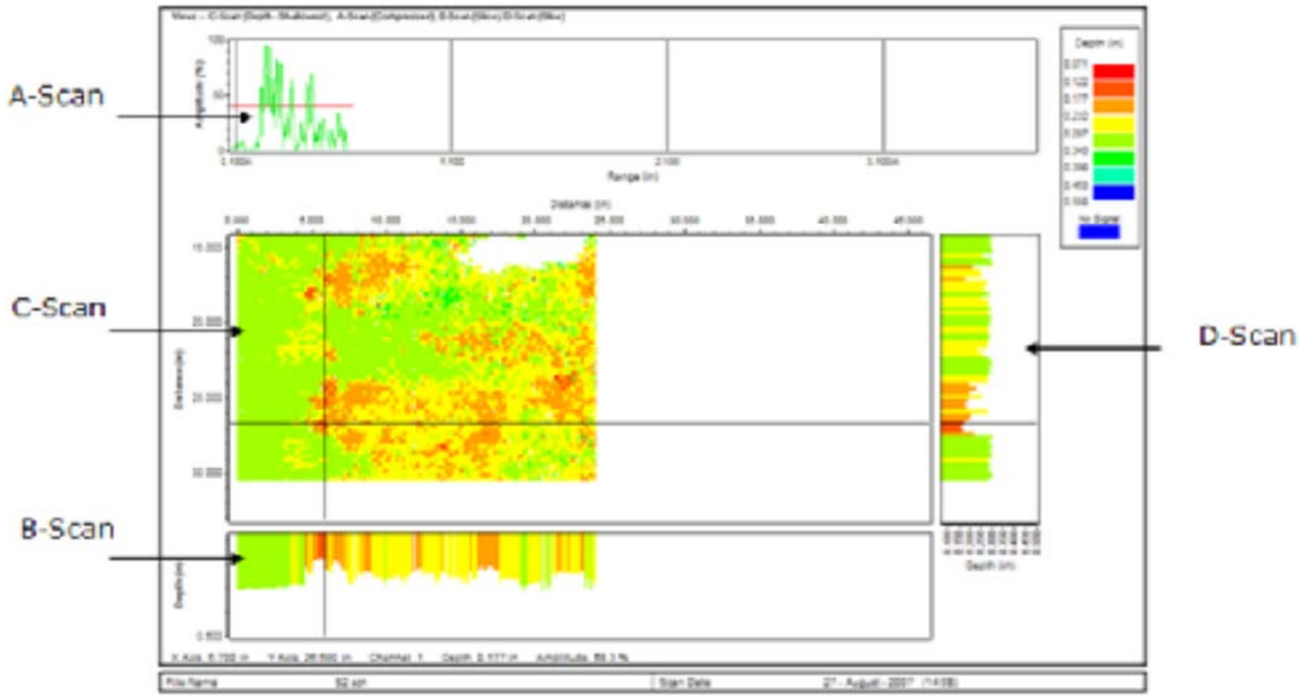


Figure 50—D-Scan

8.9.2.5 Phased Array S-Scan Display

The S-scan or sector display (see Figure 51) shows two-dimensional imaging of ultrasonic reflectors by analyzing data then plotting information from a multitude of angles simultaneously. The image is a cross-sectional view of the area where the ultrasound passes through. Location and size information can be measured for any reflectors that are in the sectorial scan.

Phased array ultrasonics accomplishes this by using a transducer that contains multiple elements, commonly 8 to 128, that are excited at intervals to create constructive interference in the wavefront of ultrasonic energy. This constructive interference is controlled by the amount of time delay in element excitation and can steer the sound through a range of angles. This array of beam angles is then plotted to create the sector scan. The ultrasonic energy provides responses in a pulse-echo fashion as with conventional straight-beam and angle-beam techniques.

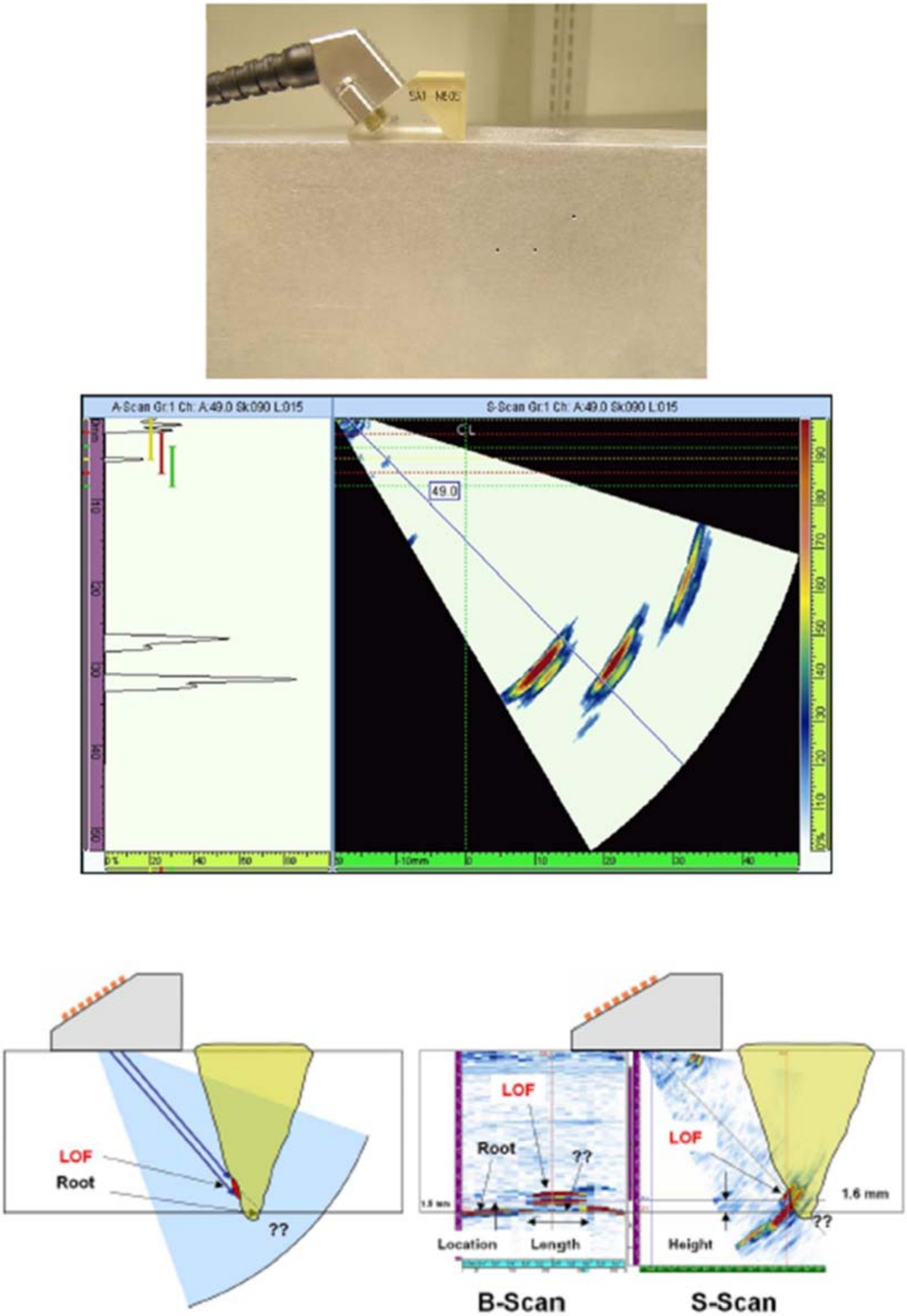


Figure 51—S-Scan

8.9.2.6 Time of Flight Diffraction (TOFD) B-Scan and D-Scan Displays (see Figure 52 and Figure 53)

The B-scan and D-scan displays are a different format than the B-scan and D-scan displays acquired in any other ultrasonic technique utilizing information provided in a pulse echo fashion. TOFD B-scan and D-scan images provide defect sizing information for through-wall extent by using diffracted signals rather than pulse echo signals. The TOFD B-scan and D-scan displays are created by stacking A-scan displays at a preset interval or collection step and viewing the data in a grayscale image where 100 % amplitude of the sine wave in either the positive or negative direction is plotted as all black or all white with gray images of signals less than 100 % amplitude.

TOFD passes sound energy through a weld area by utilizing a transmitting transducer on one side of the weld and a receiving transducer on the other (see Figure 54). Any changes in the material, such as discontinuities, are vibrated by the induced ultrasonic energy. This vibration of discontinuities produces diffracted signals from the discontinuity that are then received by the receiving transducer.

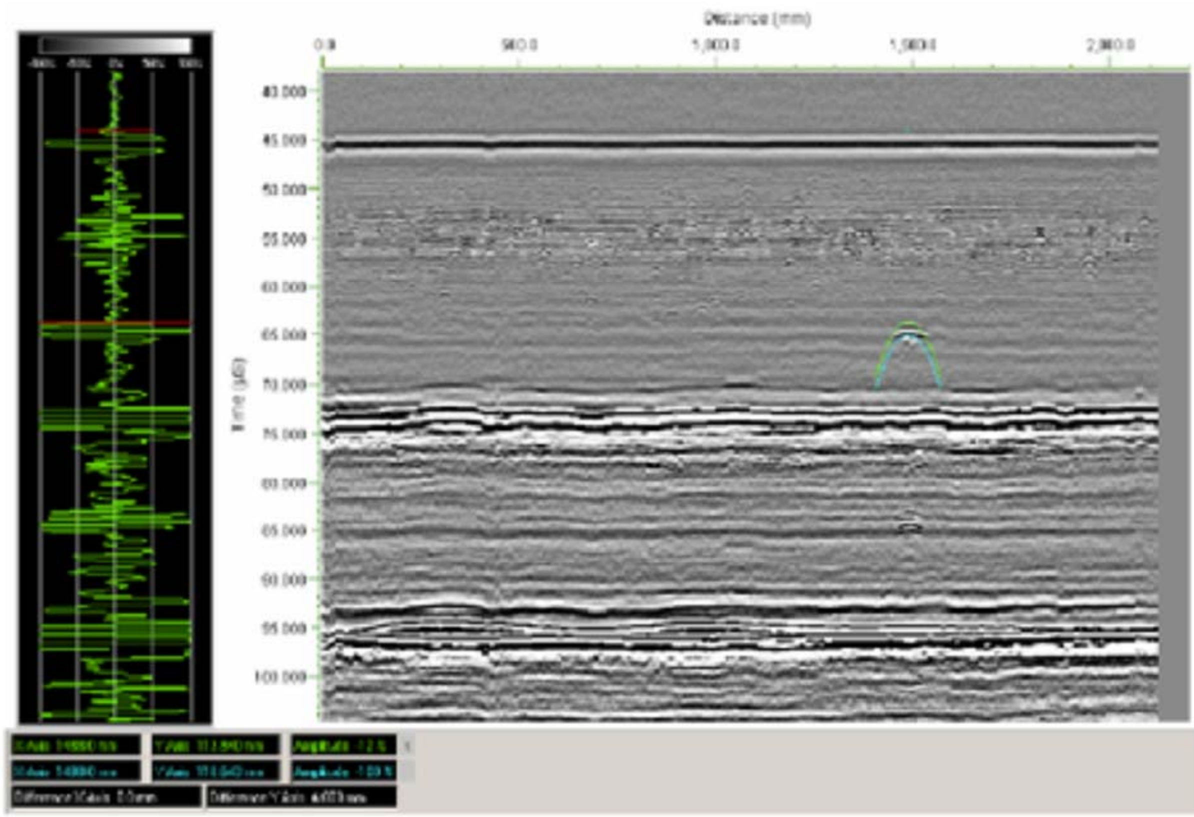


Figure 52—TOFD D-Scan Display

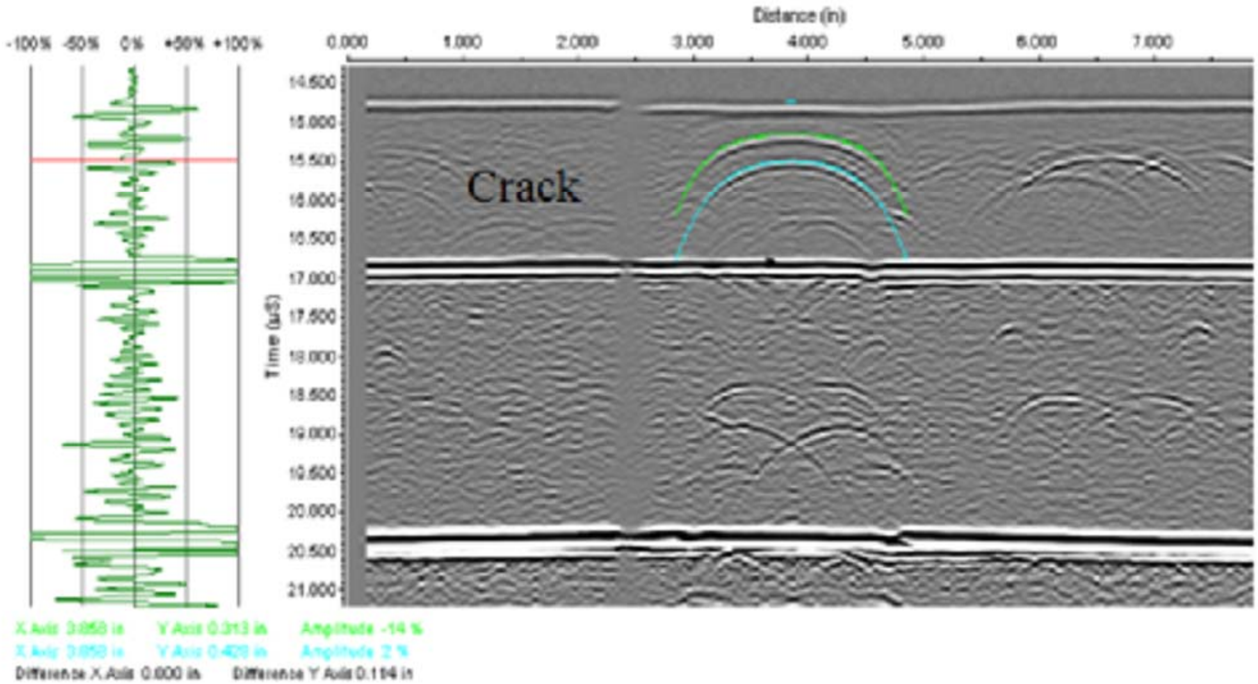
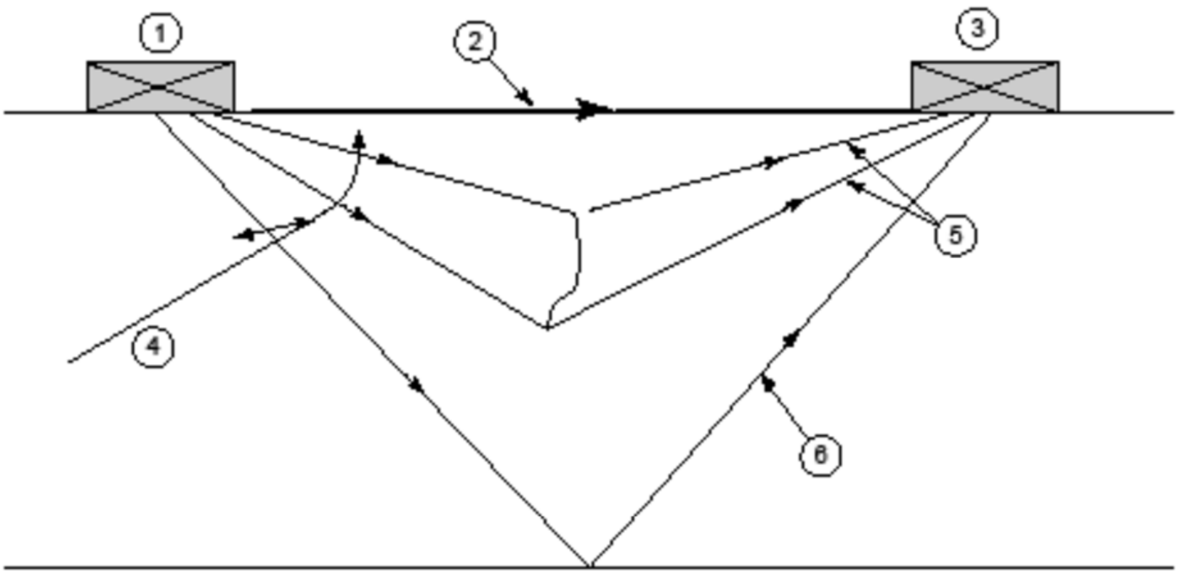


Figure 53—TOFD B-Scan



Key
1 transmitter
2 lateral wave
3 receiver
4 longitudinal wave and shear wave beam spread
5 diffracted energy from flaw tips
6 back wall echo

Figure 54—TOFD Transducer Arrangement and Ultrasonic Energy Beam Propagation

The set of TOFD probes can be manipulated along a weld or across a weld to create scans. Standard TOFD weld inspection is accomplished by moving TOFD probes along the weld, with one transducer on each side of the weld, where the ultrasonic energy is perpendicular to the weld. This is a TOFD D-scan or nonparallel scan. The TOFD probes can also be manipulated across an area parallel to the sound path to evaluate an indication from a position 90° from the perpendicular imaging. This is a TOFD B-scan or parallel scan. This can only be accomplished if the weld cap has been removed for the purpose of weld inspection, and is most often used to provide more accurate imperfection location information once they have been located with the TOFD D-scan.

8.9.2.7 Requirements for Ultrasonic Inspection

ASME Section V, Article 4, lists the general requirements for ultrasonic examination. Codes and specifications may indicate that compliance with these requirements is mandatory. ASME B31.3 and ASME Section VIII, Division 1, requires ultrasonic examination be performed in accordance with ASME Section V, Article 4, which requires a written procedure to be qualified and followed. Some procedural requirements to be included are:

a) weld, base metal types, and configurations to be examined;

b) technique (straight or angle beam);

c) couplant type;

d) ultrasonic instrument type;

e) instrument linearity requirements;

f) description of calibration;

g) calibration block material and design;

h) inspection surface preparation;

i) scanning requirements (parallel and perpendicular to the weld);

j) scanning techniques (manual or automated);

k) evaluation requirements;

l) data to be recorded;

m) reporting of indications in terms of the acceptance standards of the referencing code;

n) postexamination cleaning.

8.9.3 Ultrasonic Examination System Calibration

8.9.3.1 General

Ultrasonic examination system calibration is the process of adjusting the controls of the ultrasonic instrument such that the UT display of the sound path is linear. Calibration is to ensure that there is sufficient sensitivity to detect discontinuities of the size and type expected in the product form and process.

The inspection system includes the examiner, the ultrasonic instrument, cabling, the search unit including wedges or shoes, couplant, and a reference standard. The search unit transducer should be of a size, frequency, and angle capable of detecting the smallest rejectable defect expected to be in the part being examined. The ultrasonic instrument is required to meet the requirements of ASME Section V, Article 5, Paragraph T-530, and should provide the functionality to produce the required display of both the calibration reflectors and discontinuities located during the examination.

The reference standard (calibration block) should have the same composition and heat treatment condition as the product being examined. It should also have the same surface condition as the part being examined. The reference standard should be of an acceptable size and have known reflectors of a specified size and location. These reflectors should be acceptable to the referencing code. ASME Section V, Article 4, Figure T-434.2.1 and Figure T-434.3, details the requirements for basic calibration block construction.

Calibration system checks are required to be performed prior to and at the completion of an examination. In addition, a system check is required with any change in the search unit, cabling, and examiner, and after a specified time frame, such as four hours. The temperature of the calibration standard should be within 25 °F (14 °C) of the part to be examined. If the temperature falls out of that range, the reference standard is brought to within 25 °F (14 °C), and a calibration check should be performed. For high-temperature work, special high-temperature transducers and couplants are usually necessary. Consideration should be given to the fact that temperature variations within the wedge or delay line can cause beam angle changes or alter the delay on the time base. System checks are typically performed at a minimum of every four hours during the process of examination, but can be done more often at the examiner's discretion after any instance of suspected system irregularity.

If, during a system calibration check, it is determined that the ultrasonic equipment is not functioning properly, all areas tested since the last successful calibration should be re-examined.

8.9.3.2 Echo Evaluation With Distance Amplitude Correction

The distance amplitude correction (DAC) curve allows an echo evaluation of unknown reflectors by comparison of the echo height with respect to the DAC (%DAC).

Due to attenuation and beam divergence inherent to all materials, the echo amplitude from a given size reflector decreases as the distance from the probe increases. To set up a DAC curve, the maximum response from a specified reference reflector (e.g. flat bottom or side drilled hole) is recorded at different depths over the required test range. The calibration block with reference reflectors should be of the same material as the part under test. The curve is plotted through the peak points of the echo signals from the reflectors as shown in Figure 55. The curve represents the signal amplitude loss based upon distance, from the same size reference reflector using a given probe. The gain setting used to establish the DAC during the initial calibration is referred to as the primary reference level sensitivity. Evaluation is performed at this sensitivity level.

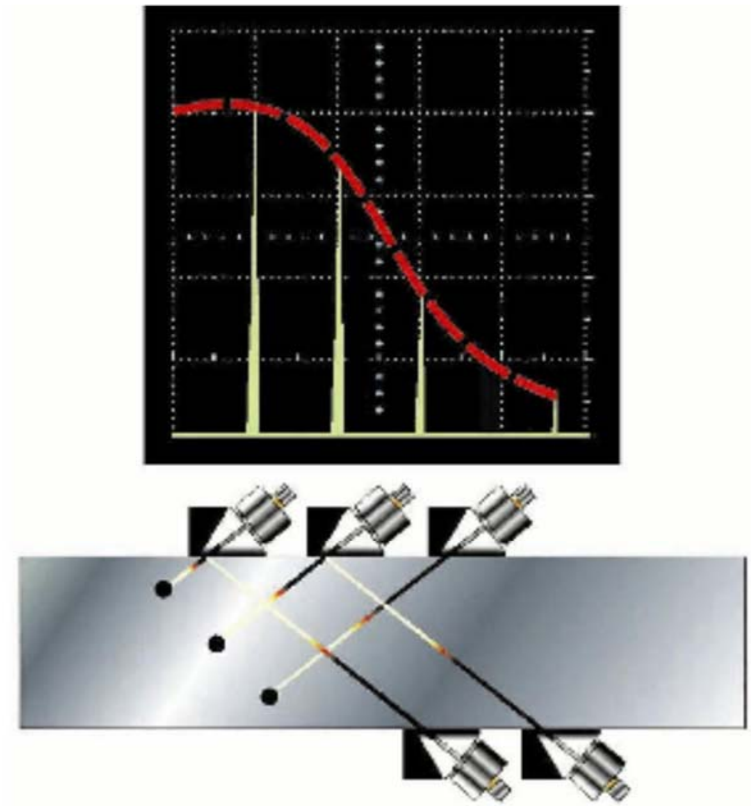


Figure 55—DAC Curve for a Specified Reference Reflector

Unknown reflectors (flaws) are evaluated by comparing their echo amplitude against the height of the DAC curve (i.e. 50 % DAC, 80 % DAC, etc.) at the sound path distance of the unknown reflector (see Figure 56). Material characteristics and beam divergence are automatically compensated for because the reference block and the test object are made of the same material, and have the same heat treatment and surface condition.

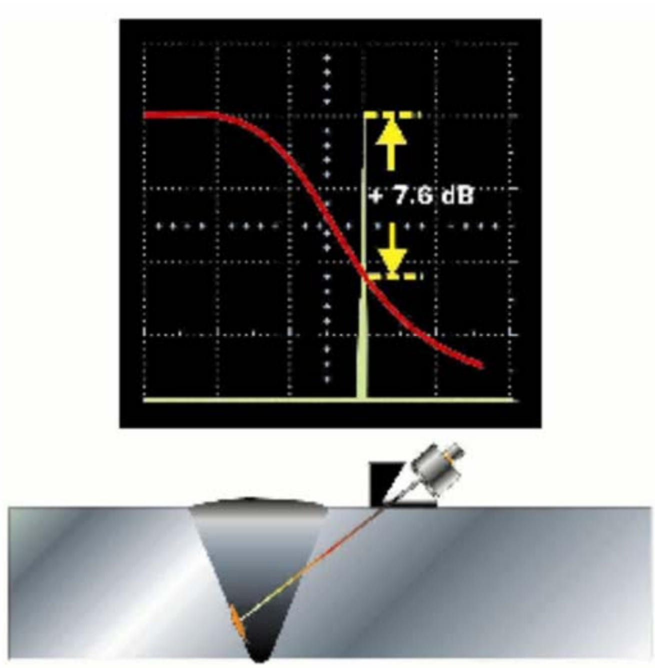


Figure 56—DAC Curve for an Unknown Reflector

8.9.4 Surface Preparation

Prior to ultrasonic examination, all scan surfaces should be free from weld spatter, surface irregularities, and foreign matter that might interfere with the examination. The weld surface should be prepared such that it permits a meaningful examination.

8.9.5 Examination Coverage

The volume of the weld, HAZ, and a portion of the adjacent base material on both sides of the weld should be examined by moving the search unit over the examination surface in order to scan the entire examination volume. Each pass of the transducer should overlap the previous pass by at least 10 % of the transducer element dimension. The rate of search unit movement should not exceed 6 in. (150 mm) per second unless the calibration was verified at an increased speed, and the instrument is capable of resolving imperfections at that speed. In many cases, the search unit is oscillated from side to side to increase the chances of detecting fine cracks that are oriented other than perpendicular to the sound beam.

8.9.6 Straight Beam Examination

A straight beam examination should be performed adjacent to the weld to detect reflectors that would interfere with the angle beam examining the weld, such as a lamination in the base material. All areas having this type of reflector should be identified as the system response in these areas will be different from that in unaffected locations.

8.9.7 Angle Beam Examination

8.9.7.1 General

Typically, there are two different angle beam examinations performed on a weld: a scan for reflectors that are oriented parallel to the weld, and a scan for reflectors that are oriented transverse to the weld. In both cases, the scanning should be performed at a gain setting at least two times (+6 dB) the reference level sensitivity established during calibration. Evaluation of indications, however, should be performed at the primary reference level sensitivity. In both cases, the search unit should be manipulated such that the ultrasonic energy passes through the required volume of the weld and HAZ.

During examination for reflectors that are oriented parallel to the weld, the sound beam is directed at approximate right angles to the weld, preferably from both sides of the weld. For reflectors that are oriented transverse to the weld, the sound beam is directed parallel to the weld and a scan is performed in one direction around the weld, then the search unit is turned 180° and another scan is performed until the ultrasonic energy has passed through the required volume of weld and HAZ in two directions.

