API RECOMMENDED PRACTICE 577 FIRST EDITION, OCTOBER 2004
Welding Inspection and Metallurgy

1 Scope
API 577 provides guidance on welding inspection pertaining to fabrication and repair of refinery and chemical plant equipment and piping and to aid the inspector in fulfilling their role implementing API 510, API 570, API Std. 653 and API RP 582.

API 577 does not require all welds to be inspected or the specific techniques to be used. A welding engineer should be consulted on any critical, specialized or complex welding issues.

2 Reference Codes and Standards
Many codes and standards are referenced in API 577 users should always insure they have the most recent revision available or the specific revision dictated by the contract.
<u>API Documents</u>

- API 510- Pressure Vessel Inspection Code
- API 577- Piping Inspection Code
- API RP 578- Material Verification Program for New and Existing Alloy Piping Systems
- API RP 582- Recommended Practice, Supplementary Welding Guidelines for Chemical, Oil, and Gas Industries
- API Std. 570- Welded Steel Tanks for Oil Storage
- API Std. 653- Tank Inspection, Repair, Alteration, and Reconstruction
- API Publ. 2201- Procedures for Welding or Hot Tapping on Equipment in Service

<u>ASME Documents</u>

- B31.3 Process Piping
- BPV Code Section V, Nondestructive Examination
- BPV Code Section VIII, Rules for Construction of Pressure Vessels
- BPV Code Section IX, Qualification Standard for Welding and Brazing (WPS, BPS, Welder, Brazer, Operator)

<u>ASNT Documents</u>

- ACCP- Central Certification Program
- ASNT-TC-1A- Personnel Qualification and Certification in Nondestructive Testing
- ASNT-CP-189- Standard for Qualification and Certification of Nondestructive Testing Personnel

<u>AWS Documents</u>

- AWS A2.4- Standard Symbols for Welding, Brazing, and Nondestructive Examination
- AWS A3.0- Standard Welding Terms and Definitions
- AWS A5.1 thru 5.34- Series of Filler Metal Specifications
- AWS B1.10- Guide for the Nondestructive Inspection of Welds

<u>Other documents are recommended for study</u>

3 Terms and Definitions
The following definitions apply for the purposes of this publication:
<u>Actual throat:</u> The shortest distance between the weld root and the face of a fillet weld.

<u>Air carbon arc cutting (CAC-A):</u> A carbon arc cut-ting process variation that removes molten metal with a jet of air.

<u>Arc blow:</u> The deflection of an arc from its normal path because of magnetic forces.

<u>Arc length:</u> The distance from the tip of the welding electrode to the adjacent surface of the weld pool.

Arc strike: A discontinuity resulting from an arc, consisting of any localized re-melted metal, heat-affected metal, or change in the surface profile of any metal object.

Arc welding (AW): A group of welding processes that produces coalescence of work pieces by heating them with an arc. The processes are used with or without the application of pressure and with or without filler metal.

Autogenous weld: A fusion weld made without filler metal.

Back-gouging: The 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.

Backing: A material or device placed against the back-side of the joint, or at both sides of a weld in welding, to sup-port and retain molten weld metal.

Base metal: The metal or alloy that is welded or cut.

Bevel angle: The angle between the bevel of a joint member and a plane perpendicular to the surface of the member.

Burn-through: A non-standard term for excessive visible root reinforcement in a joint welded from one side or a hole through the root bead. Also, a common term used to reflect the act of penetrating a thin component with the welding arc while hot tap welding or in-service welding.

Constant current power supply: An arc welding power source with a volt-ampere relationship yielding a small welding current change from a large arc voltage change. (SMAW/GTAW)

Constant voltage power supply: An arc welding power source with a volt-ampere relationship yielding a large welding current change from a small voltage change. (GMAW/FCAW)

Crack: A fracture type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement.

Defect: A discontinuity or discontinuities that by nature or accumulated effect (for example total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications. The term designates rejectability.

Direct current electrode negative (DCEN): The arrangement of direct current arc welding leads in which the electrode is the negative pole and workpiece is the positive pole of the welding arc. Commonly known as straight polarity.

Direct current electrode positive (DCEP): The 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. Commonly known as reverse polarity.

Discontinuity: An interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics. A dis-continuity is not necessarily a defect.

Distortion: The change in shape or dimensions, temporary or permanent, of a part as a result of heating or welding.

Filler metal: The metal or alloy to be added in making a welded joint.

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.

Fusion line: A non-standard term for weld interface.

Groove angle: The total included angle of the groove between workpieces.

Heat affected zone (HAZ): The portion of the base metal whose mechanical properties or microstructure have been altered by the heat of welding or thermal cutting.

Heat input: the energy supplied by the welding arc to the workpiece. Heat input is calculated as follows: heat input = $(V \times i)/60v$, where V = voltage, i = amperage, v =weld travel speed (in./min.)

Hot cracking: Cracking formed at temperatures near the completion of solidification.

Inclusion: Entrapped foreign solid material, such as slag, flux, tungsten, or oxide.

Incomplete fusion: A weld discontinuity in which complete coalescence did not occur between weld metal and fusion faces or adjoining weld beads.

Incomplete joint penetration: A joint root condition in a groove weld in which weld metal does not extend through the joint thickness.

Inspector: An individual who is qualified and certified to perform inspections under the proper inspection code or who holds a valid and current National Board Commission.

Interpass temperature, welding: In multi-pass weld, the temperature of the weld area between weld passes.

IQI: Image quality indicator. "Penetrameter" is another common term for IQI.

Joint penetration: The distance the weld metal extends from the weld face into a joint, exclusive of weld reinforcement.

Joint type: A weld joint classification based on five basic joint configurations such as a butt joint, corner joint, edge joint, lap joint, and t-joint.

Lack of fusion (LOF): A non-standard term indicating a weld discontinuity in which fusion did not occur between weld metal and fusion faces or adjoining weld beads.

Lamellar tear: A 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 metal weakened by the presence of small dispersed, planar shaped, nonmetallic inclusions parallel to the metal surface.

Lamination: A type of discontinuity with separation or weakness generally aligned parallel to the worked surface of a metal.

Linear discontinuity: A discontinuity with a length that is substantially greater than its width.

Longitudinal crack: A crack with its major axis orientation approximately parallel to the weld axis.

Nondestructive examination (NDE): The act of determining the suitability of some material or component for its intended purpose using techniques that do not affect its serviceability.

Overlap: The protrusion of weld metal beyond the weld toe or weld root.

Oxyacetylene cutting (OFC-A): An oxygen gas cutting process variation that uses acetylene as the fuel gas.

PMI (Positive Materials Identification): Any physical evaluation or test of a material (electrode, wire, flux, weld deposit, base metal, etc.), which has been or will be placed into service, to demonstrate it is consistent with the selected or specified alloy material designated by the owner/user. These evaluations or tests may provide either qualitative or quantitative information that is sufficient to verify the nominal alloy composition.

Peening: The mechanical working of metals using impact blows.

Penetrameter: Old terminology for IQI still in use today but not recognized by the codes and standards.

Porosity: Cavity-type discontinuities formed by gas entrapment during solidification or in thermal spray deposit.

Preheat: Metal temperature value achieved in a base metal or substrate prior to initiating the thermal operations.

Recordable indication: Recording on a data sheet of an indication or condition that does not necessarily exceed the rejection criteria but in terms of code, contract or procedure will be documented.

Reportable indication: Recording on a data sheet of an indication that exceeds the reject flaw size criteria and needs not only documentation, but also notification to the appropriate authority to be corrected. All reportable indications are recordable indications but not vice-versa.

Root face: The portion of the groove face within the joint root.

Root opening: A separation at the joint root between the workpieces.

Shielding gas: Protective gas used to prevent or reduce atmospheric contamination.

Slag: A nonmetallic product resulting from the mutual dissolution of flux and nonmetallic impurities in some welding and brazing processes.

Slag inclusion: A discontinuity consisting of slag entrapped in the weld metal or at the weld interface.

Spatter: The metal particles expelled during fusion welding that do not form a part of the weld.

Tack weld: A weld made to hold the parts of a weldment in proper alignment until the final welds are made.

Throat theoretical: The 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. This dimension is based on the assumption that the root opening is equal to zero.

Transverse crack: A crack with its major axis oriented approximately perpendicular to the weld axis.

Travel angle: The angle less than 90 degrees between the electrode axis and a line perpendicular to the weld axis, in a plane determined by the electrode axis and the weld axis.

Tungsten inclusion: A discontinuity consisting of tungsten entrapped in weld metal.

Undercut: A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.

Underfill: A condition in which the weld joint is incompletely filled when compared to the intended design.

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

Welding: A joining process that produces coalescence of base metals 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.

Welding engineer: An individual who holds an engineering degree and is knowledgeable and experienced in the engineering disciplines associated with welding.

Weldment: An assembly whose component parts are joined by welding.

Weld joint: The junction of members or the edges of members which are to be joined or have been joined by welding.

Weld reinforcement: Weld metal in excess of the quantity required to fill a joint.

Weld toe: The junction of the weld face and the base metal.

4 Welding Inspection

4.1 General

Welding inspection includes much more than visual inspection or non-destructive examination of the completed weld. Other issues are important, such as review of specifications, joint design, cleaning procedures, the development and qualification of welding procedures and welder qualification.

Welding inspection activities can be separated into three stages corresponding to the welding work process.

- Tasks performed prior to welding
- Tasks performed during welding
- Tasks performed upon completion of welding

4.2 Tasks performed prior to welding

1. Review drawings, standards, codes, and specifications
2. Review requirements for the weldment with the personnel involved
3. Review the WPS(s) and welder performance qualification record(s) (WPQ) to assure they are acceptable for the work.
4. Confirm the NDE examiner(s), procedure(s) and equipment of the inspection organization are acceptable for the work.
5. Confirm welding equipment and instruments are calibrated and operate.
6. Confirm heat treatment and pressure testing procedures and associated equipment are acceptable.
7. Ensure all filler metals, base materials, and backing ring materials are properly marked and identified and if required, perform PMI to verify the material composition.
8. Confirm weld preparation, joint fit-up, and dimensions are acceptable and correct.
9. Confirm the preheat equipment and temperature.
10. Confirm electrode, filler wire, fluxes, and inert gases are as specified and acceptable.

4.3 Tasks performed during welding

1. Establish a quality assurance and quality control umbrella with the welding organization.
2. Confirm welding parameters and techniques are supported by the WPS and WPQ.
3. Complete physical checks, visual examination, and in-process NDE.

4.4 Tasks performed upon completion of welding

1. Verify post-weld acceptance, appearance and finishing of the welded joints.
2. Verify NDE is performed at selected locations and review examiner's findings.
3. Verify post-weld heat treatment is performed to the procedure and produces acceptable results.
4. Verify pressure test is performed to the procedure.
5. Perform a final audit of the inspection dossier to identify inaccuracies and incomplete information.

4.5 Non-conformances and Defects

At any time during the welding inspection, if defects or non-conformances are identified, they should be brought to the attention of those responsible for the work or corrected before welding proceeds further.

Defects should be completely removed and re-inspected following the same tasks outlined in this section until the weld is found to be acceptable.

Corrective action for a non-conformance will depend upon the nature of the non-conformance and its impact on the properties of the weldment. Corrective action may include reworking the weld.

4.6 NDE Examiner Certification

The referencing codes or standards may require that an examiner be qualified in accordance with a specific code and certified as meeting the requirements.

ASME Section V, Article 1, when specified by the referencing code, requires NDE personnel be qualified with one of the following:

a. ASNT SNT-TC-1A

b. ANSI/ASNT CP-189

The employer must develop and establish a written practice or procedure that details the employer's requirements for certification of personnel.

a. Training, experience and examination prerequisites prior to certification
b. Recertification requirements.