To inspect for transverse flaws, the angle beam transducers should be rotated 90°, or additional transverse flaw inspection using other techniques may be performed to supplement automated ultrasonic weld inspection techniques.

8.9.7.2 Supplemental Angle Beam Examination

When inspecting a weld with TOFD, the presence of the lateral wave and back-wall indication signals may obscure detection of flaws present in these zones. ASME BPVC, Section V, requires that the weld's near and far surfaces (i.e. both top and bottom surfaces) be examined by angle beam with the angles chosen that are closest to being perpendicular to the weld interfaces. This examination may be performed manually or mechanized; if mechanized, the data should be collected in conjunction with the TOFD examination.

8.9.8 Automated Ultrasonic Examination (AUT)

Volumetric Inspection of welds may be performed using one of the four automated ultrasonic weld inspection techniques.

a) Pulse Echo Raster Scanning: This technique inspects with zero degree compression and two angle beam transducers interrogating the weld from either side simultaneously. The compression transducers examine for corrosion or laminar defects in the base metal and the angle beam transducers scan the volume of the weld metal.

b) Pulse Echo Zoned Inspection: The zoned inspection is a line scan technique. The technique uses an array of transducers on either side of the weld with the transducer angles and transit time gates set to ensure that the complete volume of the weld is inspected.

c) Time of Flight Diffraction (TOFD): This is a line scan technique used in the pitch-catch mode. The multimode transducers are used to obtain the maximum volume inspection of the weld region. More than one set of transducers may be required for a complete volumetric inspection.

d) Phased Array (PA) Inspection: This technique utilizes an array of transducer elements to produce steering of the ultrasonic beam axis or focusing of the ultrasonic beam over a specified range. This allows the user the ability to inspect certain portions or zones of the component being tested using many different beam angles.

8.9.9 Discontinuity Evaluation and Sizing

8.9.9.1 General

UT procedures should include the requirements for the evaluation of discontinuities. Typically, any imperfection that causes an indication in excess of a certain percentage of DAC curve should be investigated in terms of the acceptance standards. The procedure should detail the sizing technique to be used to plot the through-thickness dimension and length.

One commonly used sizing technique is called the “intensity drop” or “6 dB drop” technique. This sizing technique uses the beam spread of the transducer to quickly estimate the axial length of the reflector. Using this technique, the transducer is positioned on the part such that the amplitude from the reflector is maximized. This point is marked with a grease pencil. The UT instrument is adjusted to set the signal to 80 % full screen height (FSH). The transducer is then moved laterally until the echo has dropped to 40 % FSH (6 dB). This position is also marked. The transducer is then moved laterally in the other direction, past the maximum amplitude point, until the echo response again reaches 40 % FSH. This point is marked with the grease pencil. The two outside marks produce the approximate axial size of the flaw.

Other sizing techniques should be used to obtain a more precise measurement of the length and through-wall dimension of the flaw. With advances in technologies, a number of other through-thickness sizing techniques are described in Sections 9.9.9.2–9.9.9.5.

8.9.9.2 ID Creeping Wave Method

The inside diameter (ID) creeping wave method uses the effects of multiple sound transfer modes, such as longitudinal waves and shear waves to qualitatively size flaws. The method is used for the global location of flaws in the bottom $^1/_3$, middle $^1/_3$, and top $^1/_3$ regions of the object/weld. Three distinct waves are presented with the ID creeping wave method:

a) High-angle refracted longitudinal wave of approximately 70°;

b) direct 30° shear wave which mode converts to a 70° refracted longitudinal wave;

c) indirect shear or “head” wave which mode converts at the inside diameter from a shear wave to a longitudinal wave, and moves along the surface.

8.9.9.3 Tip Diffraction Method

Tip diffraction methods are very effective for sizing flaws that are open to the inside or outside diameter surface. For ID connected flaws, the half "V" path or one and one half "V" path technique is used. For outside diameter (OD) connected flaws, two techniques are available: the time-of-flight tip diffraction technique and the time measurement technique of the tip diffracted signal and the base signal.

8.9.9.4 High-Angle Longitudinal Method

The high-angle refracted longitudinal wave method is very effective for very deep flaws. Dual-element, focused, 60, 70, and OD creeping waves are used to examine the outer one-half thickness of the component material. Probe designs vary with the manufacturer. Depth of penetration is dependent upon angle of refraction, frequency, and focused depth. Many of these transducers are used not only for sizing, but also for detection and confirmation of flaws detected during the primary detection examination. For coarse-grain materials, these probes work well where shear-wave probes are ineffective.

8.9.9.5 Bimodal Method

The bimodal method is a dual-element tandem probe with the transducer crystals located one in front of the other. The probe also generates an ID creeping wave. The wave physics are essentially the same. The pseudofocusing effect of the dual-element crystals is very effective for ID connected flaws in the mid-wall region, 30 % to 60 % through the wall depth. A low-angle shear wave (indirect) mode converts at the ID to produce an ID creeping wave, which detects the base of the flaw. A further low-angle shear-wave mode converts at the ID to a longitudinal wave, which reflects a longitudinal wave from the flaw face. A high-angle refracted longitudinal wave detects the upper extremity of the flaw (70°). The bimodal method can be used to confirm the depth of shallow to deep ID connected flaws. However, very shallow flaws of less than 10 % to 20 % tend to be slightly oversized, and very deep flaws tend to be slightly undersized.

Significant training and experience are required to effectively utilize some of the more advanced UT detection and sizing techniques.

8.9.9.6 Phased Array Method

The phased array method utilizes an array of transducer elements, excited in precise timing patterns, to produce steering or focusing of the ultrasonic beam over a specific range of angles in the component being inspected. The system consists of a computerized ultrasonic pulser/receiver instrument that contains the collection setup and analysis software, an umbilical cable, and the phased array probe/wedge. The phased inspection may be performed manually, or with an encoder for semi-automated scans, or with a mechanized scanner for fully automated scanning.

The method allows the user the ability to inspect certain portions or zones of the component under test using many different beam angles. The results may be viewed as A-scan, B-scan, C-scan, or as Sectorial scan images. Multiple views may be viewed simultaneously as well to assist with data analysis. This technique is also used in a single-axis scan motion, which makes it more efficient than manual scanning for data collection.

8.10 Hardness Testing

8.10.1 Hardness Testing for PQR and Production Welds

Hardness testing of the base metal, weld, and HAZ is often required to ensure that the welding process, and any PWHT, has resulted in an acceptable relative hardness. Testing production welds and HAZ requires a clean, flat area on the weld and on the base material as close as possible to the toe of the weld to accommodate the hardness testing instrument in the area of interest. The HAZ can be difficult to locate and is often assumed for testing purposes to be just adjacent to the toe of the weld. Hardness testing for a PQR is easier because the coupon is cross-sectioned and etched to identify the weld, weld interface, and HAZ. API 582 details hardness test requirements for PQRs and production welds. High hardness is particularly an issue with hardenable materials where the weld size is small compared to the base metal being welded (i.e. tube-to-tubesheet welds).

Hardness testing of production welds often utilizes portable equipment. Field measurements tend to have greater variability and so additional measurements may be required to verify results. However, hardness testing performed as part of the PQR uses laboratory equipment where significantly greater accuracy is possible. Portable hardness testers are not substitutes for the bench top models, and results from portable testers are prone to error, due to the limited capabilities of such equipment, as well as their improper use.

8.10.2 Hardness Testing for Repair Welds

On-site hardness testing may be required on pressure-retaining welds after any PWHT in accordance with API 582 and NACE SP0472. Hardness testing of repair welds can be conducted with portable hardness testers in accordance with either ASTM A833, ASTM A1038, or ASTM A956

Using API RP 582 as a reference, the HAZ hardness readings may include locations as close as possible (approximately 0.2 mm) to the weld interface (see Figure 57). The surface should be polished and should not exceed 16 µin. (0.4 µm) maximum. After the surface has been polished, it should be etched to identify the weld metal, weld interface, and HAZ.

An example of how hardness measurements may be conducted is shown in Figure 57. Five impressions in an area of approximately 1 in.^{2} (650 mm^2) should constitute a test. Because field hardness measurements tend to have greater variability, additional assessments such as field metallography replication (FMR) can be conducted to determine whether an excessively hard HAZ microstructure has been formed.

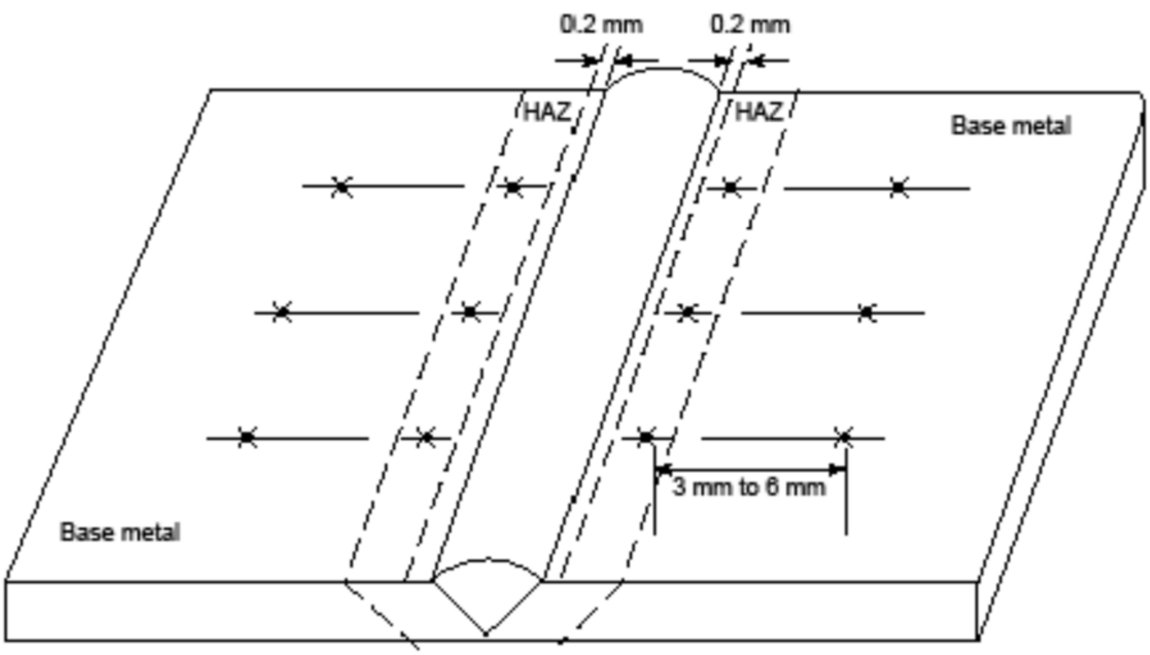


Figure 57—Location of Hardness Measurements

8.11 Pressure and Leak Testing/Examination (LT)

Where a hydrostatic or pneumatic pressure test is required by code, the inspector should adopt code and specification requirements relevant to vessels or piping. API 510, API 570, API 574, ASME B31.3, and ASME PCC-2 provide guidance on the application of pressure tests. Pressure tests should be conducted at temperatures appropriate for the material of construction, above what is known as the minimum design material temperature (MDMT) to avoid brittle fractures.

Some codes and specifications identify the test pressure and duration. Others provide a general direction without a specific set of guidelines. The test should be held long enough for a thorough visual inspection to be completed to identify any potential leaks. Typically, a pressure test should be held for at least 30 min, or as specified by the referencing code or specification. The inspector should be aware of the effect that changing temperature of the test medium has in causing an increase or decrease of pressure during the test period.

Pneumatic pressure tests often require special approvals and additional safety considerations due to the amount of stored energy in the system. Where pneumatic LT is conducted, the inspector should verify safe pressure-relieving devices, and the cordoning off of test areas to exclude all but essential personnel, and the inspector should use extreme caution. Safety professionals should provide the necessary direction to ensure the safety of all personnel in the area.

LT may be required by code or specification to demonstrate system tightness or integrity, or may be performed during a hydrostatic pressure test to demonstrate containment of a sealed unit such as a pressure vessel. ASME Section V, Article 10, addresses LT methods and indicates various test systems to be used for both open and closed units, based upon the desired test sensitivity. LT of a welded tube-to-tubesheet joint may be specified for service applications that are sensitive to small tube-to-tubesheet joint leaks. Helium LT is especially effective for tube-to-tubesheet joints when highly sensitive LT is required.

NOTE LT is not the same as, nor is it a substitute for, hydrostatic or pneumatic testing.

One of the most common methods used during pneumatic LT is the direct pressure bubble test. This method employs a liquid bubble solution that is applied to the areas of a closed system under pressure. A visual test is then performed to note any bubbles that are formed as the leakage gas passes through it. When performing the bubble test, some items of concern include the temperature of the surface to be inspected, pretest and posttest cleaning of the part to be inspected, lighting, visual aids, and the hold time at a specific pressure prior to application of the bubble solution. Typically, the area under test is found to be acceptable when no continuous bubble formation is observed. If the unit under pressure is found to have leakage, it should be depressurized, the leaks repaired per the governing code, and the test repeated.

A wide variety of viscous fluids and methods can be used, dependent on the desired result. Considerations for system design limitations may prevent the use of water (the most common type of leak test). Drying, hydrostatic head, and support limitations should be addressed before water is used. The required sensitivity of the results may also require a more sensitive leak test medium and method.

NOTE Publications on pressure testing safety are available from several sources, including (but not limited to) Interstate Natural Gas Association of America (INGAA), Health and Safety Executive (HSE), and Mechanical Contractors Association of America (MCAA). These are not the only sources on the subject. Information on them is included in the bibliography.

9 Welding Inspection

9.1 General

Weld inspection is a critical part of an overall weld quality assurance program. Welding inspection includes much more than just the NDE of a partially completed or completed weld. Important issues prior to welding include review of codes, standards, specifications, design, cleaning procedures, welding procedures, and welder qualifications.

Welding inspection activities can be separated into three primary stages corresponding to the phase of the welding work process. Inspectors should perform specific tasks prior to welding, during welding, and upon completion of welding. Codes, standards, and specifications will dictate the amount of inspection that is to be performed. Along with performing the required inspections, complete and accurate documentation shall be generated. In almost every case, the documentation alone will serve as proof that the required inspections were performed in accordance with codes, standards, specifications, and regulatory requirements.

9.2 Tasks Prior to Welding

The importance of tasks in the planning and weld preparation stage should not be understated. Many welding problems can be avoided during this stage when it is easier to make changes and corrections, rather than during or after the welding is in progress or has been completed. Such tasks may include the following.

9.2.1 Drawings, Codes, and Standards

Review applicable drawings along with standards, codes, internal specifications, and all welding documentation, including the WPS, PQR, and WPQ, in order to understand the requirements for the weldment and identify any inconsistencies.

9.2.1.1 Quality Control Items to Assess

Items that should be reviewed in drawings, codes, and standards include the following.

a) Welding symbols and weld sizes are clearly specified (see Annex A). Note that welding symbols are often not included in plans for in-service welding and repairs.

b) Weld joint designs and dimensions are clearly specified (see Annex A).

c) Dimensions are detailed—the inspector may need to seek help from others (e.g., welding engineer) to determine potential for distortion.

d) Welding consumables are specified.

e) Proper handling of consumables, if any, is identified.

f) Base material requirements are specified (such as the use of impact tested materials where notch ductility is a requirement in low-temperature service).

g) Mechanical properties and required testing are identified on the PQR.

h) Weather protection and wind-break requirements are defined in the referencing code or standard.

i) Preheat requirements and acceptable preheat methods are defined.

j) PWHT requirements and acceptable PWHT methods are defined.

k) Inspection hold-points and NDE requirements are defined.

l) Additional requirements, such as production weld coupons, are clearly specified.

m) Pressure testing requirements, if any, are clearly specified.

n) Appropriate type/degree of NDE is specified.

o) WPS and corresponding PQR for essential, nonessential, and, if applicable, supplementary variables have been reviewed and addressed.

p) WPQ has been reviewed to ensure proper testing was performed to allow the welder to produce a production weld according to the relevant WPS.

9.2.2 Welding Requirements

Review requirements for the welding personnel involved with executing the work, such as the welding organization and inspection organization.

9.2.2.1 Quality Control Items to Assess

Welding requirement quality control items that should be reviewed are as follows.

a) Competency of welding organization to perform welding activities in accordance with codes, standards, and specifications.

b) Competency of inspection organization to perform specified inspection tasks.

c) Competency of welding organization to perform welder/welding operator qualifications.

9.2.3 Procedures and Qualification Records

Review the WPS(s), PQR(s), and WPQ(s) for the welding process to ensure they are acceptable to code/specification and are applicable to the work to be performed.

9.2.3.1 Quality Control Items to Assess

Welding procedure and qualification records that should be reviewed include the following.

a) WPS(s) and supporting PQR(s), including those developed for making repairs, are properly qualified and meet applicable codes, standards, and specifications for the work.

b) WPQ(s) meet requirements for the WPS.

9.2.4 NDE Information

Confirm that the NDE examiner(s), NDE procedure(s), and NDE equipment of the inspection organization are acceptable for the work.

9.2.4.1 Quality Control Items to Assess

NDE information that should be reviewed includes the following.

a) NDE examiners are properly certified for the NDE technique and their certifications are current (see Section 4.6).

b) NDE procedures are current and accurate.

c) Calibration of NDE equipment is current.

d) NDE procedures and techniques specified are appropriate, and capable of producing the specified acceptance/rejection criteria.

9.2.5 Heat Treatment and Pressure Testing

Confirm heat treatment and pressure testing procedures and associated equipment are acceptable.

9.2.5.1 Quality Control Items to Assess

Heat treatment and pressure testing procedures that should be reviewed include the following.

a) Heat treatment procedure is acceptable and matches the requirements shown on the PQR, reviewed, and acceptable;

b) Pressure testing procedures detail test requirements, are reviewed, and are acceptable.

c) PWHT equipment calibration is current.

d) Pressure testing equipment and gauges are calibrated and meet appropriate test requirements.

9.2.6 Materials

Ensure all filler materials, base materials, and backing ring materials are properly marked and identified, and, if required, ensure completion of PMI at point of installation to verify the material composition.

9.2.6.1 Quality Control Items to Assess

Details that should be reviewed on materials used during welding include the following.

a) Material test certifications are available and items properly marked (including backup ring if used).

b) Electrode marking, bare wire flag tags, identification on spools of wire, etc., are as specified.

c) Filler material markings are traceable to a filler material certification.

d) Base material markings are traceable to a material certification.

e) Recording of filler and base material traceability information is performed.

f) Base material stampings are low stress and not detrimental to the component.

g) Paint striping (or other) color code is in accordance with the specification and correct for the material of construction when used.

h) PMI records supplement the material traceability and confirm the material of construction.

9.2.7 Weld Preparation

Confirm weld preparation, joint fit-up, and dimensions are appropriate to the relevant design and welding procedure.

9.2.7.1 Quality Control Items to Assess

Details related to weld preparation that should be reviewed include the following.

a) Weld preparation surfaces are free of contaminants and base metal defects such as laminations and cracks.

b) Preheat, as specified by the referencing code, specification, or WPS if required, is applied for thermal cutting and welding process.

c) Hydrogen bake-out, as specified, is performed to approved procedure.

d) Weld joint is free from oxide and sulfide scales and hydrocarbon residue.

e) Weld joint type, bevel angle, root face, and root opening are per the appropriate welding procedure.

f) Alignment is acceptable to project requirements.

g) Piping socket welds have proper gap.

9.2.8 Welding Consumables

Confirm electrode and filler material are identified and segregated as required, and fluxes and inert gases are identified, as specified, and acceptable.

Confirm storage ovens for welding consumables are provided with a visible temperature indication and can operate with automatic heat control.

9.2.8.1 Quality Control Items to Assess

Details related to welding consumables that should be reviewed include the following.

a) Filler material type and size are correct per procedure.

b) Filler materials are being properly handled and stored (see Section 7.7).

c) Filler materials are clean and free of contaminants.

d) Coating on coated electrodes is neither damaged nor wet.

e) Flux is appropriate for the welding process and being properly handled.

f) Inert gases, if required, are appropriate for shielding and backing.

g) Gas composition is per the appropriate welding procedure and meets purity requirements.

h) Shielding gas and purging manifold systems are periodically bled to prevent backfilling with air.

i) Filler material is properly identified as an alloy and segregated from other welding process areas as necessary.

9.3 Tasks During Welding Operations

Welding inspection during welding operations should include audit parameters to verify the welding is performed to the procedures. Such tasks may include the following.

9.3.1 Quality Assurance

Establish a quality assurance and quality control audit procedure with the welding organization.

9.3.1.1 Quality Control Items to Assess

Details on welding quality assurance and quality control audit procedures that should be reviewed include the following.

a) Welder is responsible for quality craftsmanship of weldments.

b) Welder has been tested and certified to the procedure being used.

c) Welder has received any special training, and mock-up weldments have been performed if required.

d) Welder and appropriate quality control personnel understand the inspection hold-points.

e) Welder is responsible for welding per the WPS and has ready access to the approved version before and during welding.

f) Reference Annex B.

9.3.2 Welding Parameters and Techniques

Confirm welding parameters and techniques are listed in the WPS and WPQ.

9.3.2.1 Quality Control Items to Assess

Details related to welding parameters and welding technique that should be reviewed include the following:

a) essential variables are being met during welding;

b) filler material, fluxes, and inert gas composition/flow rate as specified in the WPS;

c) purge technique, flow rate, O_2 analysis, etc.;

d) equipment settings such as amps, volts, and wire feed speed or rate;

e) travel speed (the primary element in determining heat input);

f) heat input (where appropriate);

g) supplementary essential variables (as required) are being met during welding;

h) preheating during tack welding and tack welds removed (if required);

i) preheat and interpass temperatures;

NOTE The maximum interpass temperature should be specified for austenitic stainless steels, duplex stainless steels, and nonferrous alloys (e.g. type-300 stainless steels). The maximum interpass temperature should also be specified for carbon/low-alloy steels that require impact testing.

j) mock-up weldment that simulates the production weld joint, meets requirements of the welding engineer, and is used to demonstrate welder capability or weld procedure parameters as required.

9.3.3 Weldment Examination

Complete physical checks, visual examination, and in-process NDE.

9.3.3.1 Quality Control Items to Assess

Details related to examination of the weldment that should be reviewed include the following.

a) Tack welds to be incorporated in the weld are tied in to the root and free of defects.

b) Weld root has complete penetration (determined by NDE).

c) Cleaning between weld passes and of back-gouged surfaces is acceptable and completed as specified on WPS.

d) Additional NDE that may be required between weld passes and on back-gouged surfaces meets the appropriate acceptance criteria.

e) In-process rework, noted through visual inspection, is completed and defect removal is accomplished.

f) In-process ferrite measurement, if required, is performed and recorded.

g) Final weld reinforcement and fillet weld size meets work specifications and drawings.

h) All additional welds are identified on the “as-built” drawing weld map to account for any additional required NDE.

9.4 Tasks Upon Completion of Welding

Final tasks upon completion of the weldment and work should include those that ensure final weld quality before placing the weldment in service.

9.4.1 Appearance and Finish

Complete visual inspection of completed weldment for obvious defects such as undercut, cold lap, porosity, etc., to ensure the weldment complies with the owner–user specification.

9.4.1.1 Quality Control Items to Assess

Details related to weld appearance and completion that should be reviewed include the following.

a) Size, length, and location of all welds conform to the drawings/specifications/code.

b) Temporary attachments and attachment welds are removed, blended with the base metal, and any required NDE is completed.

c) Required NDE is completed and discontinuities reviewed against acceptance criteria per the referencing code or standard.

d) Material verification completion PMI conducted on the weld(s), base material, fittings, and valve components during prefabrication and at the point of installation, if required by the specification.

e) Welder stamping/marking of welds confirmed.

f) Field hardness check is performed.

9.4.2 NDE Review

Verify NDE is performed at selected locations and review examiner's findings to ensure compliance with code/specification requirements.

9.4.2.1 Quality Control Items to Assess

Details related to NDE that should be reviewed include the following.

a) Specified locations are examined.

b) Specified number of examinations are completed.

c) NDE is performed after final PWHT.

d) Representation of work of each welder is included in random examination techniques as specified in the construction code or standard.

e) Radiographic quality is in accordance with the requirements listed in ASME Section V, Article 2, Non-Destructive Examination, and inspector is in agreement with examiner's interpretations and findings.

f) Document that all NDE and associated tables have been correctly executed and documented.

g) Check joints for delayed cracking of thick sections, especially highly constrained joints, joints of high-strength materials, and services having a potential for delayed cracking.

9.4.3 Postweld Heat Treatment

Verify PWHT is reviewed and accepted to be in accordance with the specified procedure.

9.4.3.1 Quality Control Items to Assess

Details related to PWHT that should be reviewed include the following.

a) Before the PWHT begins:

   1) paint marking and other detrimental contamination removed;
   2) temporary attachments removed;
   3) machined surfaces protected from oxidation;
   4) equipment internals, such as valve internals, removed to prevent damage;
   5) equipment adequately supported to prevent distortion;
   6) thermocouples fastened properly;
   7) thermocouples adequately monitor the different temperature zones and thickest/thinnest parts in the fabrication;
   8) temperature monitoring system calibrated;
   9) local heating bandwidth is adequate;
   10) insulation is applied to the component where required for local heating.

b) After PWHT is completed:

   1) temperature and hold time are per the PWHT procedure;
   2) heating rate and cooling rate are per the PWHT procedure;
   3) hardness indicates an acceptable heat treatment.

9.4.4 Pressure Testing

Verify pressure test is performed, reviewed, and accepted, and is in accordance with the referencing procedure.

9.4.4.1 Quality Control Items to Assess

Details related to pressure testing that should be reviewed include the following.

a) Pressure meets test specification.

b) Test duration is as specified.

c) Metal temperature of component meets minimum and maximum requirements.

d) Pressure drop or decay is acceptable per procedure.

e) Visual examination does not reveal leakage or material defects.

f) All welds and components are accessible for visual inspection and not covered with paint, insulation, or other matter.

9.4.5 Documentation Audit

Perform a final audit of the inspection package to identify inaccuracies and incomplete information.

9.4.5.1 Quality Control Items to Assess

Details related to the inspection package that should be reviewed include the following.

a) All verifications in the quality plan were properly executed.

b) Inspection reports are complete, accepted, and signed by the responsible parties.

c) Inspection reports and NDE examiner's interpretations and findings are accurate.

d) All documentation is retained as required by the referencing code and company specifications.