4.7 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.

Hazards commonly encountered include:

Arc radiation	Air contamination
Airborne debris	Heat
Ultraviolet and infrared light	Sparks

PPE and preventative measures includes:

eye protection using proper filters
proper clothing to cover the skin
Proper ventilation
filtered breathing protection

5 Welding Processes

5.1 GENERAL

The API 577 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 Arc Welding (SW)

In all of the above processes, the inspector should be familiar with:

- The basic principles of operation, equipment, torches, gases and electrical characteristics
- Classification and Specification of electrodes and filler metal
- The advantages and limitations of each process

5.2 SHIELDED METAL ARC WELDING (SMAW)

SMAW is the most widely used of the various arc welding processes. Some of the process characteristics should be familiar to the API 577 inspector, like when to use alternating current (ac) or direct current (dc) and the significance of the flux covering on the electrode.

Some commonly accepted advantages of the SMAW process include:

- Equipment is relatively simple, inexpensive, and portable.
- Process can be used in areas of limited access.
- Process is less sensitive to wind and draft than other welding processes.
- Process is suitable for most of the commonly used metals and alloys.

Limitations associated with SMAW are:

- Deposition rates are lower than for other processes such as GMAW.
- Slag usually must be removed at stops and starts, and before depositing a weld bead adjacent to or onto a previously deposited weld bead.

5.3 GAS TUNGSTEN ARC WELDING (GTAW)

GTAW can be used with or without the addition of filler metal. The CC type power supply can be used with either DC or AC, the choice depends largely on the metal to be welded.

- *Direct current* electrode negative welding is typically performed when welding steel and stainless and 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 welding aluminum and magnesium.
- *Direct current electrode positive* provides cleaning action during the portion of the AC wave, when the electrode is positive with respect to the work piece.

Some commonly accepted advantages of the GTAW process include:

- Produces high purity welds, generally free from defects.
- Little post-weld cleaning is required.
- Allows for excellent control of root pass weld penetration.
- Can be used with or without filler metal, dependent on the application.

Limitations associated with GTAW process are:

- Deposition rates are lower than the rates possible with consumable electrode arc welding processes.
- Has a low tolerance for contaminants on filler or base metals.
- Difficult to shield the weld zone properly in drafty environments.

5.4 GAS METAL ARC WELDING (GMAW)

GMAW may be operated in semiautomatic, machine, or automatic modes. It employs a constant voltage (CV) power supply, and uses either the short circuiting, globular, or spray methods to transfer metal from the electrode to the work:

The type of molten metal transfer is determined by:

- the type and amount of welding current
- Electrode diameter and composition
- Electrode extension
- Shielding gas

1. Short Circuiting Transfer (GMAW-S)

a) GMAW-S uses the lowest range of welding currents, voltages and electrode diameters (<21 volts)
b) Process produces a fast freezing weld pool that is generally suited for joining thin metal
c) Work well for out of position welds, or root passes (especially open root)
d) Most prone to lack of sidewall fusion when welding thick plate or heavy wall pipe or a nozzle attachments.

2. Globular Transfer (GMAW-G)

a) GMAW-G uses relatively low current and medium voltages (below 250 A but above 22 volts).
b) GMAW-G is characterized by a drop size with a diameter typically greater than that of the electrode
c) This process is limited to the flat position and can produce spatter

3. Spray Transfer (GMAW-SP)

a) GMAW-SP results in a highly directed stream of discrete drops that are accelerated by arc forces
b) Spatter and noise are negligible
c) Due to its high arc forces with high current, applying this process to thin sheets may be difficult
d) The thickness limitation of the spray arc transfer has been overcome by the use of pulsed GMAW
e) Pulsed GMAW is a variation of the GMAW in which the current is pulsed to obtain the advantage of spray transfer at the less average currents than that of spray transfer mode.

Some commonly accepted advantages of the GMAW process include:

- The only consumable electrode process that can be used to weld most commercial metals and alloys.
- Deposition rates are significantly higher than those obtained with SMAW.
- Minimal post-weld cleaning is required due to the absence of a slag.

Limitations associated with GMAW are:

- The welding equipment is more complex, more costly, and less portable than that for SMAW.
- The welding arc should be protected from air drafts that will disperse the shielding gas.
- When using the GMAW-S process, the weld is more susceptible to lack of adequate fusion.

5.5 FLUX CORED ARC WELDING (FCAW)

FCAW is a welding process that uses an arc between continuous tubular electrode and the weld pool. The process can be used with an external shielding gas or without additional shielding from a supplied gas. FCAW is performed on DCEP.

Some commonly accepted advantages of the FCAW process include:

- The metallurgical benefits that can be derived from the flux inside the wire.
- Slag that supports, shapes and protects the weld bead.
- High deposition and productivity rates. (higher than SMAW, similar to GMAW).
- Shielding is produced at the surface of the weld that makes it more tolerant of stronger air currents. (similar to SMAW, better than GMAW)

Limitations associated with FCAW process are:

- Equipment is more complex, more costly, and less portable than that for SMAW.
- Self-shielding FCAW generates large volumes of welding fumes, and requires suitable exhaust equipment.
- Slag requires removal between passes.
- Backing material is required for root pass welding.

5.6 SUBMERGED ARC WELDING (SAW)

Submerged arc welding is a welding process that uses an arc between a flux covered bare metal electrode 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. 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.

Some commonly accepted advantages of the SAW process include:

- Provides very high metal deposition rates.
- Produces repeatable high quality welds for large weldments and repetitive short welds.

Limitations associated with SAW are:

- A power supply capable of providing high amperage at 100% duty cycle is recommended.
- Weld is not visible during the welding process.
- Equipment required is more costly and extensive, and less portable.
- Process is limited to shop applications and flat position.

5.7 STUD ARC WELDING (SW)

SW is an arc welding process that uses an arc between a metal stud, or similar attachment, and the work piece. Once the end of the stud and the mating work area form a molten pool, they are brought into contact by pressure.
The process is often fully automatic or may be used with a gun that is semiautomatic. A stud gun holds the tip of the stud against the work. Direct current on a CC power source is typically used for SW with the stud gun connected to the negative terminal (DCEN). SW is often used to weld studs that help to support concrete, insulation or refractory for highways, bridges or pressure vessels.

Some commonly accepted advantages of the SW process include:

- High productivity rates compared to manually welding studs to base metal.
- Considered an all-position process.

Limitations of SW are:

- Process is primarily suitable for only carbon steel and low-alloy steels.
- Process is specialized to a few applications.

6 Welding Procedures

6.1 General

Welding Procedure Specifications (WPS) detail the steps necessary to make welds and generally consist of a written description, weld joint details, welding process variables, and data from qualification testing to prove that the procedure produces weldments that meet design requirements. Most welding codes require that a WPS is used to weld, fabricate and repair pressure vessels, piping and tanks.

All welding codes and standards will have varying requirements for the development of welding procedures. API 577 does not contain details regarding WPS development or qualification however, reference is made to the requirements contained in the ASME Boiler Pressure Vessel Code Section IX. Therefore, users of API 577 must be familiar with the development and qualifications of WPS’s in accordance with ASME Section IX.

While a WPS provides a written detail of welding instructions (variables), these details need to be proven by welding a test coupon. The data obtained from welding the test coupon is illustrated on a Procedure Qualification Record (PQR). Once the WPS is validated by the PQR, welders may be tested and the subsequent data obtained here is recorded on a welder qualification record, often known as a Welder Performance Qualification (WPQ) or in other codes as a Welder Qualification Test Record (WQTR).

A completed WPS breaks down all welding variables by describing them as essential, nonessential, or supplementary essential variables:

1. *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 must be re-qualified.
2. *Nonessential variables* do not affect the mechanical properties of the weld. They may be changed on the WPS without re-qualifying the welding procedure.
3. *Supplementary essential variables* apply or when specified by the end user. They are treated as essential variables when they apply which is usually when notch toughness is required.

6.2.1 Essential Variables typically include the following information as a minimum:

a. Welding Process (SMAW, GTAW, GMAW, etc…)
b. Base metal specification (ASTM A36, AISI 4130, API 5L, etc…)
c. Filler metal (E6010, ER70S-6, E71T-1, etc…)
d. Welding current (AC, DC) also polarity (DCEP, DCEN)
e. Welding position (2F, 3F, 3G, 5G, etc…)
f. Shielding gas, if used (Ar, CO2, He, etc…)
g. Preparation of base metal (bevel, V, J, etc…)
h. Fitting and alignment (Root opening, Root face, etc…)
i. Backside of joint (steel backing bar, purging, chill rings, etc…)
j. Peening (hammering to relive stress, deformation of the weld face)
k. Preheat (Heat applied prior to welding- torch, heat blanket, coils)
l. Post-weld heat treatment (heat applied after welding to normalize, anneal)
m. Welding technique (stringer, weave, single pass, multi-pass)

6.2.2 The WPS should also reference the supporting PQR(s) used to qualify the welding procedure. Both API 577 and ASME Section IX permit formatting of the WPS in any manner, however ASME Section IX does provide sample forms in Appendix B.

6.3 Procedure Qualification Record

The PQR is a document that records the actual variables used in welding a test coupon. It also records the results and subsequent data obtained from mechanical and non-destructive testing of the welded coupon. And finally, it serves as a testimony to the accuracy and the qualification of the corresponding WPS(s). Mechanical tests and non-destructive testing are required to qualify a welding procedure to demonstrate the properties of the test weld. Typically, testing includes tension/tensile testing, guided bend testing, notch toughness testing (CVN), hardness measurements, fillet weld break testing, macro-etch testing, nick break testing and UT or RT inspection.

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 code. Testing parameters and subsequent data should also be recorded separately on a test data form to record the events of testing apart from supporting the WPS.

6.4 REVIEWING A WPS AND PQR

The job of reviewing the WPS and PQR is one of the most common responsibilities of the welding inspector to verify they are acceptable for the welding to be done. The initial step is to verify the WPS has been properly completed and addresses the requirements of Section IX and the construction/repair code. The second step is to verify the PQR has been properly completed 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. For simplicity purposes, the following list is for a single weld process on the WPS:

6.4.1 Items to be Included in the WPS

a. Name of the company using the procedure.
b. Name of the individual that prepared the procedure.
c. Unique number or designation that will distinguish it from any others, and date.
d. Supporting PQR(s).
e. Current revision and date, if revised.
f. Applicable welding process (i.e., SMAW, GTAW, GMAW, FCAW, SAW).
g. Type of welding process (i.e., automatic, manual, machine, or semi-automatic).
h. Joint design information applicable to the process (i.e. type of joint, groove angle, root spacing, root face dimensions, backing material and function).
i. Base metals P-number and group number of the metals being joined, or specification type and grade, or chemical analysis and mechanical properties.
j. Thickness range the procedure is to cover.
k. Diameter (for piping) the procedure is to cover.
l. Filler metal specification (SFA number).
m. AWS classification number.
n. F-number (see QW-432).
o. A-number (see QW-442).
p. Filler metal size.
q. Deposited metal thickness.
r. Electrode-flux class and trade name, if used.
s. Consumable insert, if used.
t. Position and progression qualified for use in production welding.
u. Minimum preheat temperature (including preheat maintenance requirements) and maximum interpass temperature the weldment is to receive throughout welding.
v. Post-weld heat treatment temperature and hold time (if applied).
w. Type, composition, and flow rates for shielding, trailing, and backing gases (if used).
x. Current, polarity, amperage range, and voltage range for production welding (for each electrode size, position, and thickness, etc.).
y. Tungsten electrode size and type (if GTAW).
z. Metal transfer mode (if GMAW or FCAW).
aa. Technique including string or weave bead, initial and interpass cleaning, peening, passes greater than 1/2 in. (12.7 mm) thickness, and other weld process specific nonessential variables.