9.5 Nonconformances and Defects

9.5.1 General

At any time during the welding inspection, if defects or nonconformances to the referencing code, standard, or specification are identified, they should be brought to the attention of those responsible for the work and corrected before welding proceeds further. Defects should be completely removed and reinspected following the tasks/methods outlined in this section until the weld is found to be acceptable. Corrective action for a nonconformance depends upon the nature of the nonconformance and its impact on the properties of the weldment. Corrective action may include reworking the weld. See Section 8.1 for common types of discontinuities or flaws that can lead to defects or nonconformances.

9.5.2 Repair Welds

When inspection identifies a rejectable defect, the inspector should mark the area for repair, remove the defect, verify defect removal (typically using PT or MT), and all necessary repair welding is performed. Repair welding should be performed according to a weld repair procedure accepted by the inspector or engineer. After the repair, the weld should be reinspected, using the same method(s) that initially identified the defect(s). If the inspection indicates that the repair is acceptable, no further action is needed, and the equipment/piping may be placed back into service. If the inspection indicates that the defect was not removed or that a new defect is present, the welder and inspector (and welding engineer, if applicable) should evaluate the reason for the nonconformance of the weld repair in order to make appropriate changes before a second repair is performed.

There are many factors that should be evaluated when determining the number of times a welded joint can successively be repaired before a complete cut-out of the weld is required. Such factors include, but are not limited to, weld application, base metal material and thickness, heat treatment, complexity of the weld configuration/position (e.g. furnace tubes or boiler tubes), and size of the weld. The welding engineer or inspector should be notified when a weld has failed a weld quality test more than two times to help determine the cause(s) of the defect(s) and the appropriate path forward.

9.6 NDE Examiner Certification

9.6.1 Referencing Codes or Standards

The referencing codes or standards may require the examiner to be qualified in accordance with a specific code and certified as meeting the requirements. Typically, weld construction standards such as ASME for pressure vessels or piping, and API 510 for in-service pressure vessel examination or API 570 for in-service piping examination, refer to certification of qualification by third parties, for example:

a) ASNT SNT-TC-1A;

b) ANSI/ASNT CP-189.

These references provide the employer guidelines (SNT-TC-1A) or standards (CP-189) for the certification of NDE inspection personnel. They also require the employer to develop and establish a written practice or procedure that details the employer's requirements for the qualification and certification of inspection personnel. It includes the training and experience prerequisites prior to certification and recertification requirements. A certification scheme in accordance with ISO 9712 may be specified for domestic or international work. ISO 9712 outlines certification guidelines generally organized under a national scheme and vested in the individual. In the United States, the scheme is managed by ASNT as the ASNT Central Certification Program (ACCP). Although an inspection company's written practice may allow the employer to appoint a Level III, the owner–user may prefer that, at least for initial certification, a Level III Examiner be certified by examination.

9.6.2 Owner-User Qualification

If the referencing code or specification does not indicate a specific qualification standard, qualification may involve demonstration of competency by the personnel performing the examination or other requirements specified by the owner–user. The API in-service inspection documents go further than this and for a number of specific circumstances, such as fitness-for-service (FFS) and welds not subject to hydrotest, may require the use of personnel who have passed a performance test such as the API Qualification of Ultrasonic Testing Examiners (QUTE) or owner–user accepted equivalent. A new document is being developed by API to further define the QUTE program, including some definition of "equivalence."

In order to successfully complete the examination, candidates should detect, characterize, and locate, for example, at least 80 % of the known flaws in the weld sections they have been requested to examine. Candidates who misinterpret or miss more than 20 % of known imperfections (e.g. misinterpreting a geometric reflector as a flaw) shall be deemed to have failed the test. The owner–user may choose a different pass-point.

9.6.2.1 Candidate Requirements

Prior to testing, candidates should be advised that they will be given a pass/fail evaluation upon conclusion of the test and will not be provided with specific knowledge regarding the type of flaw, if any, in each weld. No other data should be made available in order to ensure the confidentiality of data relating to flaw, numbers, locations, types, and sizes.

9.6.2.2 Term

The approval test should typically be valid for a period of three years, after which the candidate should be retested. If at any time the performance of an operator is called into question, the operator may be retested at the owner–user's discretion.

9.6.2.3 Approval

Approval of any candidate under this specification is restricted to the specific owner–user administering the test, and it should be utilized for compliance with the referenced paragraphs in API 510 and API 570 and should not be deemed as an API certification or endorsement in any form.

9.7 Weld Inspection Data Recording

9.7.1 Reporting Details

Results of the weld inspection should be completely and accurately documented. The inspection report in many cases becomes a permanent record to be maintained and referenced for the life of the weld or part being inspected.

9.7.1.1 General Information

General information reported for weld inspections should include:

a) customer or project;

b) contract number or site;

c) date of inspection;

d) component/system;

e) subassembly/description;

f) weld identification;

g) weld type/material/thickness.

9.7.1.2 Inspection Information

Inspection information reported on weld inspections should include:

a) date of inspection;

b) procedure number;

c) examiner;

d) examiner certification information;

e) inspection method;

f) visual aids and other equipment used;

g) weld reference datum point.

9.7.1.3 Inspection Results

Weld inspection results typically reported should include:

a) inspection sheet number;

b) inspection limitations;

c) a description of all recordable and reportable indications;

d) for each recordable indication:

    1) indication number;

    2) location of indication (from both weld reference datum and centerline);

    3) upstream or downstream (clockwise or counterclockwise) from an established reference point;

    4) size and orientation of indication;

    5) type of indication (linear or rounded);

    6) acceptability per the acceptance standards of the referencing code;

7) remarks or notes;

8) a sketch of indication;

9) reviewer and level of certification;

10) reviewer's comments.

9.7.2 Terminology

When reporting the results of an inspection, it is important to use standard terminology. Examples of standard terminology are shown in Table 8, Table 9, and Table 10.

Table 8—Conditions That May Exist in a Material or Product

Definition	Description or Comment
A-1 Indication: A condition of being imperfect; a departure of a quality characteristic from its intended condition.	No inherent or implied association with lack of conformance with specification requirements or with lack of fitness for purpose, i.e. indication may or may not be rejectable.
A-2 Discontinuity: An interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics. A discontinuity is not necessarily a defect.	No inherent or applied association with lack of conformance with specification requirements or with lack of fitness for purpose, i.e. imperfection may or may not be rejectable. An unintentional discontinuity is also an imperfection. Cracks, inclusions, and porosity are examples of unintentional discontinuities that are also imperfections. Intentional discontinuities may be present in some material or products because of intentional changes in configuration; these are not imperfections and are not expected to be evaluated as such.

Table 9—Results of Nondestructive Examination

Definition	Description or Comment
B-1 Indication: The response or evidence from the application of a nondestructive examination.	When the nature or magnitude of the indication suggests that the cause is an imperfection or discontinuity, evaluation is required.

Table 10—Results of Application of Acceptance/Rejection Criteria

Definition	Description or Comment
C-1 Flaw: An imperfection or unintentional discontinuity, which is detectable by a nondestructive examination.	No inherent or implied association with lack of conformance with specification requirements or lack of fitness for purpose, i.e. a flaw may or may not be rejectable.
C-2 Defect: A flaw (imperfection or unintentional discontinuity) of such size, shape, orientation, location, or property, which is rejectable.	Always rejectable, either for: a) lack of conformance to specification requirements; b) potential lack of fitness for purpose; c) both. A defect (a rejectable flaw) is by definition a condition that must be removed or corrected.

10 Metallurgy

10.1 General

A general understanding of the major principles is important to the inspector, due to the wide variety of base metals that may be joined by welding during the repair of equipment, and the significant impact on the metals resulting from the welding process. The welding process can affect both the mechanical properties and the corrosion resistance properties of the weldment. This section is designed to provide an awareness of metallurgical effects important to personnel performing inspections, but is not to be considered an in-depth resource of metallurgy.

Based on the concept that this section provides a basic understanding, this section does not describe all aspects of metallurgy such as crystalline structures of materials and atomic configurations, which are left to other more complete metallurgy texts.

10.2 Structure of Metals and Alloys

10.2.1 General

Metals are crystalline in nature and have a structure in which the atoms of each crystal are arranged in a specific geometric pattern based upon several factors including material type/grade and heat treatment condition. The physical properties of metallic materials including strength, ductility, and toughness can be attributed to the chemical make-up and orderly arrangement of these atoms.

Metals in molten or liquid states have no orderly arrangement to the atoms contained in the melt. As the melt cools, a temperature is reached at which clusters of atoms bond with each other and start to solidify, developing into solid crystals within the melt. The individual crystals of pure metal are identical except for their orientation and are called grains. As the temperature is reduced further, these crystals change in form, eventually touch, and where the grains touch, an irregular transition layer of atoms is formed, called the grain boundary. Eventually, the entire melt solidifies, interlocking the grains into a solid metallic structure called a casting.

Knowledge of cast structures is important since the welding process is somewhat akin to making a casting in a foundry. Because of the similarity in the shape of its grains, a weld can be considered a small casting. A solidified weld may have a structure that looks very much like that of a cast piece of equipment. However, the thermal conditions that are experienced during welding produce a cast structure with characteristics both beneficial and deleterious, unique to welding.

10.2.2 Castings

Since the structure of a completed weld is akin to a casting, it is important to review the nature of castings. The overall arrangement of the grains, grain boundaries, and phases present in the casting is called the microstructure of the metal. Microstructure is an area of specialty that inspectors should understand, as it is largely responsible for the physical and mechanical properties of the metal. Because castings used in the refinery industry are typically alloyed, they typically contain several microstructural phases. A phase is any structure that is physically and compositionally distinct. As the chemical composition is altered or temperature changed, new phases may form or existing phases may disappear.

Cast structures, depending on their chemical composition, can exhibit a wide range of mechanical properties for several reasons. In general, it is desirable to keep the size of grains small, which improves strength and toughness. This can be achieved by maximizing the cooling rate or minimizing the heat input (in the case of welding). This increases the rate of crystal formation and decreases the time available for crystal growth, which has a net effect of reducing crystalline grain size.

The properties of the cast structure can also be impaired by compositional variations in the microstructure called segregation. Because of the solubility of trace and alloying elements, such elements as carbon, sulfur, and phosphorous can vary in a pure metal; these elements can cause variations in the solidification temperature of different microstructural phases within the melt. As the melt cools, these elements are eventually contained in the microstructural phases that solidify last in spaces between the grains. These grain boundary regions can have a much higher percentage of trace elements than the grains themselves, which may lead to reductions in ductility and strength properties. This effect can be minimized by using high-purity melting stocks, by special melting practices (melting under vacuum or inert gas, for example) to minimize contamination and/or subsequent heat treatment to homogenize the structure. In many carbon steels, this is achieved using oxygen scavengers such as aluminum, silicon, or silicon plus aluminum, and the steels are often described as “killed” or “fully killed” steels. Minimizing trace elements or “inclusions” at this stage is often important as they can provide sites for formation of in-service defects such as hydrogen-assisted cracking.

Gases such as hydrogen which become entrapped in the melt as it solidifies can also affect the casting’s integrity. In some cases, these gases create voids or porosity in the structure, or can lead to cracking. Weldments are particularly prone to cracking because of trapped hydrogen gases. This problem can be avoided by careful cleaning of the weld bevels to remove hydrocarbons and moisture, the use of low-hydrogen electrodes, correct storage or baking of electrodes, and use of proper purging techniques with high-quality welding gases.

For refinery applications, castings are used primarily for components having complex shapes in order to minimize the amount of machining required. These include pump components (casings, impellers, and stuffing boxes) and valve bodies.

10.2.3 Wrought Materials

The majority of metallic materials used for the fabrication of refinery and chemical plant equipment are used in the wrought form rather than cast. Mechanical working of the cast ingot produces wrought materials by processes such as rolling, forging, or extrusion, which are normally performed at an elevated temperature. These processes result in a microstructure that has a uniform composition and a smaller, more uniform grain shape.

Wrought materials may consist of one or more microstructural phases that may have different grain structures. Austenitic stainless steels, for example, are composed of microstructural phases call austenite, which have grains of the same crystal structure. Many nickel, aluminum, titanium, and copper alloys are also single-phase materials. Single-phase materials are often strengthened by the addition of alloying elements that lead to the formation of nonmetallic or intermetallic precipitates. The addition of carbon to austenitic stainless steels, for example, leads to the formation of very small iron and chromium carbide precipitates in the grains and at grain boundaries. The effect of these precipitates is to strengthen the alloy. However, the formation of chromium carbide precipitates on the grain boundaries during welding (or other high-temperature exposure) depletes the area adjacent to the grain boundaries of chromium. This microstructure in austenitic stainless steel is referred to as a “sensitized microstructure.” As a result, the chromium-depleted area adjacent to the grain boundary may experience severe intergranular corrosion. In general, greater strengthening occurs with the finer distribution of precipitates. This effect is usually dependent on temperature; at elevated temperatures, the precipitates begin to break down and the strengthening effect is lost.

Alloys may also consist of more than one microstructural phase and crystal structure. A number of copper alloys including some brasses are composed of two distinct phases. Plain carbon steel is also a two-phase alloy. One phase is a relatively pure form of iron called ferrite. By itself, ferrite is a weak material. With the addition of more than 0.06 % carbon, a second phase called pearlite is formed which adds strength to steel. Pearlite is a lamellar (i.e. plate-like) mixture of ferrite and Fe_3C iron carbide.

As a result of fast cooling such as quenching in nonalloyed steels and also with the addition of alloying elements such as chromium to steel, other phases may form. Rather than pearlite, phases such as bainite or martensite may be produced. These phases tend to increase the strength and hardness of the metal with some loss of ductility. The formation of structures such as bainite and martensite may also be the result of rapid or controlled cooling and reheating within certain temperature ranges often termed “quenching” and “tempering.” With certain exceptions, such as hard facing products, bainite and martensite structures are not considered desirable.

10.2.4 Welding Metallurgy

Welding metallurgy is concerned with melting, solidification, gas–metal reactions, slag–metal reactions, surface phenomena, and base metal reactions. These reactions occur rapidly during welding due to the rapid changes in temperature caused by the welding process. This is in contrast to metallurgy of castings, which tends to be slower and often more controlled. There are three parts of a weld: the weld metal, heat-affected metal (zone), and base metal. The metallurgy of each area is related to the composition of the base and weld metal, the welding process, and welding procedures used.

Most typical weld metals are rapidly solidified and, like the structure of a casting described earlier, usually solidify in the same manner as a casting and have a fine-grain dendritic microstructure. The solidified weld metal is a mixture of melted base metal and deposited weld filler metal, if used. In most welds, there also can be some segregation of alloy elements. The amount of segregation is determined by the chemical composition of the weld and the base metal. Consequently, the weld is less homogeneous than the base metal, which can negatively affect the mechanical properties of the weld.

The HAZ is adjacent to the weld and is that portion of the base metal that has not been melted, but whose mechanical properties or microstructure have been altered by the heat of welding. There typically is a change in grain size or grain structure and hardness in the HAZ of steel. The size or width of the HAZ is dependent on the heat input used during welding. For carbon steels, the HAZ includes those regions heated to greater than 1350 °F (730 °C). Each weld pass applied has its own HAZ and the overlapping heat-affected zones extend through the full thickness of the plate or part welded.

The third component in a welded joint is the base metal. Most of the common carbon and low-alloy steels used for tanks and pressure vessels are weldable. The primary factor affecting the weldability of a base metal is its chemical composition and carbon content of carbon steels. Each type of metal has welding procedural limits within which sound welds with satisfactory mechanical properties can be made. If these limits are wide, the metal is said to have good weldability, and if the limits are narrow, the metal is said to have poor weldability.

A significant aspect of welding metallurgy is the gas–metal reaction between the molten weld metal and gases present during welding. Gas–metal reactions depend on the presence of oxygen, hydrogen, or nitrogen, individually or combined in the shielding atmosphere. Oxygen can be drawn in from the atmosphere or occur from the dissociation of water vapor, carbon dioxide, or metal oxide. Air is the most common source of nitrogen, but it can also be used as a shielding gas for welding of austenitic or duplex stainless steels. There are many sources of hydrogen. In SMAW or SAW, hydrogen may be present as water in the electrode coating or loose flux. Hydrogen can also come from lubricants, water on the work piece, surface oxides, contaminated filler metal, or humidity or rain.

An important factor in selecting shielding gases is the type of mixture. A reactive gas such as carbon dioxide can break down at arc temperatures into carbon and oxygen. This is not generally a problem on carbon and low-alloy steels. However, on high-alloy and reactive metals, this can cause an increase in carbon content and the formation of oxides that can lower the corrosion-resistant properties of the weld. High-alloy materials welded with gas-shielded processes usually employ inert shielding gases or mixtures with only slight additions of reactive gases to promote arc stability.

10.3 Physical Properties

10.3.1 General

The physical properties of base metals, filler metals, and alloys being joined can have an influence on the efficiency and applicability of a welding process. The nature and properties of gas shielding provided by the decomposition of fluxing materials or the direct introduction of shielding gases used to protect the weldment from atmospheric contamination can have a pronounced effect on its ability to provide adequate shielding and on the final chemical and mechanical properties of a weldment.

The physical properties of a metal or alloy are those which are relatively insensitive to structure and can be measured without the application of force. Examples of physical properties of a metal are the melting temperature, the thermal conductivity, electrical conductivity, the coefficient of thermal expansion, and density.

10.3.2 Melting Temperature

The melting temperature of different metals is important to know because the higher the melting point, the greater the amount of heat that is needed to melt a given volume of metal. This is seldom a problem in arc welding since the arc temperatures far exceed the melting temperatures of carbon and low-alloy steels. The welder simply increases the amperage to get more heat, thus controlling the volume of weld metal melted per unit length of weld at a given voltage or arc length and travel speed.

A pure metal has a definite, specific melting temperature that is just above its solidification temperature. However, complete melting of alloyed materials occurs over a range of temperatures, depending primarily upon the percentages of alloying elements. Alloyed metals start to melt at a temperature which is just above its solidus temperature, and, because they may contain different metallurgical phases, melting continues as the temperature increases until it reaches its liquidus temperature.

10.3.3 Thermal Conductivity

The thermal conductivity of a material is the rate at which heat is transmitted through a material by conduction or thermal transmittance. In general, metals with high electrical conductivity also have high thermal conductivity. Materials with high thermal conductivity require higher heat inputs to weld than those with lower thermal conductivity and may require a preheat. Steel is a poor conductor of heat as compared with aluminum or copper. As a result, it takes less heat to melt steel. Aluminum is a good conductor of heat and has the ability to transfer heat efficiently. This ability of aluminum to transfer heat so efficiently also makes it more difficult to weld with low-temperature heat sources.

The thermal conductivity of a material decreases as temperatures increase. The alloying of pure metals also decreases a material’s thermal conductivity. Generally, a material that contains substantial alloying elements would have a resultant lower thermal conductivity, and lower heat inputs are required to raise the material to a desired temperature.

10.3.4 Electrical Conductivity

The electrical conductivity of a material is a measure of its efficiency while conducting electrical current. Metals are good conductors of electricity. Metals that have high electrical conductivity are more efficient in conducting electrical current than those with low electrical conductivity.

Aluminum and copper have high electrical conductivity as compared to iron and steel. Their electrical resistance is also much lower, and as a result, less heat is generated in the process of carrying an electrical current. This is one of the reasons that copper and aluminum are used in electric wiring and cables.

The ability of steel to carry an electrical current is much less efficient and more heat is produced by its high measure of electrical resistance. Accordingly, steel can be heated with lower heat inputs than that required for aluminum or copper because of its lower measure of electrical conductivity and higher electrical resistance.

10.3.5 Coefficient of Thermal Expansion

As metals are heated, there is an increase in volume. This increase is measured in linear dimensions as the temperature is increased. This linear increase with increased temperature, per degree, is expressed as the coefficient of thermal expansion. An example of this would be the increased length of a steel bar that has been heated in its middle with an oxyfuel torch. As the bar is heated, there is a measurable increase in length that correlates to the temperature and the specified coefficient of thermal expansion for the material at that temperature. This coefficient of thermal expansion may not be constant throughout a given temperature range because of the phase changes that a material experiences at different temperatures and the increases or decreases in volume that accompany these phase changes.

Metals with a high coefficient of thermal expansion are much more susceptible to warping and distortion during welding. The increases in length and shrinkage that accompany the heating and cooling during welding should be anticipated, and procedures established that would ensure that proper tolerances are used to minimize the effects of thermal conditions. The joining of metals whose coefficients of thermal expansion differ greatly can also contribute to thermal fatigue conditions, and result in a premature failure of the component. Welding procedures are often employed that specify special filler metals that minimize the adverse effects caused by inherent differences between the metals being joined. Additional controls include avoidance of excessive restraint during welding and PWHT to relieve the residual stresses generated during the welding process.

10.3.6 Density

The density of a material is defined as its mass per unit volume. Castings, and therefore welds, are usually less dense than a wrought material of similar composition. Castings and welds contain porosity and inclusions that produce a metal of lower density. This is an important factor employed during RT of welded joints.

The density of a metal is important to a designer, but more important to the welder is the density of shielding gases. A gas with a higher density is more efficient as a shielding gas than one of a lower density as it protects the weld environment longer before dispersion.

10.4 Mechanical Properties

10.4.1 General

The mechanical properties of base metals, filler metals, and completed welds are of major importance in the consideration of the design and integrity of welded structures and components. Engineers select materials of construction that provide the required material properties at operating temperatures and pressures. For the inspector, verification that mechanical properties meet the design requirements is essential. Inspectors should understand the underlying principles of mechanical properties and the nature of tests conducted to verify the value of those properties. This is one of the fundamental principles of performing welding procedure qualification tests. Examples of mechanical properties of metals and alloys are the tensile strength, yield strength, ductility, hardness, and toughness.

10.4.2 Tensile and Yield Strength

Tensile testing is used to determine a metal's ultimate tensile strength, yield strength, and elongation and reduction in area. A tensile test is performed by pulling a test specimen to failure with increasing load.

Stress is defined as the force acting in a given region of the metal when an external load is applied. The nominal stress of a metal is equal to the tensile strength. The ultimate tensile strength of a metal is determined by dividing the external load applied by the cross-sectional area of the tensile specimen.

Strain is defined as the amount of deformation, or change in shape, that a specimen has experienced when stressed. Strain is expressed as the length of elongation divided by the original length of the specimen prior to being stressed.

When the specimen is subjected to small stresses, the strain is directly proportional to stress. This continues until the yield point of the material is reached. If the stress were removed prior to reaching the yield point of the metal, the specimen should return to its original length, and this is considered elastic deformation. However, stress applied above the yield point produces a permanent increase in specimen length and the yielding is considered plastic deformation. Continued stress may result in some work hardening (strength increase of a material via plastic deformation) with an increase in the specimen strength. Uniform elongation will continue, and the elongation will begin to concentrate in one localized region within the gauge length, as does the reduction in the diameter of the specimen. The test specimen is said to begin to "neck down." The necking-down continues until the specimen can no longer resist the stress and the specimen separates or fractures. The stress at which this occurs is called the ultimate tensile strength.

For design purposes, the maximum usefulness should be based on the yield strength of a material, as this is considered the elastic/plastic zone for a material, rather than only on the ultimate tensile strength or fracture strength of a material.

10.4.3 Ductility

In tensile testing, ductility is defined as the ability of a material to deform plastically without fracturing, measured by elongation or reduction of area.

Elongation is the increase in gauge length, measured after fracture of the specimen within the gauge length, usually expressed as a percentage of the original gauge length. A material's ductility, when subjected to increasing tensile loads, can be helpful to the designer for determining the extent to which a metal can be deformed without fracture in metalworking operations such as rolling and extrusion, or during service conditions.

The tensile specimen is punch marked twice in the central section of the specimen, this distance is measured, and the diameter of the reduced area prior to subjecting it to the tensile load is measured. After the specimen has been fractured, the two halves of the fractured tensile specimen are fitted back together as closely as possible, and the distance between the punch marks is again measured. The increase in the after-fracture gauge length as compared to the original gauge length prior to subjecting the specimen to tensile loads is the elongation of the specimen. This is usually expressed as the percentage of elongation within 2 in. (50 mm) of gauge length. The diameter at the point of fracture is also measured and the reduction in area from the original area is calculated. This reduction in area is expressed as a percentage. Both the elongation and the reduction in area percentage are measures of a material's ductility.

The design of components can be based on yield strength as well as tensile strength. Permanent deformation resulting from plastic flow occurs when the component's elastic limit is exceeded. A material subjected to loads beyond its elastic limit may become strain hardened, or work hardened. This results in a higher effective yield strength; however, the overall ductility based on the strain-hardened condition is lower than that of a material which has not been subjected to loads exceeding the elastic limit. Some materials also deteriorate in terms of ductility due to thermal cycling in service. Reduction in ductility in these cases may decrease so far that cracking during in-service repair may be very difficult to avoid. This is sometimes experienced during the repair welding of complex alloy exchanger tubesheets.

One of the most common tests used in the development of welding procedures is the bend test. The bend test is used to evaluate the relative ductility and soundness of welded joint or weld test specimen. The specimen is usually bent in a special guided test jig. The specimens are subjected to strain to the convex side of the specimen by bending the specimen to a specified radius that is based on the type of material and specimen thickness. Codes generally specify a maximum allowable size for cracks or other imperfections on the bend specimen. Cracks and tears resulting from a lack of ductility or discontinuities in the weld metal are evaluated for acceptance or rejection to the applicable code requirements.

10.4.4 Hardness and Hardness Testing

The hardness of a material is defined as the resistance to plastic deformation by indentation. Indentation hardness may be measured by various hardness tests, such as Brinell, Rockwell, Knoop, and Vickers.

Hardness measurements can provide information about the metallurgical changes caused by welding or cold working. In alloy steels, a high hardness measurement could indicate the presence of untempered martensite in the weld or heat-affected zone, while low hardness may indicate an overtempered condition.

There is an approximate interrelationship among the different hardness test results and the tensile strength of some metals. Correlation between hardness values and tensile strength should be used with caution when applied to welded joints or any metal with a heterogeneous structure.

A field test comparable to a Brinell test, commonly referred to as telebrineller, consists of applying load (force), on a 10 mm diameter hardened steel or tungsten carbide ball to a flat surface of a test specimen by striking the anvil on the Brinell device with a hammer. The impact is transmitted equally to a test bar that is held within the device that has a known Brinell hardness value and through the impression ball to the test specimen surface. The result is an indentation diameter in the test bar and the test specimen surface. The diameters of the resulting impressions are viewed using an optical comparator with a graduated scale and are directly related to the respective hardnesses of the test bar and the test specimen.