6.4.2 Items to be Included in the PQR

a. Name of the company using the procedure.
b. Unique number or designation and the date.
c. WPS(s) that the PQR supports.

d. Welding process used.
e. Type of weld for qualification (groove, fillet, other).
f. Test coupon thickness.
g. Test coupon diameter.
h. P-numbers of coupon welded.
i. Filler metal F-number.
j. Filler metal A-number.
k. Position and progression.
l. Total weld metal thickness deposited.
m. Any single weld pass thickness greater than 1/2 in. (12.7 mm).
n. Preheat temperature.
o. PWHT temperature and thickness limit.
p. Gas.
q. Electrical Characteristics.
r. Technique.
s. Proper number, size, and test results for tensile tests.
t. Proper number, type, and results for bend tests.
u. Additional test results if required by construction code or project specification.
v. Certification signature and date.
w. Welder's Name.
x. Tests Conducted by & Record number.

7 Welding Materials

7.1 GENERAL

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

7.2 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 and non-ferrous base metals. These assignments are based on comparable base metal characteristics such as composition, weldability, and mechanical properties. Table 1 lists the assignments of base metal 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.

Table 1—P-number Assignments

Base Metal	Welding
Steel and steel alloys	P-No. 1 through P-No.11, including P-No. 5A, 5B, and 5C
Aluminum and aluminum-base alloys	P-No. 21 through P-No. 25
Copper and copper-base alloys	P-No. 31 through P-No. 35

7.3 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 essentially on their usability characteristics, which fundamentally determine the ability of welders to make satisfactory welds with 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 other F-numbers. For example, a welder who qualified with an E7018 is qualified to weld with all F-4 electrodes, plus all F-1, F-2, and F-3 electrodes (with backing limitations). Consideration should be given to the compatibility of the base and filler metals from the standpoint of metallurgical properties, post-weld heat treatment, design and service requirements, and mechanical properties. A complete list of F-numbers for electrodes and welding rods is given in ASME Section IX, Table QW-432.

7.4 AWS CLASSIFICATION OF FILLER METALS

An AWS classification number identifies electrodes and welding rods. The AWS classification numbers are specified in ASME Section IIC under their appropriate AWS/SFA specification number. ASME Section IX Table QW-432 lists the AWS classification numbers and AWS/SFA specification numbers included under each of the F-numbers.

7.5 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.

7.6 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.

7.7 CONSUMABLE STORAGE AND HANDLING

Welding rods and electrodes should be stored and handled in accordance with the manufacturer's instructions and the guidelines in the applicable AWS A5.XX specification. Covered electrodes exposed to moisture can become unstable due to moisture pickup by the coating, especially low-hydrogen and stainless steel electrodes.

Low-hydrogen electrodes should be stored separately from other types of electrodes with higher hydrogen content and in heated ovens. Ovens should only be used for electrode storage as using them for food storage or cooking could cause electrode coatings to absorb moisture. Any electrodes or fluxes that have become wet should be discarded.

8 Welder Qualification

8.1 GENERAL

Welder performance qualification is similar to welding procedure qualification, to establish the welder's ability to deposit sound weld metal. A welder may be qualified by radiography of a test coupon or of an initial production weld or by bend tests of a test coupon. The responsibility for qualifying welders is restricted to the contractor or manufacturer employing the welder and cannot be delegated to another organization.

8.2 WELDER PERFORMANCE QUALIFICATION (WPQ)

The WPQ addresses all essential variables listed in QW-350 of ASME Section IX. The performance qualification test coupon is to be welded according to the qualified WPS, and the welding is supervised and controlled by the employer of the welder. The qualification is for the welding process used, and each different welding process requires qualification. A change in any essential variable listed for the welding process requires the welder to re-qualify for that process. The variable groups addressed are: joints, base metals, filler metals, positions, gas, and electrical characteristics.

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 items. An example form is available in ASME Section IX—Form QW-484 in nonmandatory Appendix B. Mechanical tests performed on welder qualification test coupons are defined in ASME Section IX, QW-452 for type and number required. Coupons are required to pass visual examination and physical testing, (unless RT is used). Welder performance qualification expires if the welding process is not used during a six-month period. The welder’s qualification can be revoked if there is a reason to question their ability to make welds. A welders log or continuity report can be used to verify that a welder’s qualifications are current.

8.3 REVIEWING A WPQ

8.3.1 Review Prior to Welding

Prior to being assigned any welding responsibility, inspectors should review welders’ qualifications to verify they are qualified to perform the welding positions and processes. When reviewing a welder qualification record, check:

a. Welders name and stamp number.
b. Welding process and type.
c. Identification of WPS used for welding test coupon.
d. Backing (if used).
e. P-number(s) of base metals joined.
f. Thickness of base metals and diameter if pipe.
g. Filler metal SFA number.
h. Filler metal F-number.
i. Consumable insert (if used).
j. Deposited thickness (for each process used).
k. Welding position of the coupon.
l. Vertical weld progression.
m. Backing gas used.
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, signature, and date.
u. X-ray results if used.

9 Non-destructive Examination

9.1 DISCONTINUITIES

Non-destructive Examination (NDE) is defined as those inspection methods, which allow materials to be examined without changing or destroying their usefulness. The welding inspector should be familiar with all NDE methods and choose the method best suited for detecting anticipated discontinuities.

Table 2 (below) lists the common types and location of discontinuities .