Rockwell hardness testing differs from Brinell testing in that the hardness number is based on an inverse relationship to the measurement of the additional depth to which an indenter is forced by a heavy (major) load beyond the depth of a previously applied (minor) load.

The Rockwell test is simple and rapid. The minor load is automatically applied by manually bringing the work piece up against the indenter until the "set" position is established. The zero position is then set on the dial gauge of the testing machine. The major load is then applied, and without removing the work piece, the major load is removed, and the Rockwell number then read from the dial.

In Rockwell testing, the minor load is always 10 kg, but the major load can be 60 kg, 100 kg, or 150 kg. Indenters can be diamond-cone indenters (commonly known as Brale), or hardened steel-ball indenters of various diameters. The type of indenters and applied loads depends on the type of material to be tested, as well as anticipated hardness.

A letter has been assigned to each combination of load and indenter. Scale is indicated by a suffix combination of H for hardness, R for Rockwell, and then a letter indicating scale employed. For instance, a value of 55 on the C scale is expressed as 55 HRC.

Vickers hardness testing follows the Brinell principle in that the hardness is calculated from the ratio of load to area of an indentation as opposed to the depth (the Rockwell principle). In the Vickers hardness test, an indenter of a definite shape is pressed into the work material, the load removed, and the diagonals of the resulting indentation measured. The hardness number is calculated by dividing the load by the surface area of the indentation. The indenter for the Vickers test is made of diamond in the form of a square-based pyramid. The depth of indentation is about one-seventh of the diagonal length. The Vickers hardness value is preceded by the designation (HV). The Vickers hardness number is the same as the diamond pyramid hardness number (DPH).

In-service hardness testing may involve the use of portable variations of the above-described methods. Alternatively, varying techniques based on rebound, indentation resistance, or comparator indentations may be applied and the results related to the hardness scales more commonly accepted. Whatever technique is employed may be acceptable as long as it produces verifiable and consistent results.

Various codes and standards place hardness requirements on base metal and welds. The test results for the material or welding procedures should be compared with the applicable standards to ensure that the requirements for hardness testing are being met, and that the test results are satisfactory with that specified by the applicable code. There are often in-service degradation requirements that are hardness related. For example, susceptibility to wet H_2S cracking in carbon steel is reduced if hardness levels are maintained below HRC 22 (respectively, a "100" reading on the HRB or a "61.5" reading on the HRA scale).

There are several issues to keep in mind when conducting field hardness tests and when comparing hardness numbers from different methods.

10.4.5 Toughness

Toughness is the ability of a metal to absorb energy and deform plastically before fracturing. An important material property to tank and pressure vessel designers is the "fracture toughness" of a metal, which is defined as the ability to resist fracture or crack propagation under stress. It is usually measured by the energy absorbed in a notch impact test. There are several types of fracture toughness tests. One of the most common is a notched bar impact test called the Charpy impact test. The Charpy impact test is a pendulum-type single-blow impact test where the specimen is supported at both ends as a simple beam and broken by a falling pendulum. The energy absorbed, as determined by the subsequent rise of the pendulum, is a measure of the impact strength or notch toughness of a material. The tests results are usually recorded in foot-pounds. The type of notch and the impact test temperature are generally specified and recorded, in addition to specimen size (if they are subsize specimens, smaller than 10 mm x 10 mm).

Materials are often tested at various temperatures to determine the ductile-to-brittle transition temperature. Many codes and standards require impact testing at or below the minimum design metal temperature based on service or location temperatures to ensure that the material has sufficient toughness to resist brittle fracture.

10.5 Preheating

Preheating, for these purposes, is defined as heating of the weld and surrounding base metal to a predetermined temperature prior to the start of welding. Additionally, a maximum allowable temperature known as the interpass temperature is generally specified on a welding procedure. The primary purpose for preheating carbon and low-alloy steels is to reduce the tendency for hydrogen-induced delayed cracking. It does this by driving moisture from the surface to be welded and slowing the cooling rate, which helps prevent the formation of martensite in the weld and base metal HAZ. However, preheating may be performed for many reasons, including the following.

a) To bring the temperature up to preheat or interpass temperatures required by the WPS;

b) To reduce shrinkage stresses in the weld and base metal, which is especially important in weld joints with high restraint;

c) To reduce the cooling rate to prevent hardening and a reduction in ductility of the weld and base metal HAZ;

d) To maintain weld interpass temperatures;

e) To eliminate moisture from the weld area;

f) To meet the requirements of the applicable fabrication code, such as the ASME Boiler and Pressure Vessel Code, depending on the intended use, chemistry, and thickness of the metal to be welded.

If preheat is specified in the WPS, it is important that the inspector confirms that the required temperature is maintained. This can be done using several methods, including thermocouples, contact pyrometer, infrared temperature measuring instruments, or temperature-indicating crayons. The inspector should remember that if preheat is required during welding, the same preheat should be applied during tack welding, arc gouging, and thermal cutting of the metal, all of which induce temperature changes similar to welding of the joint. The most important temperatures are the preheat temperature and the interpass temperature.

Preheat can be applied using several different techniques, but the most common techniques used in pipe and tank fabrication are electrical resistance coils, or an oxyacetylene or natural-gas torch. Good practice is to uniformly heat an area on either side of the weld joint for a distance three times the width of the weld. Preheat should be applied and extend to at least 2 in. (50 mm) on either side of the weld to encompass the weld and potential HAZ areas. Inspectors should exercise caution when welding metals of different chemistries or preheat requirements, ensuring that preheats for both metals are in accordance with codes and the WPS documentation. Typically, the metal with the highest preheat requirement governs and will be identified on the welding procedure.

Some alloys require controlled cooling or extended heating after weld completion, before PWHT begins. ASME Section IX defines this as “preheat maintenance.” Continuous or special heating during welding may also be necessary to avoid cracking.

10.6 Heat Treatment

The purpose of heat treatment is to impart desirable mechanical properties to a steel that are appropriate for its intended service through microstructural changes (phase transformations). While there are many types of heat treatments based upon the material and its specific application, the descriptions that follow are those typically used across many industries. Heat treatments are achieved by bringing the material to transformation temperatures (material based, 1700 °F to 1800 °F for steels), holding for a period of time, and cooling down at various rates.

10.6.1 Full Annealing

This process consists of heating steel to and holding at a suitable temperature above the transformation temperature range, followed by slow cooling to well below the transformation temperature. The cool-down cycle generally occurs in a furnace or as the part is contained within a heat-insulating material. The resulting material will have relatively low hardness and high toughness and ductility values for further metal working.

10.6.2 Normalizing

This method is carried out at relatively high temperatures, which causes the material's grain structure to realign, resulting in a structure that has higher hardness and greater relative strength than full annealing. The ferrous material is heated to a temperature above the transformation temperature range followed by cooling in still air to well below the transformation temperature range. Unlike full annealing, the material is removed from the furnace and air-cooled.

10.6.3 Carburizing

The purpose of carburizing is to diffuse carbon atoms to the outer layer of a material to form carbides which significantly increase the material's surface hardness at the sacrifice of ductility. Typical applications include wear surfaces such as blades. Carburizing is performed at relatively high temperatures, 1700 °F (930 °C), in either a carbon-rich liquid bath or gas environment. Dimensional changes are a typical result of this operation.

10.6.4 Hardening

Hardening or hardenability is defined as that property of a ferrous alloy that determines the depth and distribution of hardness induced by quenching. It is important to note that there is no close relation between hardenability and hardness, which is the resistance to indentation. Hardness depends primarily on the carbon content of the material, whereas hardenability is strongly affected by the presence of alloying elements such as chromium, molybdenum, and vanadium, and to a lesser extent by carbon content and alloying elements such as nickel, copper, and silicon. For example, a standard medium-carbon steel, such as AISI 1040 with no alloying elements, has a lower hardenability than AISI 4340 low-alloy steel, which has the same amount of carbon but contains small amounts of chromium, nickel, molybdenum, and silicon as alloying elements. Other factors can also affect hardenability to a lesser extent than chemical composition; these include grain structure, alloy homogeneity, amount of certain microstructural phases present in the steel, and overall microcleanliness of the steel.

Welding variables such as heat input, interpass temperature and size of the weld bead being applied all affect the cooling rate of the base metal HAZ, which in turn affects the microstructure (ferrite/pearlite/martensite formation) and resulting hardness. The cooling rate of the base metal can also be affected by the section size of the base metal being welded, temperature of the metal being welded, and weld joint geometry. If the alloying elements that increase hardenability are found in the base metal HAZ, the cooling rate during welding necessary to produce a high hardness HAZ are generally lower than for plain carbon steel without high percentages of alloying elements.

The simplest means to determine hardenability is to measure the depth to which a piece of steel hardens during quenching from an elevated temperature. There are several standardized tests for determining hardenability. A typical test of hardenability is called the Jominy End Quench Test. In this test, a round bar is heated to a predetermined elevated temperature until heated evenly through the cross-section. The specimen is then subjected to rapid quenching by spraying water against the bottom end of the round bar. The hardness of the test specimen is measured as a function of distance away from the surface being quenched. Steels that obtain high hardness well away from the quenched surface are considered to have high hardenability. Conversely, steels that do not harden well away from the quenched surface are considered to have low hardenability.

It may be important for the designer, welding engineer, and inspector to understand the hardenability of the steel as it can be an indirect indicator of weldability. Hardenability relates to the amount of martensite that forms during the heating and cooling cycles of welding. This is most evident in the base metal HAZ. Significant amounts of martensite formation in the HAZ can lead to hydrogen-assisted cracking or a loss in ductility and toughness. Certain steels with high hardenability form martensite when they are cooled in air. Other steels with low hardenability require much faster cooling rates to form martensite. Knowing the hardenability helps the engineer or inspector determine if preheat or PWHT are required, or if a controlled cooling practice may be acceptable to produce a serviceable weld and acceptable properties in the HAZ.

Hardening of the weld and base metal HAZ are important because of hydrogen-assisted cracking that occurs in carbon and low-alloy steels. As the hardness of the base metal HAZ increases, so does the susceptibility to hydrogen-assisted cracking. The hardness limits currently recommended for steels in refinery process service are listed in Table 11. Hardness values obtained in excess of these usually indicate that PWHT is necessary, regardless of whether it is specified on the welding procedure specification. In those instances where PWHT is needed, an alternate welding procedure qualified with PWHT is necessary.

Hardness in excess of those listed can result in stress corrosion cracking in service due to the presence of sulfides in the process. The 200 BHN limit for carbon steel is equally as important in sulfur-containing oils as is the limit for Cr-Mo steels.

Table 11—Brinell Hardness Limits for Steels in Refining Services

Base Metal	Brinell Value
Carbon Steel	200
C-$^{1}/_{2}$ Mo	225
1-$^{1}/_{4}$ Cr-$^{1}/_{2}$ Mo	225
2-$^{1}/_{4}$ Cr-1 Mo	241
5, 7, 9, Cr-Mo	241
12 Cr	241

10.6.5 Tempering

The purpose of tempering is to decrease material brittleness, increasing its ductility and toughness, and to relieve residual stresses, either from its manufacturing process or imparted during previously applied heat treatment operations. The resulting operation generally results in a reduction of yield and tensile strength.

10.6.6 Postweld Heat Treatment

PWHT produces both mechanical and metallurgical effects in carbon and low-alloy steels that varies widely depending on the composition of the steel, its past thermal history, the temperature and duration of the PWHT, and heating and cooling rates employed during the PWHT. The need for PWHT is dependent on many factors, including chemistry of the metal, thickness of the parts being joined, joint design, welding processes, and service or process conditions. The type of PWHT is selected by considering the changes being sought in the equipment or structure. For example, a simple stress relief to reduce residual stresses is performed at a lower temperature than a normalizing heat treatment. The holding time at temperature should also be selected to allow the desired time at temperature dependent actions to take place. In some isolated cases, holding time and temperature are interchangeable, but small temperature changes have been shown to be equivalent to large changes in holding times.

The primary reason for PWHT is to relieve residual stresses in a welded fabrication. In ferritic welds, PWHT is also conducted to reduce the hardness of the HAZ. Stresses occur during welding due to the localized heating and severe temperature changes that occur. PWHT releases these stresses by allowing the metal to creep slightly at the elevated temperature. However, there may also be in-service conditions that require particular PWHT conditions. These may not be so closely detailed in construction specifications and inspectors should therefore be particularly aware of these potential requirements when allowing, authorizing, or inspecting in-service repairs.

PWHT (stress relief) can be applied by electrical resistance heating, furnace heating, or, if allowed by the code, local flame heating. Temperatures should be monitored and recorded by thermocouples attached to the part being heated. Multiple thermocouples are necessary to ensure proper PWHT of all components. Adequate support should be provided during any PWHT to prevent sagging.

10.7 Material Test Reports

There are typically two types of test reports on a material test report (MTR). A heat analysis, or mill certificate, is a statement of the chemical analysis and weight percent of the chemical elements present in an ingot or a billet. An ingot and a billet are the customary shapes into which a molten metal is cast. These shapes are the starting points for the manufacture of wrought shapes by the metal-forming process, such as rolling, drawing, forging, or extrusion. A product analysis is a statement of the chemical analysis of the end product and is supplied by the manufacturer of the material. These reports can be supplied for any form of material, including wrought products, such as plate, pipe, fittings, tubing, castings, and weld filler metals. The product analysis is more useful to the inspector and engineer because it provides a more reliable identification of the actual material being used for new fabrication or repair of existing equipment.

For the purposes of this publication, the information about MTRs pertains to product certificates for carbon, low-alloy steel, and stainless steels. However, it should be noted that the MTR documents may include, but are not limited to, the following information:

a) manufacturer of the material;

b) date of manufacture;

c) heat number of the material;

d) applicable national standard(s) to which the heat conforms, such as ASTM, ASME, or MIL-STD;

e) heat treatment, if applicable;

f) chemistry of the heat;

g) mechanical properties, at a minimum those required by the applicable National Standards;

h) any other requirement specified by the applicable National Standard;

i) any supplemental information or testing requested by the purchaser, which may include but is not limited to:

   1) impact strength;

   2) ductile-to-brittle transition temperature determination;

   3) fracture toughness;

   4) elevated mechanical property testing (i.e. tensile, hot ductility, or creep testing);

   5) hardenability;

   6) hardness;

   7) response to heat treatment (i.e. proposed postfabrication heat treatment such as precipitation hardening, necessary to achieve mechanical properties);

   8) microstructural analysis, such as grain size evaluation;

   9) nondestructive examination, such as UT.

The inspector should review the MTR to confirm that the materials being used for fabrication of new equipment or repair of existing equipment meet the requirements specified by the applicable code/standard or additional requirements specified by the user. The welding engineer can also use the information from a MTR to determine the weldability of the materials to be used, and to recommend proper welding procedures, preheat, and postweld heat treatment. The chemical analysis given in the test report can be used to calculate the carbon equivalent for that material. It is important to note that MTRs are not generally supplied to the purchaser unless requested. It is good practice for the purchaser to request the mill test reports.

10.8 Weldability of Metals

10.8.1 General

There are many books devoted to the weldability of metals and alloys. Weldability is a complicated property that does not have a universally accepted definition. The term is widely interpreted by individual experience. The American Welding Society defines weldability as “the capacity of a metal to be welded under the fabrication conditions imposed, into a specific, suitably designed structure, and to perform satisfactorily in the intended service.” Weldability is related to many factors including the following:

a) the metallurgical compatibility of the metal or alloy being welded, which is related to the chemical composition and microstructure of the metal or alloy, and the weld filler metal used;

b) the specific welding processes being used to join the metal;

c) the mechanical properties of the metal, such as (yield and tensile) strength, ductility and toughness;

d) the ability of the metal to be welded such that the completed weld has sound mechanical properties;

e) the weld joint design.

10.8.2 Metallurgy and Weldability

A primary factor affecting weldability of metals and alloys is their chemical composition. Chemical composition not only controls the range of mechanical properties in carbon and alloy steels, it has the most influence on the effects of welding on the material. The heat cycles from welding in effect produce a heat treatment on the metal that can have a substantial effect on mechanical properties, depending on the chemical composition of the metal being welded. As noted earlier, each type of metal has welding procedural limits within which sound weldments with satisfactory properties can be fabricated. If these limits are wide, the metal is said to have good weldability. If the limits are narrow, the metal is considered to have poor weldability.

The addition of carbon generally makes the metal more difficult to weld without cracking. Carbon content has the greatest effect on mechanical properties, such as tensile strength, ductility, and toughness in the base metal HAZ and weldment. Carbon content influences the susceptibility of the metal to delayed cracking problems from hydrogen. The carbon content, or carbon equivalent, of carbon steel determines the necessity for preheat and PWHT.

Alloying elements other than carbon are added to alloy steels for various reasons and can have an influence on the weldability and mechanical properties of the metal. Some alloying elements, such as manganese, chromium, nickel, and molybdenum are added to provide beneficial effects on strength, toughness, and corrosion resistance. Some of these elements are beneficial in non-heat-treated steel, while others come into play during heat treatments necessary to produce the desired mechanical properties. These alloying elements can have a strong effect on hardenability, so they can also affect the weldability of the metal being welded.

There are some elements present in carbon and alloy steels that are not deliberately added that can have an effect on weldability. These include sulfur, phosphorus, tin, antimony, and arsenic. These elements are sometimes referred to as “tramp” or “scavenger” elements.

One tool that has been developed to help evaluate the weldability of carbon and alloy steel is the carbon equivalent (CE) concept. The CE calculation establishes a theoretical carbon content of the metal and considers not only carbon, but also the effect of other alloying elements and tramp elements. Several different equations for expressing carbon equivalent are in use. One common equation for carbon and carbon–manganese steels is:

$$CE = C + \frac{Mn}{6} + \frac{C + Mo + V}{5} + \frac{Ni + Cu}{15}$$

Typically, steels with a CE less than 0.35 require no preheat. Steels with a CE of 0.35 to 0.55 usually require preheating, and steels with a CE greater than 0.55 require both preheating and a PWHT. However, requirements for preheating should be evaluated by considering other factors such as hydrogen level, humidity, and section thickness. As preheating provides a significant benefit to the weldment, it should be considered when developing a welding procedure.

10.8.3 Weldability Testing

One of the best means to determine weldability of a metal or combination of metals is to perform direct weldability testing. Direct tests for weldability are defined as those tests that specify welding as an essential feature of the test specimen. Weldability testing provides a measure of the changes induced by welding in a specified steel property and a means to evaluate the expected performance of welded joints.

The problem with predicting the performance of structures or welded equipment from a laboratory-type test is a complex one because size, configuration, environment, and type of loading are not consistent under most service conditions. For this reason, no single test can be expected to measure all of the aspects of a property as complex as weldability, and most weldments are evaluated by several tests. If tests are to be useful in connection with fabrication, they should be designed to measure the susceptibility of the weld metal–base metal system to such defects as weld metal or base metal cracks, lamellar tearing, and porosity or inclusions under typical, properly controlled welding conditions. Selection of a test method may also have to balance time and cost for emergency repairs or shutdown work.

The simplest weldability tests are those that evaluate the strength and ductility of the weld. Tests that evaluate strength include weld tension tests, shear strength, and hardness. Ductility and fracture toughness tests include bend tests and impact tests. These tests evaluate the breaking strength, ductility, and toughness of simple weld joints. These tests are the same as tests used for welding procedure and welder qualification to the ASME Boiler and Pressure Vessel Code. If the weldment has adequate strength and ductility, it is usually deemed acceptable for service.

Fabrication weldability tests that incorporate welding into their execution can be broadly classified as restraint cracking tests, lamellar tearing tests, externally loaded cracking tests, underbead cracking tests, or simple weld metal soundness tests. Some of these tests can be used to detect the susceptibility to more than one type of defect, while others are intended as single-purpose tests, and still others may be go/no-go types of tests.

Weld restraint induces stresses that can contribute to cracking of both the weld and base metal in fabrication welds. This type of cracking occurs when the rigidity of the joint is so severe that the base metal or weld metal strength cannot adequately resist the stress and strain applied by expansion and contraction of the weld joint. Weld restraint cracking specimens are designed to permit a quantitative variation in restraint under realistic welding conditions so the contribution of the weld metal, base metal, and welding processes can be evaluated with respect to contribution to cracking. Typical weld restraint test methods include the Lehigh restraint test, slot test, rigid restraint cracking (RRC) test, and circular weld restraint cracking test.

Another approach to measuring susceptibility to weld cracking is to apply an external load during welding or subsequent to welding. The loading is intended to duplicate or magnify stresses from restraint of a rigid weld joint. The tests provide an ability to control the stress and strain applied to the weld joint and, therefore, provide a relative index of the susceptibility to weld cracking. Test methods that use external loading include the implant test, tension restraint cracking (TRC) test, and Varestraint Hot Ductility test. There is also a specialized test called the Gleeble test that also applies a load to the specimen during heating or melting of the metal.

It is beyond the scope of this document to describe each test in detail; however, a general overview of different types of tests and the types of defects they can detect is given in Table 12.

Table 12—Weld Crack Tests

	Weld Metal Cracking			Base Metal Cracking		
	Solidification	**Root and Toe**	**Microcracks**	**H-assisted**	**Stress Relief**	**Lamellar Tearing**
Restraint Tests						
Lehigh Test	x	x	x	x	x	
Slot Test				x		
Tekken Test		x		x		
RRC Test	x	x	x	x		
Circular Weld Test	x	x		x		
Externally Loaded Tests						
Varestraint Test	x					
Implant Test				x	x	x
TRC Test				x		
Lamellar Tearing Test						
Cantilever Test						x
Cranfield Test						x
Underbead Cracking Test						
Longitudinal Bead Test				x		
Cruciform Test		x		x		
CTS Test				x		

10.9 Weldability of High Alloys

10.9.1 General

This section gives information about welding of high-alloy metals, such as austenitic stainless steels, precipitation hardening stainless steels, and nickel-based alloys. These materials are not as common as carbon and low-alloy steels (e.g. 1$^{1}/_{4}$ Cr-$^{1}/_{2}$ Mo through 9 Cr-1 Mo steels) but may still be used in some processes within the oil industry.

10.9.2 Austenitic Stainless Steels

Austenitic stainless steels are iron-based alloys that typically contain low carbon, chromium between 15 % to 32 %, and nickel between 8 % to 37 %. They are used for their corrosion resistance and resistance to high-temperature degradation. Austenitic stainless steels are considered to have good weldability and can be welded using any common welding process or technique. The most important considerations to welding austenitic stainless steels are solidification cracking, hot cracking, distortion, and maintaining corrosion resistance.

Solidification cracking and hot cracking (sometimes called hot shortness) are directly related to weld metal chemistry and the resultant metallurgical phases that form in the weld metal. The cracking mechanism of both solidification cracking and hot cracking is the same. Cracks can occur in various regions of the weld with different orientations. They can appear as centerline cracks, transverse cracks, and as microcracks in the underlying weld metal or adjacent HAZ. Cracking is primarily due to low-melting-point liquid phases which allow boundaries to separate under the thermal and shrinkage stresses during weld solidification and cooling.

The most common measure of weldability and susceptibility to hot cracking is the ferrite number of the weld metal. Austenitic welds require a minimum amount of delta ferrite to resist cracking. The amount of ferrite in the weld metal is primarily a function of both base metal and weld metal chemistry. For welds made without filler metal, the base metal chemistry should be appropriate to produce the small amounts of ferrite that are needed to prevent cracking. If the base metal chemistry does not allow for ferrite formation, then filler metal is recommended to produce adequate ferrite in the weld metal. Welding parameters and practices can also affect ferrite formation. For example, small amounts of nitrogen absorbed into the weld metal can reduce ferrite formation. WRC Bulletin 342 contains diagrams that accurately predict the amount of ferrite present in a weld metal based on the calculation of nickel and chromium equivalents based on weld metal and base metal chemistry. Several resources recommend a minimum of 5 % to 20 % ferrite content to prevent cracking.

Weldability of austenitic stainless steels can also be affected by the presence of high levels of low-melting-point elements like sulfur, phosphorus, and selenium. Other elements such as silicon and columbium (niobium) also increase the hot cracking susceptibility of austenitic stainless steels.

Distortion is more often a problem with welding of austenitic stainless steels than carbon or low-alloy steels. The thermal conductivity of austenitic stainless steels is about one-third that of carbon steel and the coefficient of thermal expansion is about 30 % greater. This means that distortion is greater for austenitic stainless steels than for carbon steels. More frequent tack welds may be necessary for stainless steels to limit shrinkage.

Welding can reduce the corrosion resistance of regions of the HAZ of some austenitic stainless steels. Areas exposed to temperatures between 800 °F to 1650 °F (430 °C to 900 °C) for a long enough time may precipitate chromium carbides at the grain boundaries. Using low-carbon-content stainless steels such as Type 304L or 316L, or stabilized grades of stainless steels such as Type 321 and 347, can prevent this phenomenon. It is also important to select the proper filler metal to prevent a loss in corrosion resistance. Low-carbon electrodes or stabilized grades of bare filler metal should be used.

Oxidation of the underside of welds made without proper shielding can also be detrimental to the corrosion resistance of austenitic stainless steels. To prevent a loss in corrosion resistance, the root of the weld should be protected by using an inert backing gas such as argon or nitrogen.

10.9.3 Nickel Alloys

Nickel alloys, such as Alloy C276 or Alloy 625, suffer from similar problems as austenitic stainless steels. In general, most nickel-alloy materials are considered to have less weldability than austenitic stainless steels. Some nickel alloys, such as Alloy 825, Alloy 600, and Alloy 625, have similar welding characteristics to austenitic stainless steels, while Alloy 200, Alloy 400, and Alloy B-2 have very different welding characteristics than austenitic stainless steels.

One of the main differences between nickel-alloy and carbon steels and austenitic stainless steels is the tendency for nickel-alloy welds to be sluggish during welding. This means for nickel alloys that the molten weld pool will not move as easily as it does for other metals. This sluggish tendency means the welder should move the weld pool with a weave or oscillation pattern to ensure good sidewall fusion. If some oscillation is not used, a high convex weld contour will result, which will cause sidewall LOF, weld undercut, or slag inclusions. The formation of a slightly concave weld bead profile will be more resistant to centerline cracking. It is also important that the bevel angle for nickel alloys be wide enough to allow for this necessary oscillation of the welding torch.

The wider weld bevel will also be beneficial with respect to weld penetration. Nickel alloys also suffer from shallower weld penetration as compared to carbon steels and austenitic stainless steel. To overcome this, the weld joint is modified by having a wider bevel and thinner root face.

Nickel alloys are also susceptible to hot cracking, in some cases more so than austenitic stainless steels. This hot tearing will occur as the weld pool cools and solidifies. To help prevent hot cracking, the weld joint should be designed to minimize restraint and the weld should be allowed to cool as quickly as possible. The faster a nickel-alloy weld solidifies (freezes), the less time it spends in the temperature range where it can tear. For this reason, preheating, which slows down the cooling rate of the weld, could actually be harmful, as it permits more opportunity for hot tearing to occur.

As with austenitic stainless steels, the weldability of nickel alloys can also be affected by the presence of high levels of low-melting-point elements like sulfur, phosphorus, zinc, copper, and lead. All of these contaminants can lead to cracking in either the weld or base metal.

11 Refinery and Petrochemical Plant Welding Issues

11.1 General

This section provides details of specific welding issues encountered by the inspector in refineries and petrochemical plants. This section will be expanded as more issues reflecting industry experience are added.

11.2 Hot Tapping and In-Service Welding

11.2.1 General

API 2201 provides an in-depth review of the safety aspects to be considered when hot tapping or welding on in-service piping or equipment. Prior to performing this work, a detailed written plan should be developed and reviewed. The following is a brief summary of welding related issues.

Two primary concerns when welding on in-service piping and equipment are burn-through and cracking. Burn-through will occur if the unmelted area beneath the weld pool can no longer contain the pressure within the pipe or equipment. Weld cracking results when fast weld-cooling rates produce a hard, crack-susceptible weld microstructure. Fast cooling rates can be caused by flowing contents inside the piping and equipment, which remove heat quickly.

11.2.2 Electrode Considerations

Hot tap and in-service welding operations should be carried out only with low-hydrogen consumables and electrodes (e.g. E7016, E7018, and E7048). Extra-low-hydrogen consumables such as EXXXX-H4 should be used for welding carbon steels with a carbon equivalent greater than 0.42 % or where there is potential for hydrogen-assisted cracking (HAC) such as cold-worked pieces, high strength, and highly constrained areas.

Cellulosic-type electrodes (e.g. E6010, E6011, and E7010) may be used for root and hot passes. Although low-hydrogen electrodes are preferred, some refining locations and the pipeline industry prefer to use cellulosic electrodes frequently because they are easy to operate and provide improved control over the welding arc. Root pass with low-hydrogen electrodes reduces risk of HAC. It also reduces risk of burn-through because the amount of heat directed to the base metal is less than when using cellulosic-type electrodes. However, manipulation of low-hydrogen electrode for root pass is not as easy but it can be performed by training and practice. It should be noted that cellulosic electrodes have the following adverse effects on the integrity of the weldment:

f) deep penetration, therefore higher risk of burn-through than low-hydrogen electrodes; and

g) high diffusible hydrogen, therefore higher risk of hydrogen-assisted cracking.

11.2.3 Flow Rates

An appropriate flow rate should be maintained to dissipate the heat from welding, minimizing the possibility of burn-through or combustion. The minimum flow rate is 1.3 ft/s (0.4 m/s) for liquid and gas. For liquids, a maximum flow rate is usually required to minimize risk of high hardness weld zone due to the fast cooling rate. The allowable maximum flow rate depends on the process temperature. In general, 4.0 ft/s (1.2 m/s) is the upper limit. There is no restriction on maximum velocity for gas lines, subject to maintaining preheat temperatures. It is advisable to compensate for any heat loss by preheating the weld area to at least 70 °F (20 °C) and maintaining that preheat until the weld has been completed.

For making attachment welds to equipment containing a large quantity of liquid, such as a storage tank, the weld should be 36 in. (900 mm) below the liquid/vapor line. Normal circulation within the equipment will effectively cool the weld area.

Welding on a line under no-flow conditions or intermittent-flow conditions, e.g. a flare line, should not be attempted unless it has been confirmed that no explosive or flammable mixture will be generated during the welding operation. In this respect, it should be confirmed that no ingress of oxygen in the line is possible. In cases where this requirement cannot be met, inert gas or nitrogen purging is recommended. Software that takes into account the material properties and flow conditions is often employed to determine if the conditions are safe for in-service welding.

11.2.4 Other Considerations

11.2.4.1 Burn-Through

To avoid overheating and burn-through, the welding procedure specification should be based on experience in performing welding operations on similar piping or equipment, and/or be based on heat transfer analysis. Many users establish procedures detailing the minimum wall thickness that can be hot tapped or welded in-service for a given set of conditions like pressure, temperature, and flow rate. Some users include in their procedures the use of mock-up weld coupons when the actual thickness of the material to be welded is less than $^{1}/_{4}$ in. (6 mm). The mock-up coupon represents the actual material and thickness, the welding parameters are recorded, and the weld penetration is verified by etching. This information becomes the supplement to the repair package. To minimize burn-through, the first weld pass to equipment or piping less than $^{1}/_{4}$ in. (6 mm) thick should be made with a $^{3}/_{32}$ in. (5 mm) or smaller diameter welding electrode to limit heat input. For equipment and piping-wall thicknesses where burn-through is not a primary concern, a larger diameter electrode can be used. Weaving the weld bead should also be avoided as this increases the heat input.

11.2.4.2 Hot Taps

Adverse effects can also occur from the heat on the process fluid. In addition, welds associated with hot taps or in-service welding often cannot be stress relieved and may be susceptible to cracking in certain environments. Any hot tapping or in-service welding on systems containing those listed in Table 13 should be carefully reviewed.

During repairs or alterations (including hot taps) of alloy material piping systems, material verification of the existing and the new materials is required to establish that the selected components are as specified. Additionally, in some jurisdictions the hot-tap component may be required to have a registered design, in which case this should be verified.

Buttering the surface of the run pipe prior to attaching a hot-tap nozzle is particularly recommended when attaching a nozzle to pipe fabricated from plate material to prevent lamellar tearing of the pipe where the thickness is such that this may occur as the result of weld shrinkage stresses. With in-service welding, there is the risk of high hardness and hydrogen cracking in the HAZ of the parent material. Buttering allows a more closely controlled heat input in the parent material, and also permits use of the temper bead welding technique. The temper bead welding technique tempers the HAZ of the parent material during the deposition of the second layer of weld metal. This approach is particularly useful where the cooling effect of the process fluid present is high.

Table 13—Hot Tapping/In-Service Welding Hazards Associated With Some Particular Substances

Substance	Hot Tapping/In-Service Welding Hazard
Acetylene	Explosion or unstable reaction with the addition of localized heat.
Acetonitrile	Explosion or unstable reaction with the addition of localized heat.
Amines and caustic	Stress corrosion cracking due to high thermal stress upon the addition of localized heat and high hardness of non-PWHT's weld. Hydrogen embrittlement.
Butadiene	Explosion or unstable reaction.
Chlorine	Carbon steel burns in the presence of chlorine and high heat.
Compressed air	Combustion/metal burning.
Ethylene	Exothermic decomposition or explosion.
Ethylene oxide	Exothermic decomposition or explosion.
Hydrogen	High temperature hydrogen attack. Hydrogen-assisted cracking.
Hydrogen sulfide (Wet H_2S)	Stress corrosion cracking due to high hardness of non-PWHT's weld. Hydrogen embrittlement. Pyrophoric scale.
Hydrofluoric acid	Hazardous substance.
Oxygen	Combustion/metal burning.
Propylene	Explosion or unstable reaction.
Propylene oxide	Explosion or unstable reaction.
Steam	High pressure steam can blow out.

Buttering allows a balanced welding sequence to be used, and if correctly applied can reduce the potential distortion of the pipe after welding. Normally, two layers of weld metal should be deposited, especially for dissimilar metal welds, to reduce the impact of weld dilution. The first buttering pass is generally ground to one-half its thickness, with the second pass applied as close to the edge of the first as possible. Subsequent welds passes are applied in a similar manner. The final thickness of the weld deposit at the location of the nozzle-to-pipe weld should, after grinding, be no less than $^{1}/_{4}$ in. (6 mm) or as specified in the welding procedure. The width of the buttering should be sufficient to overlap the nozzle attachment weld by $^{1}/_{4}$ in. (6 mm) on both the inside and outside diameters. Similarly, buttering should be deposited under any reinforcement plate-to-pipe welds.

The surface of the buttered layer should be ground smooth, the edges de-burred, and both the weld and the pipe local to the weld inspected by appropriate crack detection and ultrasonic methods. It is recommended that immediately before welding is commenced, a test should be carried out to check the amperage of the welding current to reduce the risk of burn-through of the run pipe during the actual welding operation. This may be done by striking an arc on a suitable piece of material similar to that of the run pipe.

11.2.5 Inspection

Inspection tasks typically associated with hot tapping or welding on in-service equipment should include the following.

a) Verifying adequate wall thickness along the lengths of the proposed welds, typically using UT.

b) Verifying the appropriate welding procedure is being employed.

NOTE Plants often have welding procedures qualified specifically for hot taps and in-service welding.

c) Ensuring the welder is appropriately qualified to use the appropriate welding procedure.

d) Verifying the flow conditions are acceptable for welding.

e) Specifying the sequence of welding full encirclement sleeves and fittings (circumferential and longitudinal welds).

f) Verifying fit-up of the hot-tap fitting.

g) Auditing welding to ensure the appropriate welding procedure is being followed.

h) Performing NDE of completed welds, as well as in-process inspection as appropriate. Typically, this includes VT or UT shear wave using special procedures for the joint configuration, and MT or PT as applicable for material and temperature. In general, MT using dry, color-contrast particles will provide the required inspection.

i) Witnessing leak testing of fitting, if specified.

j) Performing PMI testing on the hot-tap component material.

NOTE In some jurisdictions, the hot tap component may be required to have a registered design, in which case this should be verified.

k) Documenting all the above and having the responsible engineer approve the plan prior to implementation.

11.3 Lack of Fusion With GMAW-S Welding Process

The gas metal arc welding (GMAW) process can utilize various metal transfer modes. When using the low-voltage, short-circuiting mode (designated by the -S extension), the molten weld puddle is able to freeze more quickly. This allows the unique ability to weld out of position, to weld thin base metals, and to weld open butt root passes. However, the potential for LOF remains a concern. Due to this inherent nature of the welding process, the BPV Code Section IX restricts this process by:

a) requiring welders to qualify with mechanical testing rather than by radiographic examination, as detecting LOF can be difficult using RT;

b) limiting the base metal thickness qualified by the procedure to 1.1 times the test coupon thickness for coupons less than 12.7 mm thick ($^1/_2$ in.) per variable QW-403.10;

c) limiting the deposited weld metal thickness qualified by the procedure to 1.1 times the deposited thickness for coupons less than 12.7 mm thick ($^1/_2$ in.) per variable QW-404-32;

d) making variable QW-409.2 (a change from globular, spray, or pulsed spray transfer welding to short-circuit transfer mode, or vice versa) an essential variable when qualifying a welder for the GMAW-S process.

Since the transfer mode may be difficult to determine without an oscilloscope, some general characteristics are listed in a National Board Classic Bulletin, Low Voltage Short Circuiting—GMAW, from January 1985, to assist the inspector in determining the transfer mode being used. The quick freeze characteristic, which can result in LOF, is the reason this process is frequently specified in purchase requisitions.

GMAW in the short-circuiting transfer mode is of particular significance to inspectors in that many specifications, codes, and standards impose limitations or special conditions on its use. The technique can suffer from incomplete fusion particularly in the sidewall of steep or narrow weld preparations. This occurs as transfer of small fast-freezing droplets only occurs while the electrode is short-circuited by contact with the work piece. Intermittent loss of contact can leave areas of LOF. In shallow weld preparations, these are also difficult to detect with conventional radiographic techniques. Consequently, a higher standard of NDE inspection is required. In pipeline welding, automated ultrasonic has been adopted to overcome this problem. Inspectors should be aware that the risk of LOF associated with GMAW-S has caused ASME BPVC Code, Section IX, to require welders to be qualified using mechanical testing rather than by RT.

11.4 Caustic Service

Carbon steel and low-alloy steels are subject to stress corrosion cracking in caustic service. Austenitic (i.e. Type-300 series) stainless steels can be sensitive to caustic cracking in high-temperature steam environments. Cracking is a function of temperature, caustic concentration, and the level of operating or residual stress. Prior to welding or PWHT, the weld area should be cleaned, for a distance of at least 6 in. (150 mm) from the edges of the weld, with a 5 % acetic acid solution in water and then water wash to remove the neutralized caustic. Check the cleaned area with pH paper to show that the caustic has been removed. Alternatively, the area can be checked with a phenolphthalein indicator to show that caustic has been removed. If the indicator turns pink, caustic is still present on the surface. The contaminated surface should be reneutralized, recleaned, and rechecked, as necessary, until caustic is removed from the surface. Material cleanliness is an important requirement for successful welding, especially when welding nickel and nickel-alloy materials. Inspection should be performed before welding on caustic-contaminated surfaces. All areas to be welded should be ground or power-brushed clean. Nickel and nickel alloys should be cleaned with a stainless-steel wire brush. All cleaning tools including wire brushes and carbide grinding tools should be clean and free of debris or other metal fragments. Care should be taken during grinding operations since the heat of grinding may create and propagate crack-like defects on caustic-contaminated surfaces.

Although caustic stress corrosion cracks may be seen visually, crack detection is best performed with WFMT, ET, RT, or ACFM techniques. Surface preparation by grit blasting, high-pressure water blasting, or other methods is usually required. Guidelines for when PWHT is required for carbon steels may be found in NACE SP0403 and API 571.

Prior to weld repairs in caustic service, a corrosion specialist should review the details of the welding plan to ensure suitability for service. This should include a review of the welding electrode/wire selected, the weld procedure, details of weld preparation, PWHT, and the details of the NDE to be used on the completed welds. Other services that may warrant similar review include amine service, hydrofluoric acid service, hydrogen service, sour and wet H_2S service, and situations with dissimilar metal welds.

11.5 Controlled Deposition Welding

In some instances, full PWHT may have potential adverse effects on equipment and piping. In those cases, controlled-deposition welding (CDW) may be used in lieu of PWHT where PWHT is inadvisable or mechanically unnecessary. Depending on the construction code, the use of CDW may require a metallurgical review conducted by a welding and/or materials/corrosion engineer prior to using any alternative method to ensure that the proposed alternative is suitable for the application. Such a review would consider factors including the reason for the original PWHT of the equipment, susceptibility to stress corrosion cracking, stresses in the location of the weld, susceptibility to high-temperature hydrogen attack, susceptibility to creep, etc. The inspector is responsible for verifying that the methods used are in accordance with owner–user specification and the requirements of the construction code.

To the extent applicable, the selection of the welding method used should be based on the rules of the construction code applicable to the planned work along with technical consideration of the adequacy of the weld in the as-welded condition at operating and pressure test conditions.

When reference is made to materials by the ASME designation, P-number, and group number, the requirements of the repair or construction code apply to the applicable materials of the original code of construction, either ASME or other, which conform by chemical composition and mechanical properties to the ASME P-number and group number designations. CDW is limited to materials in P-No. 1, P-No. 3, and P-No. 4, with further restrictions (e.g. impact testing, hardness testing) in the applicable codes. When impact tests are required by the construction code applicable to the planned work, the PQR shall include sufficient tests to determine if the toughness of the weld metal and the HAZ of the base metal in the as-welded condition is adequate at the MDMT (such as the criteria used in ASME Code, Section VIII, Division I, Parts UG-84 and UCS 66, or ASME B31.3). If special hardness limits are necessary (e.g. as set forth in NACE SP0472 and NACE MR0103) for stress corrosion cracking resistance, the PQR shall include hardness tests as well.

The WPS shall include the following additional requirements.

a) The supplementary essential variables of ASME Code, Section IX, Paragraph QW-250, shall apply.

b) The maximum weld heat input for each layer shall not exceed that used in the procedure qualification test.

c) The minimum preheat temperature for welding shall not be less than that used in the procedure qualification test.

d) The maximum interpass temperature for welding shall not be greater than that used in the procedure qualification test.

e) The preheat temperature shall be checked to ensure that 4 in. (100 mm) of the material or four times the material thickness (whichever is greater) on each side of the weld joint will be maintained at the minimum temperature during welding. When the weld does not penetrate through the full thickness of the material, the minimum preheat temperature needs only be maintained at a distance of 4 in. (100 mm) or four times the depth of the repair weld, whichever is greater, on each side of the joint.

f) For the allowed welding processes listed below, use only electrodes and filler metals that are classified by the filler metal specification with an optional supplemental diffusible-hydrogen designator of H8 or lower. When shielding gases are used with a process, the gas shall exhibit a dew point that is no higher than −60 °F (−50 °C). Surfaces on which welding will be done shall be maintained in a dry condition during welding and free of rust, mill scale, and hydrogen-producing contaminants such as oil, grease, and other organic materials.

g) The welding technique shall be a CDW, temper bead, or half bead technique. The specific technique shall be used in the procedure qualification test.

h) For welds made by SMAW, after completion of welding and without allowing the weldment to cool below the minimum preheat temperature, the temperature of the weldment shall be raised to a temperature of 500 °F ± 50 °F (260 °C ± 30 °C) for a minimum period of two hours to assist outgassing diffusion of any weld metal hydrogen picked up during welding.

i) After the finished repair weld has cooled, the final temper bead reinforcement layer shall be removed, leaving the weld substantially flush with the surface of the base material.

In general, CDW is not usually applied to situations where the reason for PWHT is to avoid stress corrosion cracking (SCC). Welding processes for CDW are limited to SMAW, GMAW, and GTAW (for CDW in pipe welding, the FCAW process may also be employed), with a specific WPS developed and qualified for each application. If the original material specification is obsolete, the test material used should conform as much as possible to the material used for construction, but in no case shall the material be lower in strength or have a carbon content of more than 0.35 %.

Refer to WRC Bulletin 412 for additional supporting technical information regarding controlled deposition welding.

12 Safety Precautions

Inspectors should be aware of the hazards associated with welding and take appropriate steps to prevent injury while performing inspection tasks. As a minimum, the site's safety rules and regulations should be reviewed as applicable to welding operations; see Annex G for more information.

Annex A
(normative)

Terminology and Symbols

A.1 Weld Joint Types

Figure A.1 illustrates the various weld joint types that are typically encountered by the inspector. The type of joint can affect the type of weld process that can be used and the choice of NDE method.

A.2 Weld Symbols

Engineering and construction drawings often use standard symbols to represent weld details. Figure A.2 shows the corresponding symbols for several weld joint types. Figure A.3 shows some supplementary symbols that provide specific detail about the weld. Figure A.4 explains the conventions used in a weld symbol.

A.3 Weld Joint Nomenclature

Standard terminology applies to the various components of a weld joint. Figure A.5 illustrates and describes the joint terminology.

A.4 Electrode Identification

The AWS specification and classification system allows selection of an electrode that will provide a weld metal with specific mechanical properties and alloy composition. The following welding processes use an electrode identification system to designate characteristics of the electrode: SMAW, GMAW, GTAW, FCAW, SAW, and EGW. The identification systems are explained for each process in Figure A.6, Figure A.7, Figure A.8, Figure A.9, and Figure A.10.

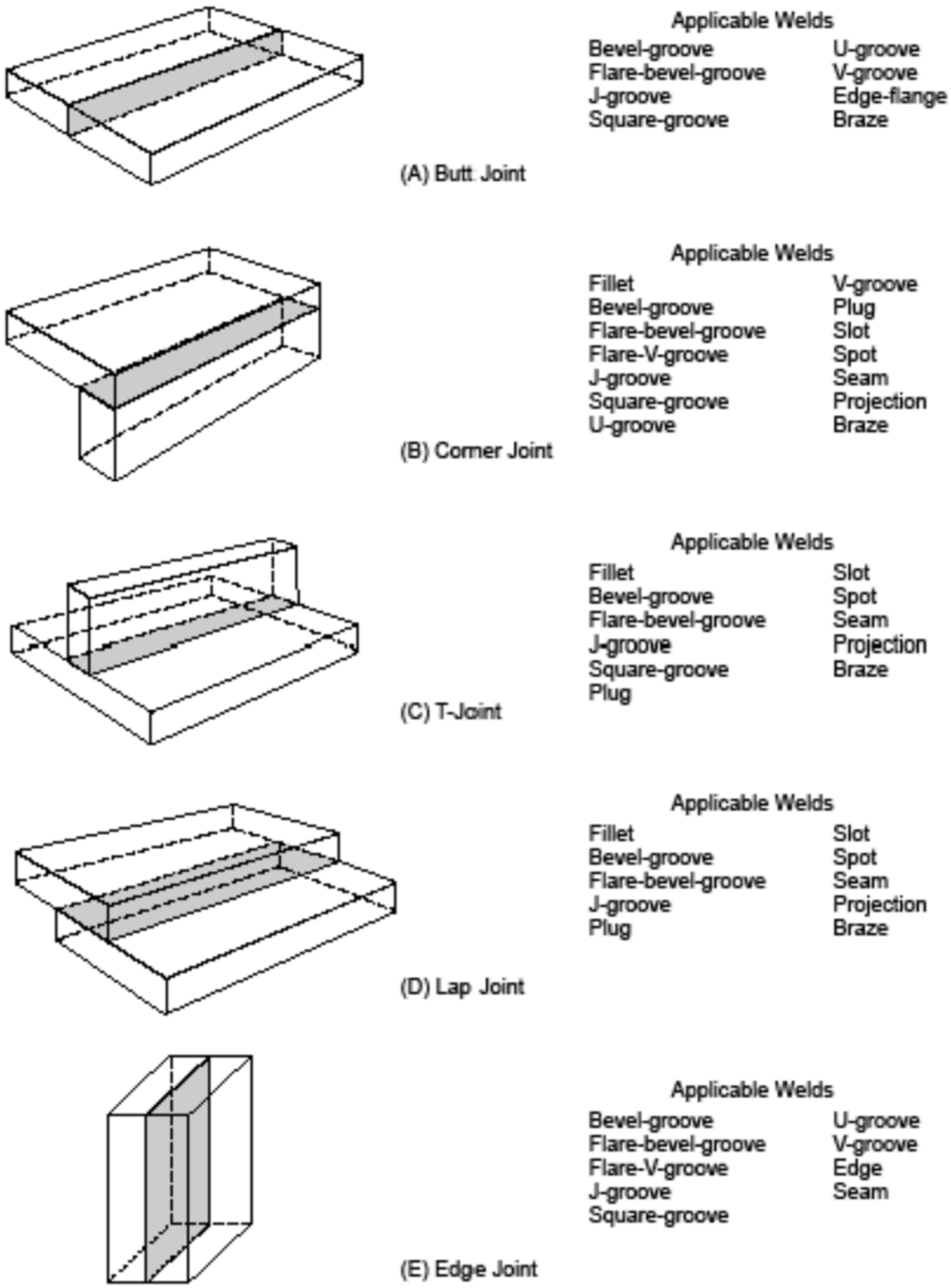
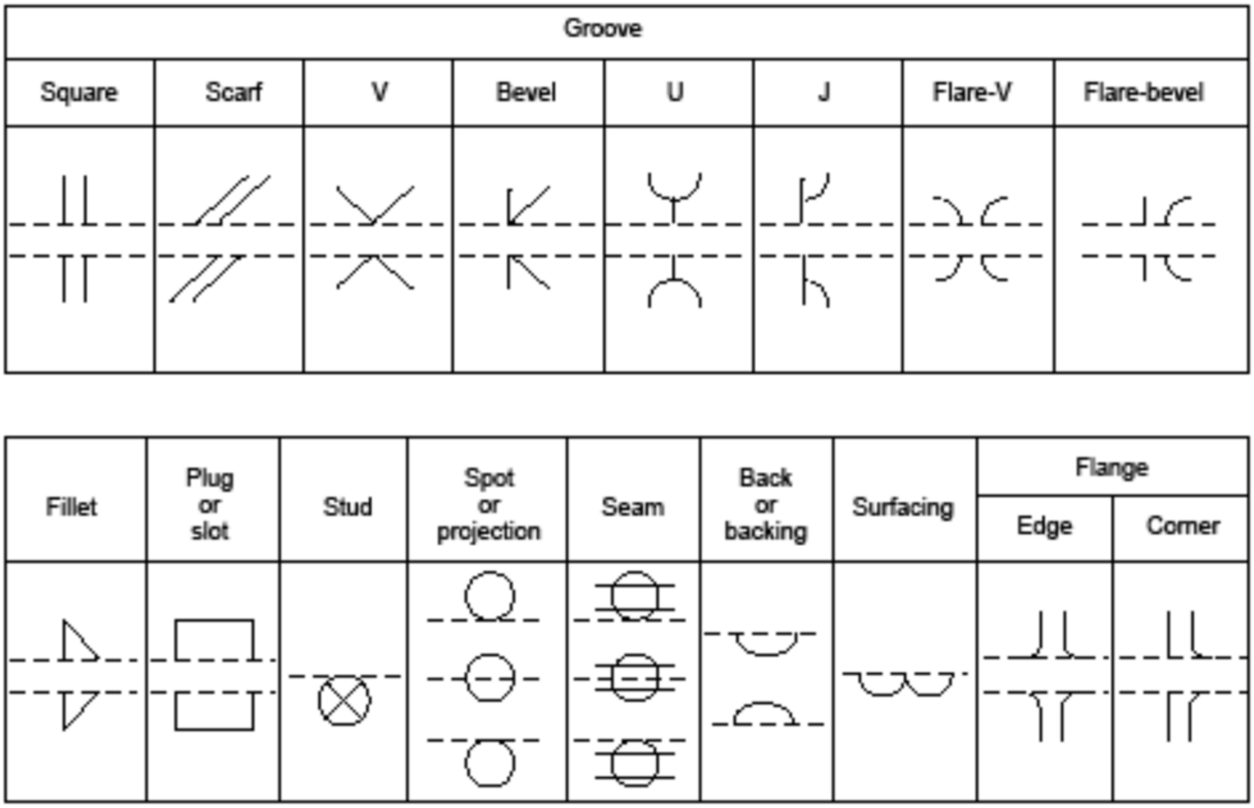


Figure A.1—Joint Types and Applicable Welds



NOTE The reference line is shown dashed for illustrative purposes.