Table 2—Common Types of Discontinuities

Type of Discontinuity	Location	Remarks
(1) Porosity (a) Uniformly scattered (b) Cluster (c) Piping (d) Aligned (e) Elongated	WM	Porosity could also be found in the BM and HAZ if the base metal is a casting.
(2) Inclusion (a) Slag (b) Tungsten	WM, WI	
(3) Incomplete fusion	WM/MI	WM between passes
(4) Incomplete joint penetration	BM	Weld root.
(5) Undercut	WI	Adjacent to weld toe or weld root in base metal.
(6) Underfill	WM	Weld face or root surface of a groove weld.
(7) Overlap	WI	Weld toe or root surface.
(8) Lamination	BM	Base metal, generally near midthickness of section
(9) Delamination	BM	Base metal, generally near midthickness of section.
(10) Seam and lap		Base metal surface generally aligned with rolling direction.
(11) Lamellar tear	BM	Base metal, near HAZ.
(12) Crack (includes hot cracks and cold cracks described in text)		
(a) Longitudinal	WM, HAZ, BM	Weld metal or base metal adjacent to WI.
(b) Transverse	WM, HAZ, BM	Weld metal (may propagate into HAZ and base metal).
(c) Crater	WM	Weld metal at point where arc is terminated.
(d) Throat	WM	Parallel to weld axis. Through the throat of a fillet weld.
(e) Toe	WI, HAZ	
(f) Root	WI, HAZ	Root surface or weld root.
(g) Underbead and HAZ	HAZ	
(13) Concavity	WM	Weld face or fillet weld.
(14) Convexity	WM	Weld face of a fillet weld.
(15) Weld reinforcement	WM	Weld face of a groove weld.

Legend:
WM—weld metal zone
BM—base metal zone
HAZ—heat-affected zone
WI—weld interface

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Figure 11 (below) illustrates the positions of discontinuities within a butt weld.

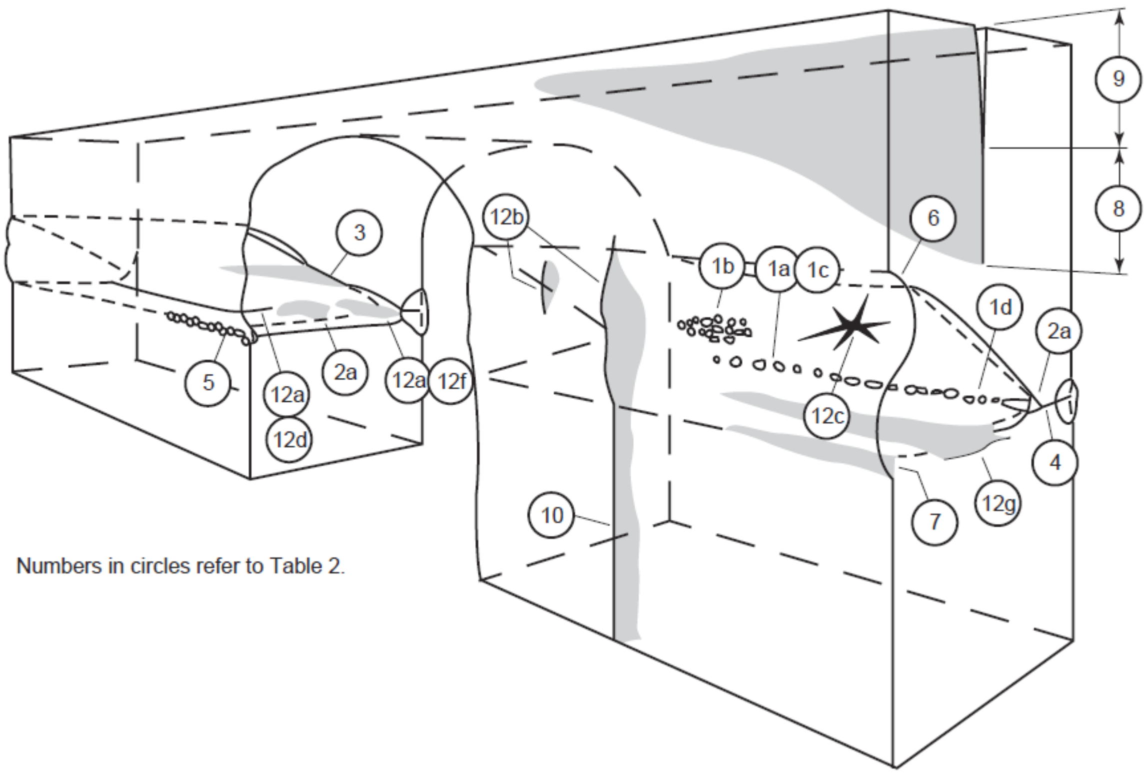

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Figure 11—Typical Discontinuities Present in a Single Bevel Groove Weld in a Butt Joint

Table 3 (below) shows the most commonly used NDE methods employed for weld inspection.

Type of Test	Symbols
Visual	VT
Magnetic Particle	MT
Wet Fluorescent Magnetic Particle	WFMT
Liquid Penetrant	PT
Leak	LT
Eddy Current	ET
Radiographic	RT
Ultrasonic	UT
Alternating Current Field Measurement	ACFM

Table 4 (below) lists the various weld joint types and common NDE methods available to inspect them.

	Inspection Methods						
Joints	RT	UT	PT	MT	VT	ET	LT
Butt	A	A	A	A	A	A	A
Corner	O	A	A	A	A	O	A
Tee	O	A	A	A	A	O	A
Lap	O	O	A	A	A	O	A
Edge	O	O	A	A	A	O	A

Legend:
RT—Radiographic examination
UT—Ultrasonic testing
PT—Penetrant examination, including both DPT (dye penetrant testing) and FPT (fluorescent penetrant testing)
MT—Magnetic particle examination
VT—Visual testing
ET—Electromagnetic examination
A—Applicable method
O—Marginal applicability (depending on other factors such as material thickness, discontinuity size, orientation, and location)

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Table 5 (below) lists the detection capabilities of the most common NDE methods for given discontinuities. The inspector should be aware of discontinuities common to specific base metals and weld processes to assure these discontinuities are detectable.

Table 5—Capability of the Applicable Inspection Method vs. Discontinuity

	Inspection Methods						
Joints	RT	UT	PT	MT	VT	ET	LT
Porosity	A	O	A	O	A	O	A
Slag inclusions	A	O	A	O	A	O	O
Incomplete fusion	O	A	U	O	O	O	U
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

Notes:
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 is applicable only to enclosed structure which may be sealed and pressurized during testing

Legend:
RT—Radiographic examination
UT—Ultrasonic testing
PT—Penetrant examination, including both DPT (dye penetrant testing) and FPT (fluorescent penetrant testing)
MT—Magnetic particle examination
VT—Visual testing
ET—Electromagnetic examination
A—Applicable method
O—Marginal applicability (depending on other factors such as material thickness, discontinuity size, orientation, and location)

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Table 6 (below) is a summary of discontinuities, NDE methods and possible solutions to the weld process.

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, ACFM	Proper heat input, proper welding technique.
	Incomplete Penetration	All	RT, UT, VT[1]	Proper heat input, proper joint design.
	Undercut	SAW, SMAW, FCAW, GMAW	VT, ACFM	Reduce 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 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.

9.3 VISUAL EXAMINATION (VT)

9.3.1 General

Visual examination is the most extensively used NDE method for welds. It includes either the direct or indirect observation of the exposed surfaces of the weld and base metal. Direct visual examination is conducted when access is sufficient to place the eye within 6 in. – 24 in. (150 mm – 600 mm) of the surface to be examined and at an angle not less than 30 degrees to the surface as illustrated in Figure 12. Mirrors may be used to improve the angle of vision. 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. These illumination requirements are to be addressed in a written visual inspection procedure.

9.3.2 Visual Inspection Tools

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

9.3.2.1 Optical Aids

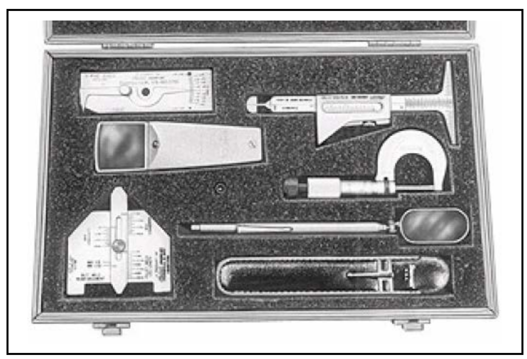
a. Lighting— Adequate illumination levels shall be established in order to ensure and effective visual inspection. Standards such as ASME Section V Article 9 specify lighting levels of 100 foot candles (1000 lux) at the examination surface.

9.3.2.2 Mechanical Aids

Steel ruler, Vernier scale caliper, micrometer, height and depth gages, Combination square set, Thickness gauge (“Feeler” gauge) and Levels.

9.3.2.3 Weld Examination Devices

Inspector’s kit (Right)—contains some of the basic tools needed to perform visual examination.



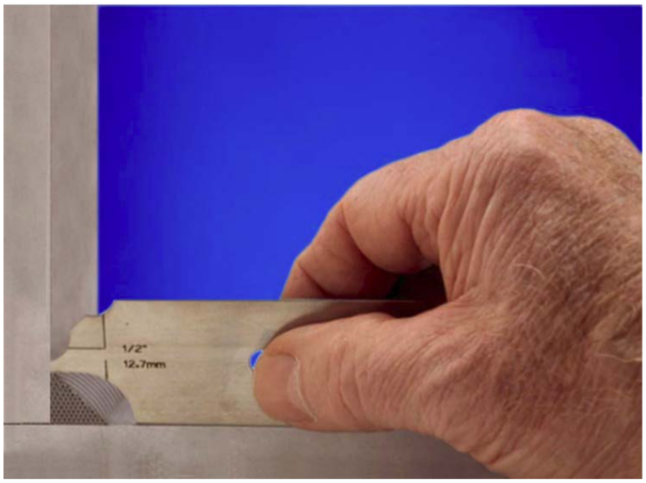
Bridge cam gauge (Right) can be used to determine the weld preparation angle prior to welding.

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).

Fillet weld gauge—offers a quick and precise means of measuring the more commonly used fillet weld sizes. The types of fillet weld gauges include: Adjustable fillet weld gauge, Skewed-T fillet weld gauge, convex/concave weld fillet gauge.

Fillet weld gauges are go/no go tools used to measure the fillet weld leg length. Gauges normally come in sets with weld leg sizes from 1/8 to 1 in. (3 - 25.4 mm).

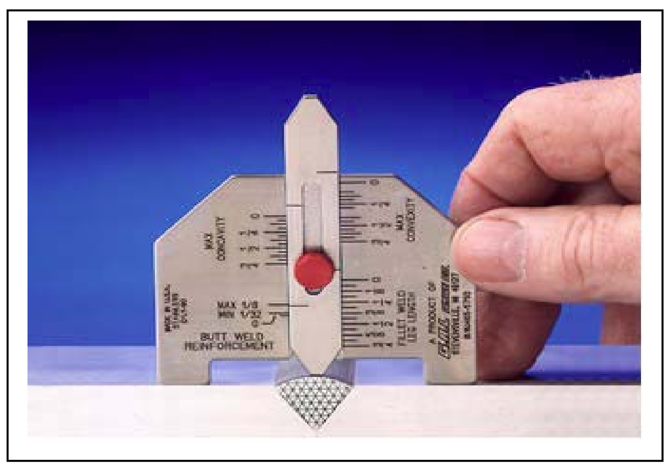
The figure below shows a convex weld fillet gauge being used to measure a flat/convex weld. For flat Or convex welds, the size of the weld is determined By measuring the leg length. (regardless of convexity)



The figure below shows a concave fillet gauge Being used to measure a flat/concave weld. For concave welds the size of the weld is determined by the dimension of the throat. (regardless of leg)

Weld reinforcement gauge (Weld size gauge) measures the size of fillet welds, the actual throat size of convex and concave fillet welds, the reinforcement of butt welds and root openings.