Figure A.2—Symbols for Various Weld Joints

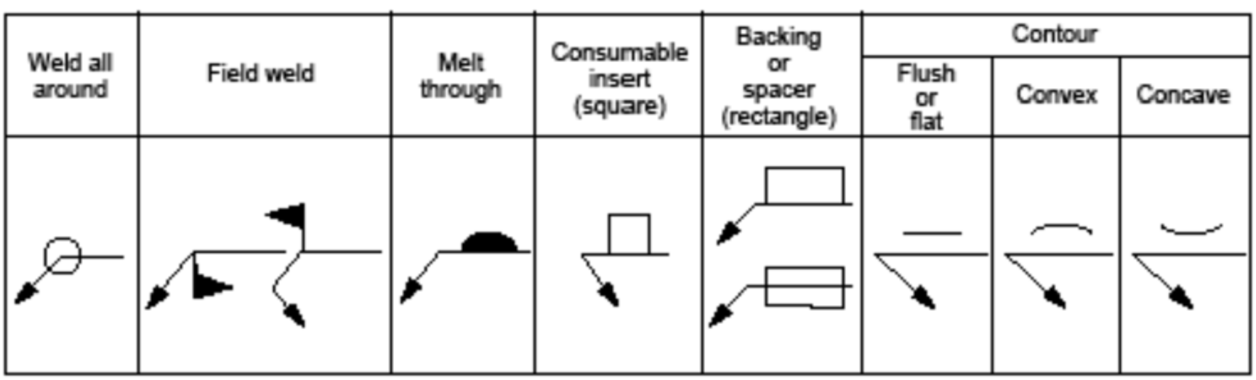
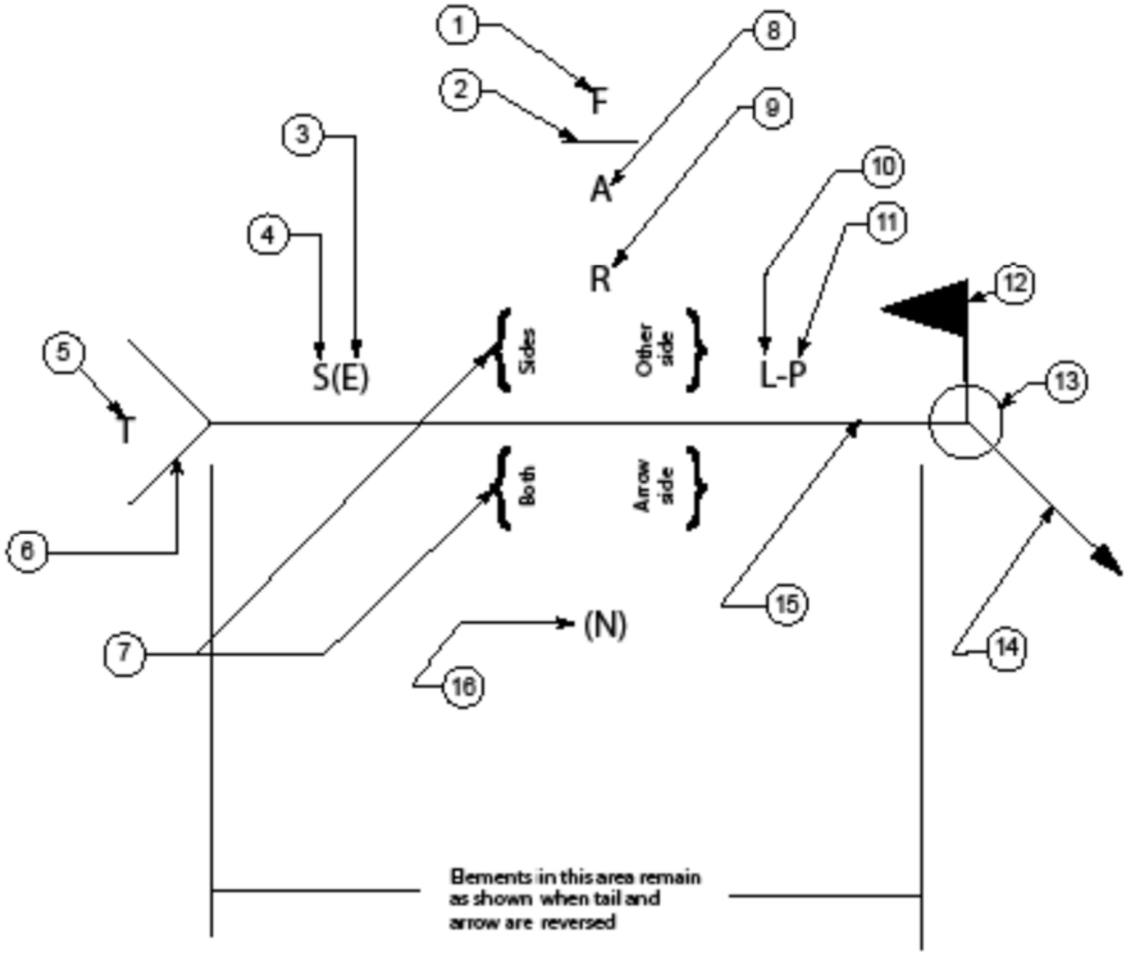


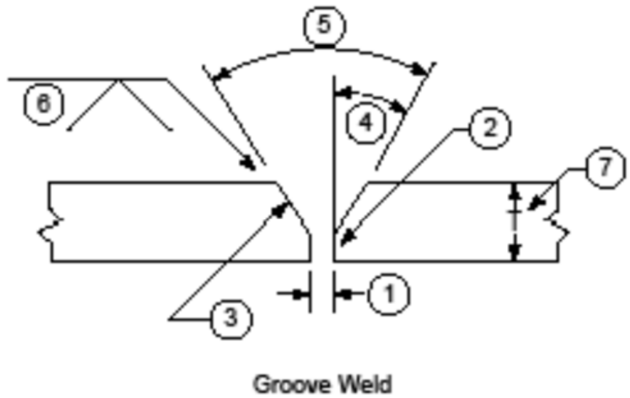
Figure A.3—Supplementary Symbols for Welds



Key

1 finish symbol
2 contour symbol
3 groove weld size
4 depth of bevel; size or strength for certain welds
5 specificaiton, process, or other reference
6 tail (omitted when reference is not used)
7 weld symbol
8 groove angle; included angle of countersink for plug welds
9 Root opening; depth of filling for plug and slot welds
10 length of weld
11 pitch (center-to-center pacing) of welds
12 field weld symbol
13 weld-all-around symbol
14 arrow connecting reference line to arrow side member of joint or arrow side of joint
15 reference line
16 number of spot, seam, stud, plug, slot, or project welds

Figure A.4—Standard Weld Symbols



Key

1. Root Opening: A separation at the joint root between the workpieces.
2. Root Face: That portion of the groove face adjacent to the joint root.
3. Groove Face: The surface of a joint member included in the groove.
4. Bevel Angle: The angle formed between the prepared edge of a member and a plane perpendicular to the surface of the member.
5. Groove Angle: The total included angle of the groove between workpieces.
6. Groove Weld Size: The joint penetration of a groove weld.
7. Plate Thickness (T): Thickness of the base metals to be welded.

Figure A.5—Groove Weld Nomenclature

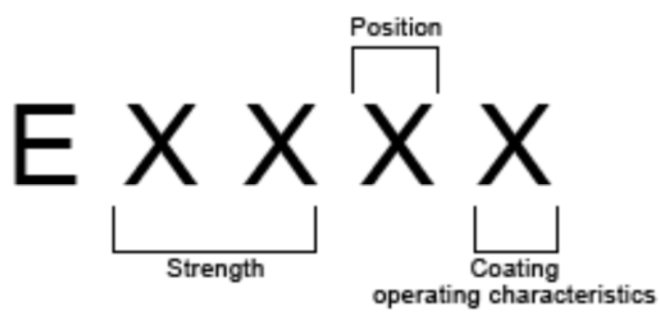


Figure A.6—SMAW Welding Electrode Identification System

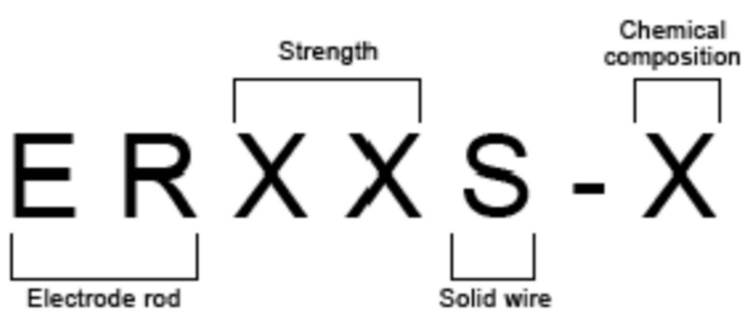


Figure A.7—GMAW/GTAW/PAW Welding Electrode Identification System

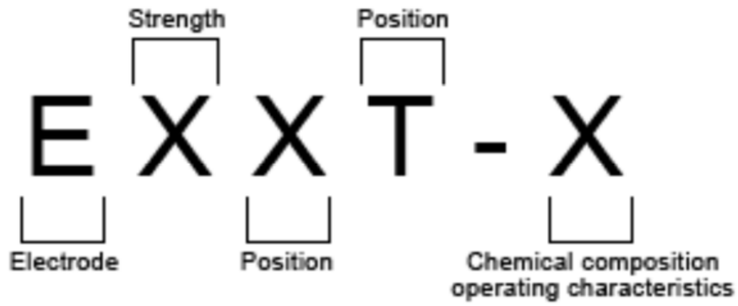
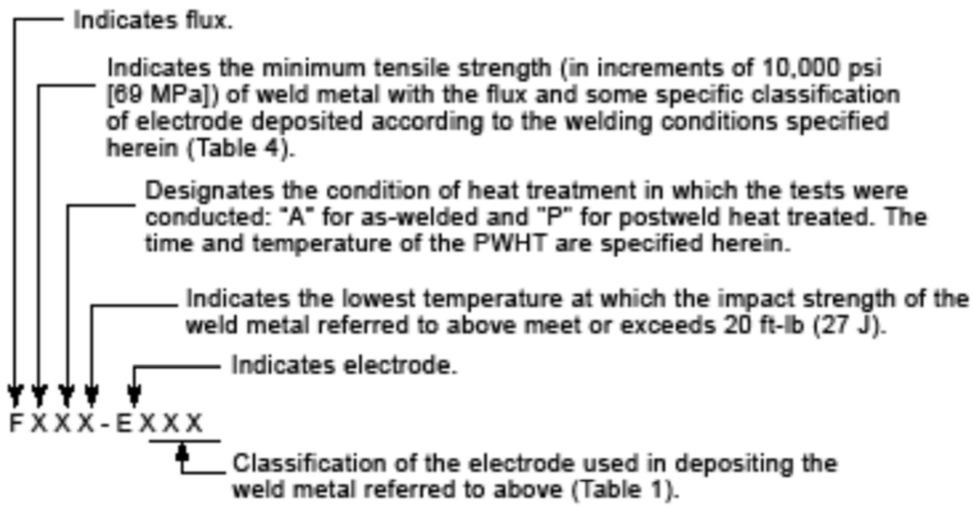


Figure A.8—FCAW Welding Electrode Identification System



EXAMPLE

F7A6-EM12K is a complete designation. It refers to a flux that will produce weld metal which, in the as-welded condition, will have a tensile strength no lower than 70,000 psi and Charpy V-notch impact strength of at least 20 ft-lb at –60 °F when deposited with an EM12K electrode under the conditions called for in this specification.

Figure A.9—SAW Welding Electrode Identification System

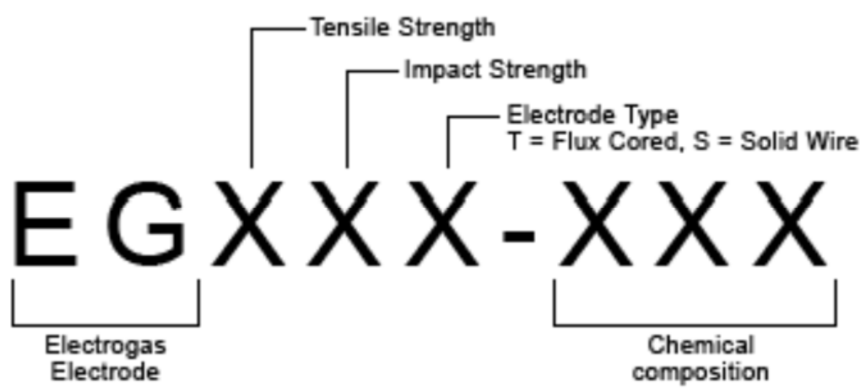


Figure A.10—EGW Welding Electrode Identification System

Annex B
(normative)

Actions to Address Improperly Made Production Welds

Production welds made by a nonqualified welder or an improper welding procedure should be avoided to ensure the final weldments meet the code/specification and user service requirements. A welder may be unqualified for several reasons, including expired qualification, not qualified for the welding process, thickness, not qualified in the technique, or not qualified for the material of construction. Figure B.1 details some potential steps to address the disposition of these welds.

A welding procedure may be improper if the weldment is made outside the range of essential variables (and supplementary essential variables, if required) qualified for the WPS. Figure B.2 details some potential steps to address weldments made with an improper welding procedure.

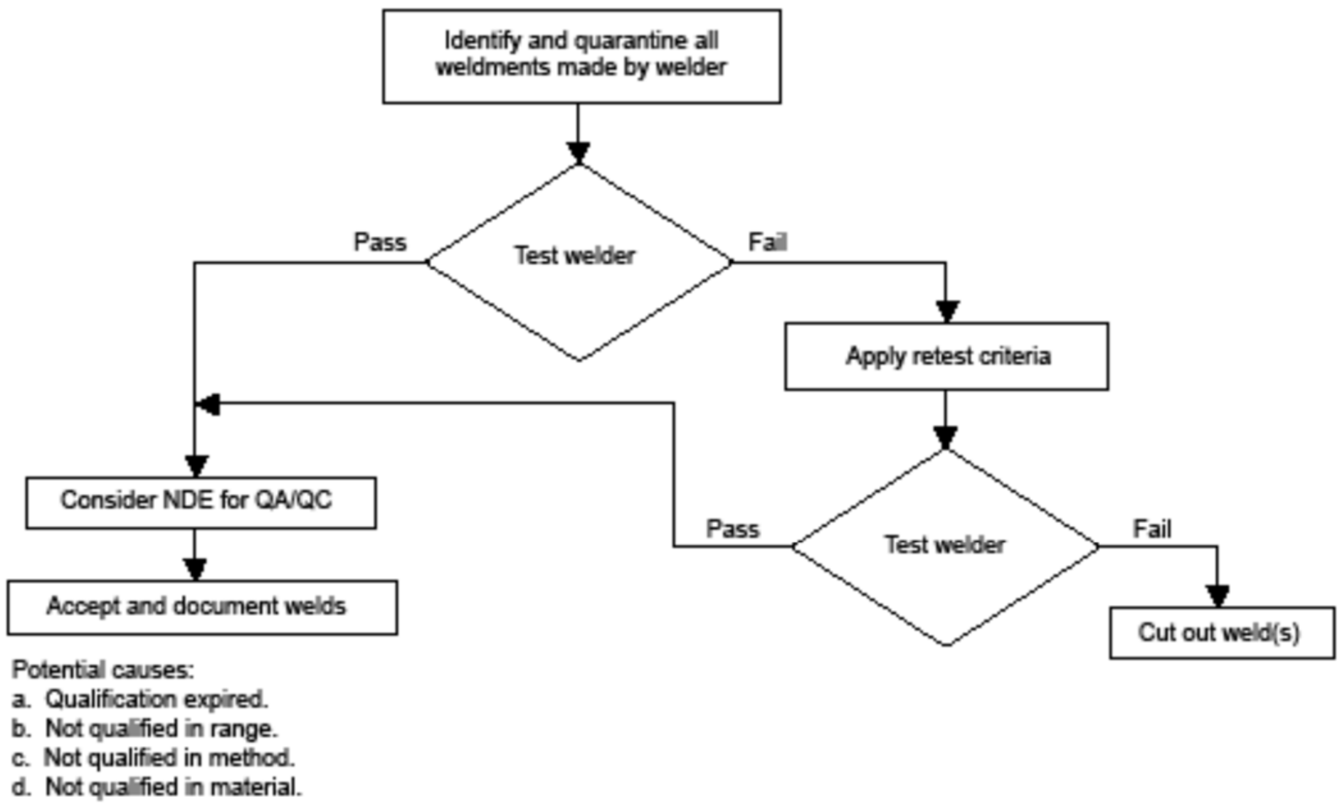


Figure B.1—Suggested Actions for Welds Made by an Incorrect Welder

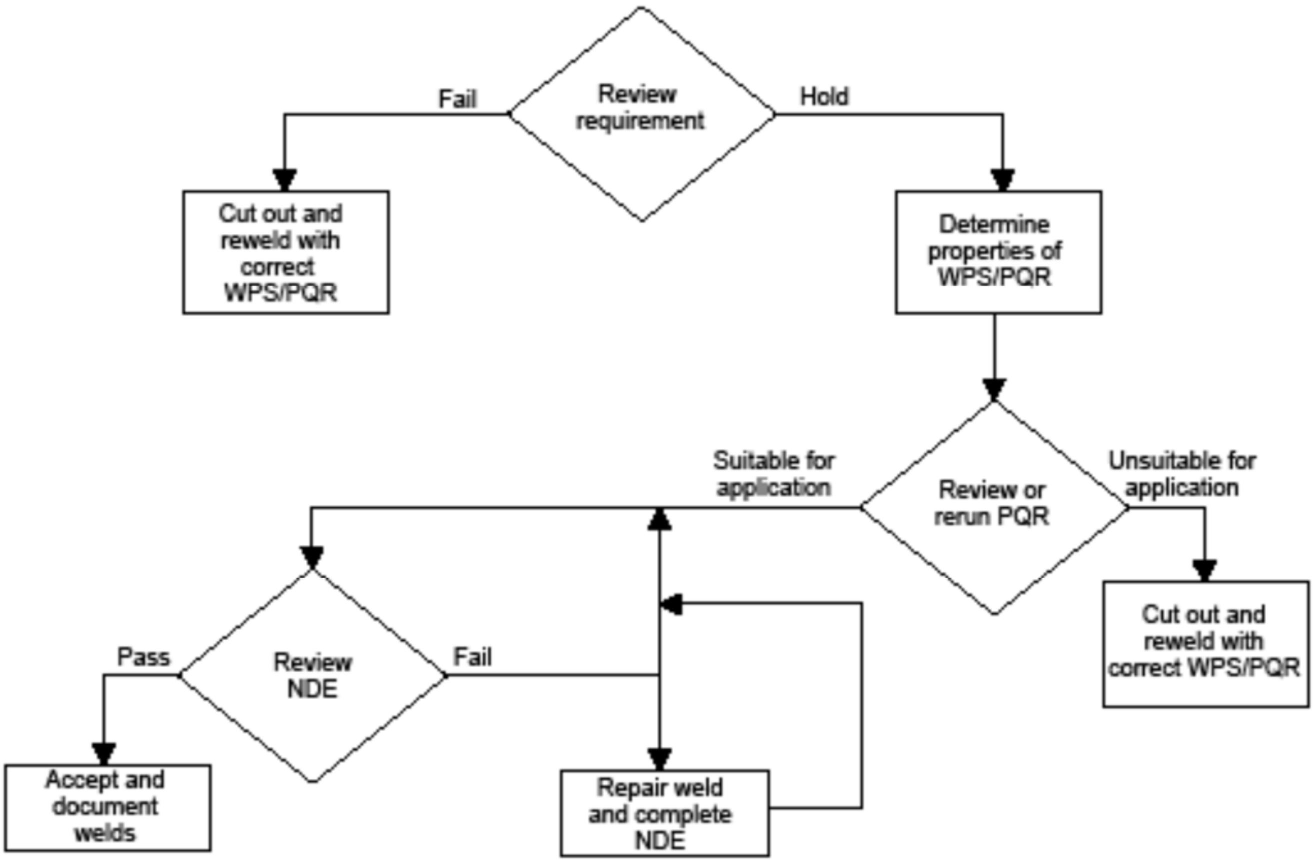


Figure B.2—Steps to Address Production Welds Made by an Improper Welding Procedure

Annex C
(informative)

WPS/PQR Review

C.1 Scope

The following exhibits are to be used as a guide for validating the welding procedure specification (WPS)/ procedure qualification record (PQR) of the processes covered in the API Recommended Practice 577. It is not intended to be used for the development of a WPS or PQR. For creating these documents, greater detail is needed and should be accomplished by qualified personnel utilizing the respective construction code or specification. It is further recognized that owner–users may have specific requirements that exceed the requirements of a code or specification. Examples include additional hardness testing, minimum preheat temperatures, or a limit on heat input. While such additional requirements are not necessarily required by code/specification, such welding procedures will need to meet these additional requirements for compliance.

API Recommended Practice 577 only considers ASME Boiler Pressure Vessel Code Section IX (ASME IX) because it is generally the development basis of the fabrication and repair of piping and pressure equipment. Other codes and standards may have similar variables or may vary greatly from ASME IX requirements.

C.2 Variables

As described below by ASME BPVC Section IX, there are three types of variables that always need to be addressed on the WPS. For the PQR, essential and supplementary essential variables need to be addressed; the documentation of nonessential variables on the PQR is optional.

C.2.1 Essential Variables

Essential variables are conditions in which a change, as described in the specific variables, is considered to affect the mechanical properties (other than toughness) of the joint. Before using a procedure specification whose essential variables have been revised and fall outside their qualified range, the procedure specification shall be requalified.

C.2.2 Supplementary Essential Variables

Supplementary essential variables are conditions in which a change will affect the toughness properties of the joint, heat-affected zone, or base material. Supplementary essential variables become additional essential variables in situations where procedure qualifications require toughness testing. When procedure qualification does not require the addition of toughness testing, supplementary essential variables are not applicable.

C.2.3 Nonessential Variables

Nonessential variables are conditions in which a change, as described in the specific variables, is not considered to affect the mechanical properties of the joint.

C.3 Documentation Requirements

The variables to be identified on the WPS/PQR are specific to each welding process; ASME IX along with other codes/specifications require essential variables to be documented on both the WPS and the PQR. Nonessential variables shall be listed on the WPS but are optional on the PQR and at the discretion of the owner–user. If nonessential variables are reported on the PQR, they must be actual variables documented during the qualification process using valid ranges. When toughness testing is required, supplementary essential variables become essential variables and shall be listed on both the WPS and the PQR. In general, supplementary essential variables apply when a PWHT is required. See ASME IX QW-200.1 and QW-200.2.

It is important to recognize that no changes to the WPS are allowed other than to nonessential variables to accommodate production requirements for which requalification is not necessary. No changes to the PQR are allowed except for editorial corrections. Any changes to essential variables and supplementary essential variables (when required) would necessitate requalification of the WPS by means of a new or additional PQR to support such changes.

C.4 Annex Utilization

There are two approaches to applying this annex. The reviewer may utilize the specific welding process variable list to ensure that the variables are listed on the proper document being reviewed or the specific WPS/PQR may be used to verify all variables have been addressed.

C.4.1 List Method by Process

When using a welding process variable list (see Section 6.2.2), verify that essential, nonessential, and supplementary essential (when required) variables are recorded on the WPS for the welding process. Also ensure that the essential and supplementary essential (when required) variables are recorded on the PQR. Additionally, verify that the actual variables recorded on the PQR support the WPS ranges.

C.4.2 Specific Process WPS/PQR Method

The specific process WPS/PQR is formatted to represent what the production WPS/PQR may look like. The variables are color coded for easy identification. The variables that shall be on the WPS are recorded while only the required variables are listed on the PQR.

Note that the PQR must show the results of mechanical testing and shall be certified by the preparing organization and signed by appropriate personnel. The sections on Test Results and Certification are common to all PQRs but contain no variables. Because of that, only the first sample PQR (in C.5.1.2) contains the Testing and Certification sections as an example.

C.4.3 Color Codes for the WPS/PQR

The following are color codes for the WPS/PQR:

Essential Variables

Nonessential Variables

Supplementary Essential Variables

C.5 Reviewing the WPS/PQR

Verify that the required variables are recorded on the respective WPS/PQR. Ensure all ASME Section IX, Article IV, Welding Data for the specific welding process has been recorded. These specific welding data paragraphs are found on the variable list for each specific welding process.

Nonessential variables used during the welding of the test coupon may be recorded. If recorded, only the actual ranges used during the welding of the test coupon are to be recorded on the PQR.

The PQR shall be certified accurate by the organization responsible for its creation.

C.5.1 Shielded Metal Arc Welding

C.5.1.1 Welding Procedure Specification

Sample ASME Section IX SMAW WPS For Review

Per QW-200.1

Organization Name: Shall be Listed **Created By: Shall be Listed** **Date: Shall be Listed**

WPS Number: Shall be listed **Supporting PQR Number: Shall be Listed**

Weliding Process(es): Shall be Listed **Type(s):** (Manual, Automatic) **Nonessential**

QW-402 Joints

Joint Design: Nonessential

Root Spacing: Nonessential

Backing: Yes or No Nonessential

Nonessential variables must be recorded on the WPS.

When listed on the PQR, ranges must be valid.

Backing Material: Backing and Retainers **Nonessential**

Drawings, sketches, or written descriptions show the general arrangement of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. Essential **Ø Group No. Supplementary**

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Deposited Weld Metal: (t) pass > 1/2 inch (13 mm) Essential

Filler Metals QW-404

Ø F-No. Essential **Ø A-No. Essential**

Ø Electrode Diameter: Nonessential **Ø in electrode diameter > 1/4 inch (6 mm): Supplementary**

Classification: Ø For Impact Testing Supplementary

Classification (SFA No.): Ø Nonessential

Deposited Weld Metal: Ø Change Essential

ASME Section IX SMAW WPS For Review (cont'd)

Positions QW-405

Position(s) of Groove: + addition Nonessential

Position(s): Ø Supplementary

Welding Progresstion: ↑↓ Nonessential

Preheat QW-406

Decrease of >100°F (56°C): Essential Preheat Maintenance: Ø Nonessential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Electrical Characteristics QW-409

Heat Input: Increase: Supplementary

Ø Current and Polarity: Nonessential If Impact Testing: Supplementary

Ø I & E Range / Amperage and Voltage Range: Nonessential

Technique QW-410

Ø String or Weave Bead: Nonessential

Ø Method Cleaning: Nonessential

Method of Back Gouging: Nonessential

Multiple or Single Pass (per side): Nonessential If Impact Tested: Supplementary

± Peening: Nonessential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

C.5.1.2 Procedure Qualification Record

ASME Section IX SMAW PQR For Review

Per QW-200.2

Organization Name: Shall be Listed Date: Shall be Listed

PQR Number: Shall be listed WPS Number: Shall be Listed

Welding Process(es) Shall be Listed

Nonessential variables must be recored on the WPS.

When listed on the PQR actual nonessential variables, including ranges, must be used.

Base Metals QW-403

Ø P-No. Essential Ø Group No. Supplementary

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Deposited Weld Metal: (t) pass > 1/2 inch (13 mm) Essential

Filler Metals QW-404

Ø F-No. Essential Ø A-No. Essential

Ø in electrode diameter > 1/4 inch (6 mm) Supplementary

Classification: Ø For Impact Testing Supplementary

Deposited Weld Metal: Ø Essential

Positions QW-405

Position(s): Ø Supplementary

Preheat QW-406

Decrease of >100°F (56°C): Essential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

ASME Section IX SMAW PQR For Review (cont'd)

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Electrical Characteristics QW-409

Heat Input: Increase: Supplementary

Ø Current and Polarity: (If Impact Testing) Supplementary

Technique QW-410

Multiple or Single Pass (per side): (If Impact Tested) Supplementary

Use of Thermal Process: *See QW-410.64 for applicability* **Essential**

Mechanical Test Results

PQR No: Shall be listed

Tensile Test QW-150 for proper number and type / Acceptance Criteria - Tension Test QW-153

Specimen No.	Width	Thickness	Area	Ultimate Load	Ultimate Unit Stress	Type of Failure Location
Tensile Tests shall be shown on the PQR with the actual test results						

Guided Bend Tests QW-160 for proper number and type / Acceptance Criteria - Tension Test QW-163

Type and Figure No.	Results
Guided Bend Test shall be recorded with the actual test results	

Toughness Test QW- 170 for proper number and type / Acceptance Criteria - Tension Test QW-172.2

Specimen No.	Notch Location	Specimen Size	Test Temperature	Ft-lb or J	Impact Values % Shear	Mils (in.) or mm	Drop weight Break (Y/N)
Tensile Tests shall be shown on the PQR with the actual test results							

Welder Name: Shall be listed Clock No.: Shall be listed Stamp No. : Shall be listed

Test Conducted by: Shall be listed Lab Test No. : Shall be listed

We certify that the statements in this record are correct and the test welds were prepared, welded, and tested in accord with the requirements of *Applicable Test Code*.

Organization: Shall be listed Date: Shall be listed

Certified by: Shall be signed

C.5.2 Gas Tungsten Arc Welding

C.5.2.1 Welding Procedure Specification

Sample ASME Section IX GTAW WPS For Review

Per QW-200.1

Organization Name: Shall be Listed Created By: Shall be Listed Date: Shall be Listed

WPS Number: Shall be listed Supporting PQR Number: Shall be Listed

Weliding Process(es): Shall be Listed

QW-402 Joints

Joint Design: Nonessential

Root Spacing: Nonessential

Backing: Yes or No Nonessential

Backing Material: Backing and Retainers **Nonessential**

Nonessential variables must be recorded on the WPS.

When listed on the PQR, ranges must be valid.

Drawings, sketches, or written descriptions show the general arrangement of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. Essential **Ø Group No. Supplementary**

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Filler Metals QW-404

Ø F-No. Essential **Ø A-No. Essential**

Ø Electrode Diameter: Nonessential

Classification: Ø For Impact Testing Supplementary **Filler metal: Essential**

± Consumable insert: Nonessential **Ø Classification (SFA No.): Nonessential**

Ø Filler metal product form: Essential

Ø t Deposited Weld Metal: Essential

ASME Section IX GTAW WPS For Review (cont'd)

Positions QW-405

+ Addition Position(s): Nonessential

Ø Position(s): Supplementary

Welding Progresstion: ↑↓ Nonessential

Preheat QW-406

Decrease of >100°F (56°C): Essential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Gas QW-408

± Trail or Ø Composition: Nonessential

Ø Single, mixture, or %: Essential

Ø Shielding flow rate: Nonessential

± or Ø Backingflow: Nonessential

- Backing or Ø composition: Essential

Ø Shielding or trailing: Essential

Electrical Characteristics QW-409

Ø Heat Input: ± Supplementary

Pulsing Current: Nonessential

Ø Current and Polarity: Nonessential

If Impact Testing: Supplementary

Ø I & E Range / Amperage and Voltage Range: Nonessential

Ø Tungsten electrode: Nonessential

C.5.2.2 Procedure Qualification Record

Sample ASME Section IX GTAW PQR For Review

Per QW-200.2

Organization Name: Shall be Listed Date: Shall be Listed

PQR Number: Shall be listed WPS Number: Shall be Listed

Welding Process(es): Shall be Listed

Nonessential variables must be recored on the WPS.

When listed on the PQR actual nonessential variables, including ranges, must be used.

Base Metals QW-403

Ø P-No. Essential Ø Group No. Supplementary

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Filler Metals QW-404

Ø F-No. Essential Ø A-No. Essential

Classification: Ø For Impact Testing Supplementary ± Filler Metal: Essential

Ø Filler metal product form: Essential

Ø t Deposited weld metal: Essential

Positions QW-405

Ø Position(s): Supplementary

Preheat QW-406

Decrease of >100°F (56°C): Essential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

ASME Section IX GTAW PQR For Review (cont'd)

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Gas QW-408

Ø Single, mixture, or %: Essential

- Backing or Ø composition: Essential **Ø Shielding or trailing:** Essential

Electrical Characteristics QW-409

Heat Input:Decrease: Supplementary

Ø Current and Polarity: (If Impact Testing) Supplementary

Technique QW-410

Multiple or Single Pass (per side): (If Impact Tested) Supplementary

Ø Single to multi electrodes: (If Impact Tested) Supplementary

Ø Closed to out chamber: Essential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

Mechanical Test Results

PQR No: Shall be listed

Tensile Test QW-150 for proper number and type / Acceptance Criteria - Tension Test QW-153

Specimen No.	Width	Thickness	Area	Ultimate Load	Ultimate Unit Stress	Type of Failure Location
Tensile Tests shall be shown on the PQR with the actual test results						

ASME Section IX GTAW PQR For Review (cont'd)

Mechanical Test Results (Cont'd)

Guided Bend Tests QW-160 for proper number and type / Acceptance Criteria - Tension Test QW-163

Type and Figure No.	Results
Guided Bend Test shall be recorded with the actual test results	

Toughness Test QW- 170 for proper number and type / Acceptance Criteria - Tension Test QW-172.2

Specimen No.	Notch Location	Specimen Size	Test Temperature	Ft-lb or J	Impact Values % Shear	Mils (in.) or mm	Drop weight Break (Y/N)
Tensile Tests shall be shown on the PQR with the actual test results							

Welder Name: Shall be listed **Clock No.:** Shall be listed **Stamp No. :** Shall be listed

Test Conducted by: Shall be listed **Lab Test No. :** Shall be listed

We certify that the statements in this record are correct and the test welds were prepared, welded, and tested in accord with the requirements of *Applicable Test Code*.

Organization: Shall be listed **Date:** Shall be listed

Certified by: Shall be signed

C.5.3 Gas Metal Arc Welding and Flux Cored Arc Welding

C.5.3.1 Welding Procedure Specification

Sample ASME Section IX GMAW & FCAW WPS For Review

Per QW-200.1

Organization Name: Shall be Listed **Created By:** Shall be Listed **Date:** Shall be Listed

WPS Number: Shall be listed **Supporting PQR Number:** Shall be Listed

Weliding Process(es): Shall be Listed

QW-402 Joints

Joint Design: Nonessential

Root Spacing: Nonessential

Backing: Yes or No Nonessential

Backing Material: Backing and Retainers Nonessential

> Nonessential variables must be recorded on the WPS.
>
> When listed on the PQR, ranges must be valid.

Drawings, sketches, or written descriptions show the general arrangement of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. Essential

Ø Group No. Supplementary

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

t Pass > 1/2 in. (13 mm) Essential

T limits (S. cir. arc) Essential

Filler Metals QW-404

Ø F-No. Essential

Ø A-No. Essential

Ø Electrode Diameter: Nonessential

Ø in electrode diameter > 1/4 inch (6 mm): Supplementary

Classification: Ø For Impact Testing Supplementary

± Filler metal or Ø Supplemental: Essential

Ø in Alloy elements: Essential

± Consumable insert: Nonessential

Ø Classification (SFA No.): Nonessential

Ø Filler metal product form: Essential

Ø t Deposited Weld Metal: Essential

ASME Section IX GMAW & FCAW WPS For Review (cont'd)

Positions QW-405

Position(s) of Groove: + addition — Nonessential

Ø Position(s): — Supplementary

Welding Progresstion: ↑↓ — Nonessential

Preheat QW-406

Decrease of >100°F (56°C): — Essential

Ø Preheat Maintenance: — Nonessential

Interpass Temperature, Increase of >100°F (56°C): — Supplementary

Post Weld Heat Treatment QW-407

Ø in PWHT: — Essential

Ø in PWHT Time and Temperature Range: — Supplementary

Gas QW-408

± Trail or Ø Composition: — Nonessential

Ø Single, mixture, or %: — Essential

Ø Shielding flow rate: — Nonessential

± or Ø Backingflow: — Nonessential

- Backing or Ø composition: — Essential

Ø Shielding or trailing: — Essential

Electrical Characteristics QW-409

> Heat Input: — Supplementary

Ø Transfer mode: — Essential

Ø Current and Polarity: — Nonessential

If Impact Testing: — Supplementary

Ø I & E Range / Amperage and Voltage Range: — Nonessential

ASME Section IX GMAW & FCAW WPS For Review (cont'd)

Technique QW-410

Ø String or Weave Bead: **Nonessential** **Ø Orifice, cup or nozzle size:** **Nonessential**

Ø Method Cleaning: **Nonessential** **Ø Method of Back Gouging:** **Nonessential**

Ø Multiple or Single Pass (per side): **Nonessential** **If Impact Tested:** **Supplementary**

Ø Single to multi electrodes: **Supplementary** **If Impact Tested:** **Supplementary**

Ø Manual or automatic: **Nonessential** **± Peening:** **Nonessential**

Ø Electrode spacing: **Nonessential**

Use of Thermal Process: *See QW-410.64 for applicability* **Essential**

C.5.3.2 Procedure Qualification Record

Sample ASME Section IX GMAW & FCAW PQR For Review

Per QW-200.2

Organization Name: Shall be Listed   Date: Shall be Listed

PQR Number: Shall be listed   WPS Number: Shall be Listed

Welding Process(es): Shall be Listed

Nonessential variables must be recored on the WPS.

When listed on the PQR actual nonessential variables, including ranges, must be used.

Base Metals QW-403

Ø P-No. Essential   Ø Group No. Supplementary

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

t Pass > 1/2 in. (13 mm) Essential   T limits (S. CIR. Arc) Essential

Filler Metals QW-404

Ø F-No. Essential   Ø A-No. Essential

Classification: Ø For Impact Testing Supplementary

± Filler Metal or Ø Supplemental: Essential   Ø Alloy elements: Essential

Ø Filler metal product form: Essential

Ø t Deposited weld metal: Essential

Positions QW-405

Ø Position(s): Supplementary

Preheat QW-406

Decrease of >100°F (56°C): Essential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

ASME Section IX GMAW & FCAW PQR For Review (cont'd)

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Gas QW-408

Ø Single, mixture, or %: Essential

- Backing or Ø composition: Essential

Ø Shielding or trailing: Essential

Electrical Characteristics QW-409

> Heat Input: Supplementary

Ø Transfer mode: Essential

Ø Current and Polarity: (If Impact Testing) Supplementary

Technique QW-410

Ø Multiple or Single Pass (per side): (If Impact Tested) Supplementary

Ø Single to multi electrodes: (If Impact Tested) Supplementary

Use of Thermal Process: *See QW-410.64 for applicability* Essential

Mechanical Test Results

PQR No: Shall be listed

Tensile Test QW-150 for proper number and type / Acceptance Criteria - Tension Test QW-153

Specimen No.	Width	Thickness	Area	Ultimate Load	Ultimate Unit Stress	Type of Failure Location
Tensile Tests shall be shown on the PQR with the actual test results						

ASME Section IX GMAW & FCAW PQR For Review (cont'd)

Mechanical Test Results (Cont'd)

Guided Bend Tests QW-160 for proper number and type / Accrptancre Criteria - Tension Test QW-163

Type and Figure No.	Results
Guided Bend Test shall be recorded with the actual test results	

Toughness Test QW- 170 for proper number and type / Acceptance Criteria - Tension Test QW-172.2

Specimen No.	Notch Location	Specimen Size	Test Temperature	Ft-lb or J	Impact Values % Shear	Mils (in.) or mm	Drop weight Break (Y/N)
Tensile Tests shall be shown on the PQR with the actual test results							

Welder Name: Shall be listed Clock No.: Shall be listed Stamp No. : Shall be listed

Test Conducted by: Shall be listed Lab Test No. : Shall be listed

We certify that the statements in this record are correct and the test welds were preapared, welded, and tested in accord with the requirements of *Applicable Test Code*.

Oranization: Shall be listed Date: Shall be listed

Certified by: Shall be signed

C.5.4 Submerged Arc Welding

C.5.4.1 Welding Procedure Specification

Sample ASME Section IX Submerged Arc Welding (SAW) WPS For Review

Per QW-200.1

Organization Name: Shall be Listed **Created By:** Shall be Listed **Date:** Shall be Listed

WPS Number: Shall be listed **Supporting PQR Number:** Shall be Listed

Weliding Process(es): Shall be Listed

QW-402 Joints

Joint Design: Nonessential

Root Spacing: Nonessential

Backing: Yes or No Nonessential

Backing Material: Backing and Retainers Nonessential

Nonessential variables must be recorded on the WPS.

When listed on the PQR, ranges must be valid.

Drawings, sketches, or written descriptions show the general arrangement of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. Essential

Ø Group No. Supplementary

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Deposited Weld Metal: (t) pass > 1/2 inch (13 mm) Essential

Filler Metals QW-404

F-No. Ø: Essential

A-No. Ø: Essential

Ø Electrode Diameter: Nonessential

Ø Flux / wire class: Essential

Ø Alloy Flux: Essential

± or Ø Supplemental filler metal: Essential

Ø Alloy elements: Essential

Ø Flux designation: Nonessential

Ø t Weld metal deposited: Essential

Ø Classification (SFA N0.): Nonessential

Ø Flux type: Essential

Ø Flux / wire class: (If Impact testing) Supplementary

Recrushed slag: Essential

ASME Section IX Submerged Arc Welding (SAW) WPS For Review (cont'd)

Positions QW-405

+ Addition position(s): Nonessential

Preheat QW-406

Decrease of >100°F (56°C): Essential

Ø Preheat Maintenance: Nonessential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Electrical Characteristics QW-409

> Heat Input: Supplementary

Ø Current and Polarity: Nonessential

If Impact Testing: Supplementary

Ø I & E Range / Amperage and Voltage Range: Nonessential

Technique QW-410

Ø String or Weave Bead: Nonessential

Ø Method Cleaning: Nonessential

Ø Method of Back Gouging: Nonessential

Ø Multiple or Single Pass (per side): Nonessential

If Impact Tested: Supplementary

Ø Electrofe Spacing: Nonessential

Ø Manual or Automatic: Nonessential

± Peening: Nonessential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

Sample ASME Section IX Submerged Arc Welding (SAW) PQR For Review

C.5.4.2 Procedure Qualification Record

Per QW-200.2

Organization Name: Shall be Listed — **Date:** Shall be Listed

PQR Number: Shall be listed — **WPS Number:** Shall be Listed

Welding Process(es): Shall be Listed

Nonessential variables must be recored on the WPS.

When listed on the PQR actual nonessential variables, including ranges, must be used.

Base Metals QW-403

Ø P-No. Essential — Ø Group No. Supplementary

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Deposited Weld Metal: (t) pass > 1/2 inch (13 mm) Essential

Filler Metals QW-404

Ø F-No. Essential — Ø A-No. Essential

Ø Flux / wire class: Essential — Ø Alloy Flux: Essential

± or Ø Supplemental filler metal: Essential — Ø Alloy elements: Essential

Ø Flux type: Essential — Ø t Weld metal deposited: Essential

Ø Flux / wire class: (If Impact testing) Supplementary — Recrushed slag: Essential

Preheat QW-406

Decrease of >100°F (56·C): Essential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

ASME Section IX Submerged Arc Welding (SAW) PQR For Review (cont'd)

Electrical Characteristics QW-409

> Heat Input: (If Impact Testing) Supplementary

Ø Current and Polarity: (If Impact Testing) Supplementary

Technique QW-410

Multiple or Single Pass (per side): (If Impact Testing) Supplementary

Ø Single to multi electrodes: (If Impact Testing) Supplementary

Use of Thermal Process: *See QW-410.64 for applicability* Essential

Mechanical Test Results

PQR No: Shall be listed

Tensile Test QW-150 for proper number and type / Acceptance Criteria - Tension Test QW-153

Specimen No.	Width	Thickness	Area	Ultimate Load	Ultimate Unit Stress	Type of Failure Location
Tensile Tests shall be shown on the PQR with the actual test results						

Guided Bend Tests QW-160 for proper number and type / Acceptance Criteria - Tension Test QW-163

Type and Figure No.	Results
Guided Bend Test shall be recorded with the actual test results	

Toughness Test QW- 170 for proper number and type / Acceptance Criteria - Tension Test QW-172.2

Specimen No.	Notch Location	Specimen Size	Test Temperature	Ft-lb or J	Impact Values % Shear	Mils (in.) or mm	Drop weight Break (Y/N)
Tensile Tests shall be shown on the PQR with the actual test results							

Welder Name: Shall be listed Clock No.: Shall be listed Stamp No. : Shall be listed

Test Conducted by: Shall be listed Lab Test No. : Shall be listed

We certify that the statements in this record are correct and the test welds were prepared, welded, and tested in accord with the requirements of ***<u>Applicable Test Code</u>***.

Organization: Shall be listed Date: Shall be listed

Certified by: Shall be signed

C.5.5 Stud Arc Welding

C.5.5.1 Welding Procedure Specification

Sample ASME Section IX Stud Welding (SW) WPS For Review

Per QW-200.1

Organization Name: Shall be Listed **Created By:** Shall be Listed **Date:** Shall be Listed

WPS Number: Shall be listed **Supporting PQR Number:** Shall be Listed

Weliding Process(es): Shall be Listed

QW-402 Joints

Ø Stud shape size: Essential

- Deletion of flux or ferrule: Essential

Nonessential variables must be recorded on the WPS.

When listed on the PQR, ranges must be valid.

Drawings, sketches, or written descriptions show the general arrangement of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø in base metal or stud metal P-No.: Essential

Positions QW-405

+ Addition position(s): Essential

Preheat QW-406

Decrease of >100°F (56°C): Essential

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Gas QW-408

Ø Single, mixture, or %: Essential

ASME Section IX Stud Welding (SW) WPS For Review (cont'd)

Electrical Characteristics QW-409

Ø in Current and Polarity: Essential

Ø in arc timing: Essential

Ø in amperage: Essential

Ø in power source: Essential

Technique QW-410

Ø in gun model or lift: Essential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

C.5.5.2 Procedure Qualification Record

Sample ASME Section IX Stud Welding (SW) PQR For Review

Per QW-200.2

Organization Name: Shall be Listed **Date: Shall be Listed**

PQR Number: Shall be listed **WPS Number: Shall be Listed**

Welding Process(es): Shall be Listed

Nonessential variables must be recored on the WPS.

When listed on the PQR actual nonessential variables, including ranges, must be used.

QW-402 Joints

Ø Stud shape size: Essential

- Deletion of flux or ferrule: Essential

Drawings, sketches, or written descriptions show the general arrangemsnt of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø in base metal or stud metal P-No.: Essential

Positions QW-405

+ Addition position(s): Essential

Preheat QW-406

Decrease of >100°F (56°C): Essential

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Gas QW-408

Ø Single, mixture, or %: Essential

ASME Section IX Stud Welding (SW) PQR For Review (cont'd)

Electrical Characteristics QW-409

Ø in Current and Polarity: Essential

Ø in arc timing: Essential

Ø in amperage: Essential

Ø in power source: Essential

Technique QW-410

Ø in gun model or lift: Essential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

Mechanical Test Results

PQR No: Shall be listed

Tensile Test QW-150 for proper number and type / Acceptance Criteria - Tension Test QW-153

Specimen No.	Width	Thickness	Area	Ultimate Load	Ultimate Unit Stress	Type of Failure Location
Tensile Tests shall be shown on the PQR with the actual test results						

Guided Bend Tests QW-160 for proper number and type / Acceptance Criteria - Tension Test QW-163

Type and Figure No.	Results
Guided Bend Test shall be recorded with the actual test results	

Toughness Test QW- 170 for proper number and type / Acceptance Criteria - Tension Test QW-172.2

Specimen No.	Notch Location	Specimen Size	Test Temperature	Ft-lb or J	Impact Values % Shear	Mils (in.) or mm	Drop weight Break (Y/N)
Tensile Tests shall be shown on the PQR with the actual test results							

Welder Name: Shall be listed Clock No.: Shall be listed Stamp No. : Shall be listed

Test Conducted by: Shall be listed Lab Test No. : Shall be listed

We certify that the statements in this record are correct and the test welds were prepared, welded, and tested in accord with the requirements of ***Applicable Test Code***.

Organization: Shall be listed Date: Shall be listed

Certified by: Shall be signed

C.5.6 Plasma Arc Welding

C.5.6.1 Welding Procedure Specification

Sample ASME Section IX Plasma Arc Welding (PAW) WPS For Review

Per QW-200.1

Organization Name: Shall be Listed Created By: Shall be Listed Date: Shall be Listed

WPS Number: Shall be listed Supporting PQR Number: Shall be Listed

Weliding Process(es): Shall be Listed

QW-402 Joints

Ø Joint Design: Supplementary

Ø Root Spacing: Nonessential

+ Backing: Yes or No Nonessential

Nonessential variables must be recorded on the WPS.

When listed on the PQR, ranges must be valid.

± **Backing Material:** Backing and Retainers Nonessential

Drawings, sketches, or written descriptions show the general arrangement of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. / melt in: Essential

Ø Group No. Supplementary

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Filler Metals QW-404

Ø F-No. Essential

Ø A-No. Essential

Ø Electrode Diameter: Nonessential

Classification: Ø For Impact Testing Supplementary

± Filler metal: Essential

± Consumable insert: Nonessential

Ø Classification (SFA No.): Nonessential

Ø Filler metal product form: Essential

Ø Alloy elements: Essential

Ø t Deposited Weld Metal: Essential

ASME Section IX Plasma Arc Welding (PAW) WPS For Review (cont'd)

Positions QW-405

+ Addition Position(s): Nonessential

Ø Position(s): Supplementary

Ø Welding Progresstion: ↑↓ Nonessential

Preheat QW-406

Decrease of >100°F (56°C): Essential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Gas QW-408

± Trail or Ø Composition%: Nonessential	Ø Composition: Essential
Ø Shielding flow rate: Nonessential	± or Ø Backingflow: Nonessential
- Backing or Ø composition: Essential	Ø Shielding or trailing: Essential

Electrical Characteristics QW-409

> Heat Input: Supplementary	± Pulsing Current: Nonessential
Ø Current and Polarity: Nonessential	If Impact Testing: Supplementary

Ø I & E Range / Amperage and Voltage Range: Nonessential

Ø Tungsten electrode: Nonessential

ASME Section IX Plasma Arc Welding (PAW) WPS For Review (cont'd)

Electrical Characteristics QW-409

> Heat Input: Supplementary **± Pulsing Current:** Nonessential

Ø Current and Polarity: Nonessential **If Impact Testing:** Supplementary

Ø I & E Range / Amperage and Voltage Range: Nonessential

Ø Tungsten electrode: Nonessential

Technique QW-410

Ø String or Weave Bead: Nonessential **Ø Orifice, cup, or nozzle size:** Nonessential

Ø Method Cleaning: Nonessential **Ø Method of Back Gouging:** Nonessential

Ø Osclillation: Nonessential **± Peening:** Nonessential

Ø Multiple or Single Pass (per side): Nonessential **If Impact Tested:** Supplementary

Ø Single to multi electrodes: **If Impact Tested:** Supplementary

Ø Closed to out chamber: Essential **Ø Electrode spacing:** Nonessential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

C.5.6.2 Procedure Qualification Record

Sample ASME Section IX Plasma Arc Welding (PAW) PQR For Review

Per QW-200.2

Organization Name: Shall be Listed | **Date: Shall be Listed**

PQR Number: Shall be listed | **WPS Number: Shall be Listed**

Welding Process(es): Shall be Listed

Nonessential variables must be recored on the WPS.

When listed on the PQR actual nonessential variables, including ranges, must be used.

QW-402 Joints

Ø Joint Design: Supplementary

Drawings, sketches, or written descriptions show the general arrangemsnt of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. / melt in: Essential | **Ø Group No. Supplementary**

Base Metal Thickness: (T) for impact testing Supplementary

Base Metal Thickness: Ø in (T) qualified Essential

Filler Metals QW-404

Ø F-No. Essential | **Ø A-No. Essential**

Classification: Ø For Impact Testing Supplementary | **± Filler metal: Essential**

± Consumable insert: Nonessential | **Ø Classification (SFA No.): Nonessential**

Ø Filler metal product form: Essential | **Ø Alloy elements: Essential**

Ø t Deposited Weld Metal: Essential

ASME Section IX Plasma Arc Welding (PAW) PQR For Review (cont'd)

Positions QW-405

Ø Position(s): Supplementary

Preheat QW-406

Decrease of >100°F (56°C): Essential

Interpass Temperature, Increase of >100°F (56°C): Supplementary

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Gas QW-408

Ø Composition: Essential

- Backing or Ø composition: Essential

Ø Shielding or trailing: Essential

Electrical Characteristics QW-409

> Heat Input: Supplementary

Ø Current and Polarity: If Impact Testing: Supplementary

Technique QW-410

Ø Multiple or Single Pass (per side): If Impact Tested: Supplementary

Ø Single to multi electrodes: If Impact Tested: Supplementary

Ø Closed to out chamber: Essential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

ASME Section IX Plasma Arc Welding (PAW) PQR For Review (cont'd)

Mechanical Test Results PQR No: Shall be listed

Tensile Test QW-150 for proper number and type / Acceptance Criteria - Tension Test QW-153

Specimen No.	Width	Thickness	Area	Ultimate Load	Ultimate Unit Stress	Type of Failure Location
Tensile Tests shall be shown on the PQR with the actual test results						

Guided Bend Tests QW-160 for proper number and type / Acceptance Criteria - Tension Test QW-163

Type and Figure No.	Results
Guided Bend Test shall be recorded with the actual test results	

Toughness Test QW- 170 for proper number and type / Acceptance Criteria - Tension Test QW-172.2

Specimen No.	Notch Location	Specimen Size	Test Temperature	Ft-lb or J	Impact Values % Shear	Mils (in.) or mm	Drop weight Break (Y/N)
Tensile Tests shall be shown on the PQR with the actual test results							

Welder Name: Shall be listed Clock No.: Shall be listed Stamp No. : Shall be listed

Test Conducted by: Shall be listed Lab Test No. : Shall be listed

We certify that the statements in this record are correct and the test welds were prepared, welded, and tested in accord with the requirements of ***Applicable Test Code***.

Organization: Shall be listed Date: Shall be listed

Certified by: Shall be signed

C.5.7 Electrogas Welding

C.5.7.1 Welding Procedure Specification

Sample ASME Section IX Electrogas (EGW) WPS For Review

Per QW-200.1

Organization Name: Shall be Listed Created By: Shall be Listed Date: Shall be Listed

WPS Number: Shall be listed Supporting PQR Number: Shall be Listed

Weliding Process(es): Shall be Listed

QW-402 Joints

Nonessential variables must be recorded on the WPS.

When listed on the PQR, ranges must be valid.

Joint Design: **Nonessential**

Root Spacing: **Nonessential**

Backing Material: Backing and Retainers **Essential**

Drawings, sketches, or written descriptions show the general arrangement of parts to be welded. A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. **Essential** Ø Group No. **Supplementary**

Base Metal Thickness: (T) for impact testing **Supplementary**

Base Metal Thickness: Ø in (T) qualified **Essential**

Deposited Weld Metal: (t) pass > 1/2 inch (13 mm) **Essential**

Filler Metals QW-404

Ø F-No. **Essential** Ø A-No. **Essential**

Ø Electrode Diameter: **Nonessential**

Classification: Ø For Impact Testing **Supplementary**

Ø Filler metal product form: **Essential**

Ø t Classification (SFA No.): **Nonessential**

ASME Section IX Electrogas (EGW) WPS For Review (cont'd)

Preheat QW-406

Decrease of >100°F (56°C): Nonessential

Post Weld Heat Treatment QW-407

Ø in PWHT: Essential

Ø in PWHT Time and Temperature Range: Supplementary

Gas QW-408

Ø Single, mixture, or %: Essential

Ø Shielding flow rate: Nonessential

Electrical Characteristics QW-409

>Heat Input: Essential

Ø Current and Polarity: Nonessential If Impact Testing: Supplementary

Ø I & E Range / Amperage and Voltage Range: Nonessential

Technique QW-410

Ø Method Cleaning: Nonessential

Ø Osclillation: Nonessential ± Peening: Nonessential

Ø Multiple or Single Pass (per side): Nonessential If Impact Tested: Supplementary

Ø Single to multi electrodes: Essential

Ø Electrode spacing: Nonessential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

C.5.7.2 Procedure Qualification Record

Sample ASME Section IX Electrogas (EGW) PQR For Review

Per QW-200.2

Organization Name: Shall be Listed **Date: Shall be Listed**

PQR Number: Shall be listed **WPS Number: Shall be Listed**

Welding Process(es): Shall be Listed

Nonessential variables must be recored on the WPS.

When listed on the PQR actual nonessential variables, including ranges, must be used.

QW-402 Joints

Nonessential variables must be recorded on the WPS.
When listed on the PQR, ranges must be valid.

Backing Material: Backing and Retainers **Essential**

Drawings, sketches, or written descriptions show the general arrangemsnt of parts to be welded.
A detailed drawing of weld groove may be specified but is not required

Base Metals QW-403

Ø P-No. **Essential** **Ø Group No.** **Supplementary**

Base Metal Thickness: (T) for impact testing **Supplementary**

Base Metal Thickness: Ø in (T) qualified **Essential**

Deposited Weld Metal: (t) pass > 1/2 inch (13 mm) **Essential**

Filler Metals QW-404

Ø F-No. **Essential** **Ø A-No.** **Essential**

Classification: Ø For Impact Testing **Supplementary**

Ø Filler metal product form: **Essential**

Post Weld Heat Treatment QW-407

Ø in PWHT: **Essential**

Ø in PWHT Time and Temperature Range: **Supplementary**

ASME Section IX Electrogas (EGW) PQR For Review (cont'd)

Gas QW-408

Ø Single, mixture, or %: Essential

Electrical Characteristics QW-409

>Heat Input: Essential

Ø Current and Polarity: If Impact Testing: Supplementary

Technique QW-410

Ø Multiple or Single Pass (per side): If Impact Tested: Supplementary

Ø Single to multi electrodes: Essential

Use of Thermal Process: *See QW-410.64 for applicability* Essential

Mechanical Test Results

PQR No: Shall be listed

Tensile Test QW-150 for proper number and type / Acceptance Criteria - Tension Test QW-153

Specimen No.	Width	Thickness	Area	Ultimate Load	Ultimate Unit Stress	Type of Failure Location
Tensile Tests shall be shown on the PQR with the actual test results						

Guided Bend Tests QW-160 for proper number and type / Acceptance Criteria - Tension Test QW-163

Type and Figure No.	Results
Guided Bend Test shall be recorded with the actual test results	

Toughness Test QW- 170 for proper number and type / Acceptance Criteria - Tension Test QW-172.2

Specimen No.	Notch Location	Specimen Size	Test Temperature	Ft-lb or J	Impact Values % Shear	Mils (in.) or mm	Drop weight Break (Y/N)
Tensile Tests shall be shown on the PQR with the actual test results							

Welder Name: Shall be listed Clock No.: Shall be listed Stamp No. : Shall be listed

Test Conducted by: Shall be listed Lab Test No. : Shall be listed

We certify that the statements in this record are correct and the test welds were prepared, welded, and tested in accord with the requirements of ***Applicable Test Code***.

Organization: Shall be listed Date: Shall be listed

Certified by: Shall be signed

Annex D
(normative)

Guide to Common Filler Metal Selection

Tables D.1 and D.2 provide generally accepted electrode selections for the base materials shown. They do not attempt to include all possible choices. Welding consumables not shown for a particular combination of base materials should be approved by the purchaser.

Table D.1—Common Welding Consumables for SMAW of Carbon and Low-Alloy Steel

Base Material[1,2,4]	**Carbon Steel**	**Carbon-Molybdenum Steel**	**1&11/4 CR-1/2 MO Steel**	**21/4 CR-1 Mo Steel**	**5CR-1/2 Mo Steel**	**9Cr-1 Mo Steel**	**21/4 Nickel Steel**	**31/2 Nickel Steel**	**9 % Nickel Steel**
Carbon Steel	AB[3]	AC	AD	AE	AF	AG	AJ	AK	*
Carbon-Molybdenum Steel		C	CD	CE	CF	CH	*	*	*
1&1^1/4 CR-^{1}/2 MO Steel			D	DE	DF	DH	*	*	*
2^1/4 CR-1 Mo Steel				E	EF	EH	*	*	*
5CR-^{1}/2 Mo Steel					F	FH	*	*	*
9Cr-1 Mo Steel						H	*	*	*
2^1/4 Nickel Steel							J	JK	LM
3^1/2 Nickel Steel								K	LM
9 % Nickel Steel									LM

*An unlikely or unsuitable combination. Consult the purchaser if this combination is needed.

Legend

- A AWS A5.1 Classification E70XX low hydrogen[5]
- B AWS A5.1 Classification E6010 for root pass[5]
- C AWS A5.5 Classification E70XX-A1, low hydrogen
- D AWS A5.5 Classification E70XX-B2L or E80XX-B2, low hydrogen
- E AWS A5.5 Classification E80XX-B3L or E90XX-B3, low hydrogen
- F AWS A5.5 Classification E80XX-B6 or E80XX-B6L, low hydrogen
- G AWS A5.5 Classification E80XX-B7 or E80XX-B7L, low hydrogen
- H AWS A5.5 Classification E80XX-B8 or E80XX-B8L, low hydrogen
- J AWS A5.5 Classification E80XX-C1 or E70XX-C1L, low hydrogen
- K AWS A5.5 Classification E80XX-C2 or E70XXC2L, low hydrogen
- L AWS A5.11 Classification ENiCrMo-3
- M AWS A5.11 Classification ENiCrMo-6

1 Table D.1 refers to coated electrodes. For bare wire welding (SAW, GMAW, GTAW), use equivalent electrode classifications (AWS A5.14, A5.17, A5.18, A5.20, A5.23, A5.28). Refer to the text for information on other processes.

2 Higher alloy electrode specified in the table should normally be used to meet the required tensile strength or toughness after postweld heat treatment. The lower alloy electrode specified may be required in some applications to meet weld metal hardness requirements.

3 Other E60XX and E70XX welding electrodes may be used if approved by the purchaser.

4 This table does not cover modified versions of Cr-Mo alloys.

5 See API 582, Section 6.1.3.

Table D.2—Common Welding Consumables for SMAW of Carbon and Low-Alloy Steel

Base Material[1,2,3]	Type 405 Stainless Steel	Type 410S Stainless Steel	Type 410 Stainless Steel	Type 304 Stainless Steel	Type 304L Stainless Steel	Type 304H Stainless Steel	Type 310 Stainless Steel	Type 316 Stainless Steel	Type 316L Stainless Steel	Type 317L Stainless Steel	Type 321 Stainless Steel	Type 347 Stainless Steel
Carbon and Low-alloy Steel	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 405 Stainless Steel	ABC	ABC	ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 410S Stainless Steel		ABC	ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 410 Stainless Steel			ABC	AB	AB	AB	AB	AB	AB	AB	AB	AB
Type 304 Stainless Steel				D	DH	DJ	A	DF	DGH	DI	DE	DE
Type 304L Stainless Steel					H	DHJ	A	DF	GH	HI	DE	DE
Type 304H Stainless Steel						J	A	DFJ	DGHJ	DIJ	DEJ	EJ
Type 310 Stainless Steel							K	AK	A	A	A	A
Type 316 Stainless Steel								F	FG	FI	EF	EF
Type 316L Stainless Steel									G	GI	EG	EG
Type 317L Stainless Steel										I	EI	EI
Type 321 Stainless Steel											E	E
Type 347 Stainless Steel												E

Legend

- A AWS A5.4 Classification E309-XX
- B AWS A5.11 Classification ENiCrFe-2 or-3[4]
- C AWS A5.4 Classification E410-XX [(0.05 % C max. and heat treatment @ 1400 °F (760 ° C) required]
- D AWS A5.4 Classification E308-XX
- E AWS A5.4 Classification E347-XX
- F AWS A5.4 Classification E316-XX
- G AWS A5.4 Classification E316L-XX
- H AWS A5.4 Classification E308L-XX
- I AWS A5.4 Classification E317L-XX
- J AWS A5.4 Classification E308H-XX
- K AWS A5.4 Classification E310-XX

[1] Table D.2 refers to coated electrodes. For bare wire welding (SAW, GMAW, GTAW), use equivalent electrode classifications (AWS A5.9, A5.14). Refer to the text for information on other processes.

[2] The higher alloy electrode specified in the table is normally preferred.

[3] See API 582, Section 6.3, for weld metal delta ferrite requirements.

[4] See API 582, Section 6.2.2, for the temperature limitation for nickel-based filler metals.

Table D.3—Copper-Nickel and Nickel-Based Alloys

Base Material[1]	70-30 and 90-10 Cu-Ni	Alloy 400 (N04400)	Nickel 200 (N02200)	Alloy 800 (N08800), 800H (N08810), 800HT (N08811)	Alloy 600 (N066000)	Alloy 625 (N06625)	Alloy 825 (N08825)	Alloy C-22 (N-06022)	Alloy C-276 (N10276)	Alloy B-2 (N10665), B-3 (N10675)	Alloy G-3 (N06985)	Alloy G-30 (N06030)
Carbon and Low-alloy Steel	BC	BC	C	A	A	A	A	D	E	F	G	H
300-Series Stainless Steel	BC	AC	AC	A	A	A	A	D	E	F	G	H
400-Series Stainless Steel	B	B	AC	A	A	A	A	D	E	F	G	H
70-30 and 90-10 Cu-Ni	B	B	C	C	C	C	C	*	*	*	*	*
Alloy 400 (N04400)		B	BC	A	A	A	A	A	A	F	A	A
Nickel 200 (N02200)			C	AC	AC	AC	AC	CD	CE	CF	CG	CH
Alloy 800 (N08800), 800H (N08810), 800HT (N08811)				KJ	A	A	A	DJ	EJ	FJ	GJ	HJ
Alloy 600 (N066000)					A	AJ	A	DJ	EJ	FJ	GJ	HJ
Alloy 625 (N06625)						J	J	DJ	EJ	FJ	GJ	HJ
Alloy 825 (N08825)							J	DJ	EJ	FJ	GJ	HJ
Alloy C-22 (N-06022)								D	EJ	FJ	GJ	HJ
Alloy C-276 (N10276)									E	FJ	GJ	HJ
Alloy B-2 (N10665), B-3 (N10675)										I	GJL	HJL
Alloy G-3 (N06985)											G	HJ
Alloy G-30 (N06030)												H

*An unlikely or unsuitable combination. Consult the purchaser if this combination is needed.

Legend

- A AWS A5.11 Classification ENiCrFe-2 or-3
- B AWS A5.11 Classification ENiCu-7
- C AWS A5.11 Classification ENi-1
- D AWS A5.11 Classification ENiCrMo-10
- E AWS A5.11 Classification ENiCrMo-4
- F AWS A5.11 Classification ENiMo-7
- G AWS A5.11 Classification ENiCrMo-9
- H AWS A5.11 Classification ENiCrMo-11
- I AWS A5.11 Classification ENiMo-10
- J AWS A5.11 Classification ENiCrMo-3
- K AWS A5.11 Classification ENiCrCoMo-1
- L AWS A5.11 Classification ENiCrMo-10 or -17

[1] Table D.3 refers to coated electrodes. For bare wire welding (SAW, GMAW, GTAW), use equivalent electrode classifications (AWS A5.14). Refer to the text for information on other processes.

Table D.4—Classification Changes in Low-Alloy Filler Metal Designations

Material	ASME P-Number (Typical)	New (Current) AWS Filler Number		Old Filler Metal Designation	
		SMAW	GTAW	SMAW	GTAW
C-1/2 Mo	3	E7018-A1	ER70S-A1, or ER80S-D2	E7018-A1	N/A ER80S-D2
1Cr-1/2 Mo and 1 1/4 Cr-0.5 Mo	4	E7018-B2L E8018-B2	ER70S-B2L ER80S-B2	E8018-B2L E8018-B2	ER80S-B2L ER80S-B2
2 1/4 Cr-1 Mo	5A	E8018-B3L E9018-B3	ER80S-B3L ER90S-B3	E9018-B3L E9018-B3	ER90S-B3L ER90S-B3
5Cr-1/2 Mo	5B	E8018-B6 E8018-B6L	ER80S-B6	E502-XX E502-XX	ER502
9Cr-1 Mo	5B	E8018-B8 E8018-B8L	ER80S-B6	E505-XX E505-XX	ER505
Cr-1Mo-1/4V	5B	E9018-B9	ER90S-B9	N/A	N/A

Annex E
(informative)

Example Report of RT Results

RADIOGRAPHIC INSPECTION REPORT

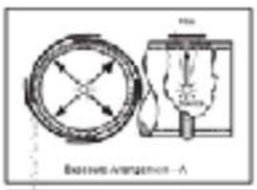
Report No.		Technique
Client	Purchase Order Number	Job Number
Project	Location	Date of Radiography

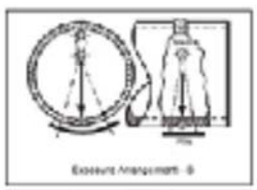
Component and Specification Data

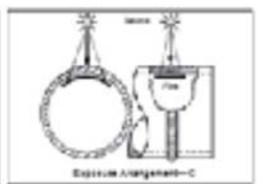
Component/System		Type of Weld New __ Repair __ R# __		Stage of Welding Root __ Intermediate __ Final __	
Material Type	Single Wall Thk.	Avg. Reinforcement	Backing Thickness	Thickness Range	Weld Process
Examination Specification		Acceptance Std. Class		RT Procedure Revs.	

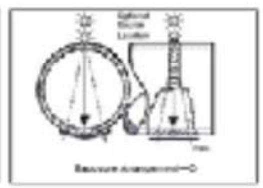
Technique Data

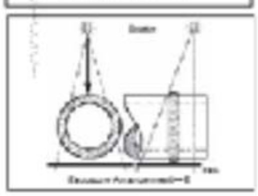
IQI Type		IQI Designation	IQI Material	Sensitivity Required Obtained		IQI Location Film Side __ Source __ Sinepair __	
IQI Selection Based on		IQI on Part Block(s) __	Shim(s) Block(s) Material and Thickness	__ & or __ __ S/S	__ X-ray __ Ir 192 __ Co. 60	Screen Thickness Front 0.10" Center-back .010"	
SFD	SOD	OFD	Focal Size	μG	Film Type(s)	No. Film in Cassette	Film Size
KV	Ma-Curies	Exp. Time	Film Processing __ Automatic __ Manual	Manual Process Time __ Temp __		Radiographic Technique A B C D E F G or RSS Attached	

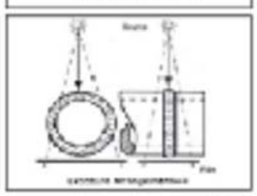

Exposure Arrangement—A


Exposure Arrangement—B


Exposure Arrangement—C


Exposure Arrangement—D


Exposure Arrangement—E


Exposure Arrangement—F

Interpretation Data

Radiograph Identification	Radiograph Location	Accept	Reject	N.A.D.	Surface Cond.	*Discontinuity Code	# of Film	Single Viewing	Composite Viewing	IQI Density	Density Area	Location and Size of Conditions	
													1
													2
													3
													4
													5
													6
													7
													8

Examiner ____ *Level* ____ *Date* ____ *Client Reviewer* ____ *Level* ____ *Date* ____

Examiner ____ *Level* ____ *Date* ____ *Client Reviewer* ____ *Level* ____ *Date* ____

***Discontinuity Code (Circle Reject Conditions)**

1 Porosity
2 Slag Inclusion
3 Tungsten Inclusion
4 Lack of Fusion
5 Lack of Penetration
6 Crack
7 Burn Through
8 Hollow Bead
9 Concave Root
10 Convex Root
11 Inside Undercut
12 Outside Undercut
13 High Low
14 Low Crown
15 Drop Through
16 Whisker
17 Oxidation

NAD—No Apparent Discontinuities
Ug—Geometric Unsharpness
SFD—Source to Film Distance
SOD—Source to Object Distance
OFD—Object to Film Distance

Annex F
(informative)

Inspection Considerations

F.1 Potential Actions by Inspector at Various Stages of the Work Preparation and Execution

F.1.1 Drawings, Codes, and Standards

— Identify and clarify missing details and information.

— Identify and clarify missing weld sizes, dimensions, tests, and any additional requirements.

— Identify and clarify inconsistencies with standards, codes, and specification requirements.

— Highlight potential weld problems not addressed in the design.

— Establish applicable accept/reject criteria.

— Verify that the appropriate type/degree of NDE has been specified.

F.1.2 Welding Procedures and Qualification Records

— Obtain acceptable WPS(s) and PQR(s) for the work.

— Qualify WPS(s) where required and witness qualification effort.

— Qualify or requalify welders where required and witness a percentage of the welder qualifications.

F.1.3 Quality Control

— Highlight deficiencies and concerns with the organizations to appropriate personnel.

— Welding procedure and qualification records that should be reviewed include the following:

a) Review the WPS(s), including those developed for making repairs, are properly qualified and meet applicable codes, standards and specifications for the work.

b) Review that PQRs are properly performed and support the WPS(s).

c) Review that WPQs meet requirements for the WPS(s).

F.1.4 NDE Information

— Identify and correct deficiencies in certifications and procedures.

— Obtain calibrated equipment.

F.1.5 Welding Equipment and Instruments

— Confirm welding equipment and instruments are calibrated and operable.

— Confirm welding machine calibration is current.

- Instruments such as ammeters, voltmeters, and contact pyrometers, have current calibrations.
- Storage ovens for welding consumables operate with automatic heat control and visible temperature indication.
- Confirm recalibration of equipment and instruments.
- Confirm replacement of defective equipment and instruments.

F.1.6 Materials

- Reject nontraceable or improperly marked materials.
- Reject and quarantine inappropriate materials and consumables.

F.1.7 Weld Preparation

- Identify and correct deficiencies in the preheat operations.
- Ensure preheat is applied to remove moisture, if required.
- Ensure preheat equipment and technique are acceptable.
- Ensure preheat coverage and temperature are correct.
- Ensure reheat applied as required.

F.1.8 NDE Review

- Require additional NDE to address deficiencies in findings.
- Check joints for delayed cracking of thick section, highly constrained and high strength material joining.
- Repeat missing or unacceptable examinations.
- Correct discrepancies.

F.1.9 Documentation Audit

- Require additional inspection verifications to address deficiencies in findings.
- Repeat missing or unacceptable examinations.
- Correct discrepancies in examination records.

Annex G
(informative)

Welding Safety

Inspectors should be aware of the hazards associated with welding and take appropriate steps to prevent injury while performing inspection tasks. As a minimum, the site's safety rules and regulations should be reviewed as applicable to welding operations.

Protective clothing, eye protection (hoods, goggles, and safety glasses as appropriate), gloves, and proper ventilation should all be used. Important to consider are the health hazards associated with potentially toxic effects of burning or welding on coatings such as zinc or cadmium, or welding on metals with iron fluoride scale still intact.

Safety material datasheets should be referenced to determine the allowable inhalation limits of the consumables, base metal, and coatings involved in any welding or cutting operation. The use of gas-shielded processes in confined spaces can create an oxygen-deficient environment. Ventilation practice in these instances should be carefully reviewed and appropriate atmosphere monitoring device(s) should be employed.

Electric shock can kill. All personnel that are directly or indirectly exposed to welding operations should be trained to avoid shock. Unexplained shocks should be reported to the supervisor for investigation and correction prior to continuing.

There are many publications covering welding safety available. The following list contains some resources that may be helpful.

API Recommended Practice 2201, *Procedures for Welding or Hot Tapping on Equipment in Service*

AWS ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*

AWS AWS-2000, *Arc Welding and Cutting Safety (Pamphlets)*

AWS CAWF, *Characterization of Arc Welding Fumes*

AWS EWH, *Effects of Welding on Health (I through VIII)*

AWS F2.2, *Lens Shade Selector*

AWS F3.2M/F3.2, *Ventilation Guide for Weld Fumes*

AWS FSW, *Fire Safety in Welding and Cutting (Pamphlets)*

AWS, *Fumes and Gases in the Welding Environment*

AWS SGSH, *The Independent Shop's Guide to Welding Safety and Health*

AWS SP, *Safe Practices*

AWS WZC D19.0, *Welding Zinc-Coated Steels*

Safety Videos published by Welding Supply or Safety Training companies

Bibliography

The following codes and standards are not referenced directly in this RP. Familiarity with these documents may be useful to the welding engineer or inspector as they provide additional information pertaining to this RP. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

[1] API Recommended Practice 572, *Inspection of Pressure Vessels*

[2] API Standard 650, *Welded Steel Tanks for Oil Storage*

[3] API Standard 653, *Tank Inspection, Repair, Alteration, and Reconstruction*

[4] API Standard 1104, *Welding of Pipelines and Related Facilities*

[5] API Publication 2207, *Preparing Tank Bottoms for Hot Work*

[6] API Publication 2217A, *Guidelines for Work in Inert Confined Spaces in the Petroleum Industry*

[7] ASME Boiler and Pressure Vessel Code, Section VIII, *Rules for Construction of Pressure Vessels*

[8] ASME Boiler and Pressure Vessel Code, Section IX, *Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*

[9] ASME Boiler and Pressure Vessel Code, Section XI, *Rules for In-service Inspection of Nuclear Power Plant Components*

[10] ASME B16.5, *Pipe Flanges and Flanged Fittings*

[11] ASME B16.9, *Factory-Made Wrought Steel Buttwelding Fittings*

[12] ASME B16.34, *Valves—Flanged, Threaded, and Welding End*

[13] ASME B31.1, *Power Piping*

[14] ASME B31.4, *Pipeline Transportation Systems for Liquids and Slurries*

[15] ASME B31.8, *Gas Transmission and Distribution Piping Systems*

[16] ASTM A106, *Standard Specification for Seamless Carbon Steel Pipe for High-Temperature Service*

[17] ASTM A335, *Standard Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service*

[18] AWS A2.4, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*

[19] AWS A3.0, *Standard Welding Terms and Definitions*

[20] AWS B1.10, *Guide for the Nondestructive Inspection of Welds*

[21] AWS JWE, *Jefferson's Welding Encyclopedia*

[22] AWS CM-00, *Certification Manual for Welding Inspectors*

[23] CASTI [14], *Guidebook to ASME Section IX—Welding Qualifications*

[24] Construction Safety Consensus Guidelines CS-S-9, INGAA Foundation [15], *Pressure Testing (Hydrostatic/Pneumatic) Safety Guidelines*

[25] EN 473 [16], *Qualification and Certification of NDT Personnel—General Principles*

[26] HSE Guidance Note GS4 [17], *Safety requirements for pressure testing*

[27] IADC [18]

[28] MCAA [19], *Guide to Pressure Testing Safety*

[29] NB-23 [20], *National Board Inspection Code*

[14] CASTI Publishing, Inc. 10566, 114 Street, Edmonton, Alberta, T5H 3J7, Canada.

[15] Interstate Natural Gas Association of America, 20 F Street, NW, Suite 450, Washington, DC 20001, www.ingaa.org.

[16] European Committee for Standardization, Avenue Marnix 17, B-1000, Brussels, Belgium, www.cen.eu.

[17] Health and Safety Executive, Regrave Court, Merton Road, Bootle, Merseyside L20 7HS, www.hse.gov.uk.

[18] International Association of Drilling Contractors, 3657 Briarpark Drive, #200, Houston, Texas 77042, www.iacdlexicon.org

[19] Mechanical Contractors Association of America, 1385 Piccard Drive, Rockville, Maryland 20850, www.mcaa.org.

[20] National Board of Boiler and Pressure Vessel Inspectors, 1055 Crupper Avenue, Columbus, Ohio 43229, www.nationalboard.org.

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