The primary use of this tool is for determining that weld Reinforcement meets the requirements of AWS D1.1



Hi-lo welding gauge (Right)—measures internal mis-alignment after fit-up, pipe wall thickness after alignment, length between scribe lines, root opening, 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.

Digital pyrometer or temperature sensitive crayons—measures preheat and inter-pass temperatures as well as part temperatures regarding in-service operating conditions.

9.12 WELD INSPECTION DATA RECORDING

9.12.1 Reporting Details

Results of the weld inspection should be completely and accurately documented. The inspection report, in many cases will become a permanent record to be maintained and referenced for the life of the weld or part being inspected. Information that might be included in an inspection report is listed in 9.12.1.1 through 9.12.1.3.

9.12.1.1 General Information

- 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.

9.12.1.2 Inspection Information

- 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.

9.12.1.3 Inspection Results

- a. Inspection sheet number.
- b. Inspection limitations.
- c. Inspection results.
- d. A description of all recordable and reportable indications.
- e. For each indication:
    - i. Indication number.
    - ii. Location of indication (from both weld reference datum and centerline).
    - iii. Upstream or downstream (clockwise or counterclockwise) from an established reference point.
    - iv. Size and orientation of indication.
    - v. Type of indication (linear or rounded).
    - vi. Acceptable per the acceptance standards of the referencing code.
    - vii. Remarks or notes.
    - viii. Include a sketch of indication.
    - ix. Reviewer and level of certification.
    - x. Reviewers comments.

9.12.2 Terminology

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

Terms	Definition	Description or Comment
Indication Discontinuity Flaw	A condition of being imperfect; a departure of a quality characteristic from its intended condition.	Not necessarily a lack of conformance with requirements or with lack of fitness for purpose. An indication may or may not be rejectable.

An indication, flaw or a discontinuity is a condition that is visible that may be intentional or unintentional geometric conditions.

Defect	A flaw, imperfection or discontinuity of such size, shape, orientation or location which is rejectable.	Indicates a lack of conformance to specification requirements. Potential lack of fitness for purpose.

A defect (a rejectable flaw) is by definition a condition, which must be removed, corrected or rejected.

10 Metallurgy

10.1 General

A general understanding of the major principles of metallurgy can be complex but is important to the inspector, due to the wide variety of base metals that may welded during the repair of equipment, and the significant impact on the metals resulting from welding. Welding metals can affect both the mechanical properties and the corrosion resistance properties of the parts being welded. This discussion will provide an awareness of metallurgical effects that are important to personnel performing welding inspections and a basic understanding of what happens to metal when subjected to the heating and cooling involved with welding.

10.2 The Structure of Metals and Alloys

Solid metals are crystalline in nature and all have a structure in which the atoms of each crystal are arranged in a specific geometric pattern like a tile floor. 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 liquid (molten) states have no structure. As the puddle cools, a temperature is reached at which clusters of atoms bond with each other and start to solidify forming a structure. The individual crystals of pure metal are called grains. As the temperature is reduced further, these crystals begin to touch each other forming layers that have grain boundary. Eventually the entire melt solidifies interlocking the grains into a solid metallic structure (casting).

10.2.1 The Structure of Castings

A weld pool is much like a casting. The overall arrangement of the grains, grain boundaries and phases present in the casting is called the microstructure of the metal. Microstructure is a significant area that inspectors should understand, as it is largely responsible for the physical and mechanical properties of the metal. Many metals used in the refinery industry are typically alloyed, which means they contain two or more elements or microstructural phases of grain size and arrangement.

In general, it is desirable to keep the size of grains small, which improves strength and toughness. This can be achieved by maximizing the time to cool rate or minimizing the heat input during welding. The properties of the crystal structure can also be impaired by compositional variations in the microstructure called segregation.

Segregation has a negative impact on the solubility of the weld pool due to the influence of trace and alloying elements that are undesirable (excessive carbon, sulfur, and phosphorous). These elements will solidify last and will land 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.

One way the segregation of undesirable elements can reduced is through the use of “oxygen scavengers” such as aluminum and silicon. These scavengers will tie up the impurities and/or bring them to the surface. The steels produced in this manner 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 induced cracking (HIC).

Gases, such as hydrogen, can become entrapped in the melt as it solidifies, affecting the integrity of the structure by creating voids, porosity and cracking. Weldments are particularly prone to cracking because of trapped hydrogen gases. This problem can be avoided by:

- Careful cleaning of surfaces to be welded to remove hydrocarbons and moisture
- Using of low-hydrogen electrodes that have been properly stored and heated
- Use of proper purging techniques with high quality welding gases.

10.2.2 The Structure of Wrought Materials

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

Austenitic stainless steels, for example, are composed of microstructural phase call austenite, which has 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 and strengthens the material but can lead to a lessoning of corrosion resistant properties.

Alloys may also consist of more than one microstructural phase and crystal structure. A number of copper alloys including some brass or tin. Plain carbon steel is also a two-phase alloy. One phase is a relatively pure form of iron called ferrite, which by itself is a fairly weak. With the addition of more than 0.06 percent 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 Fe3C iron carbide.

As a result of fast cooling or quenching a non-alloyed 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.”

10.2.3 Welding Metallurgy

Welding metallurgy is concerned with what occurs during welding:

- Melting and Solidification
- Gas/Metal reactions and Slag/Metal reactions
- Surface Phenomena and Base metal reactions.

All of these reactions occur very 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 major parts of a welded structure:

- the weld metal (weld pool- liquid and solidified)
- the heat-affected zone (HAZ)
- the base metal (unaffected by welding)

The metallurgy of each weld area will be determined by the base and weld metal compositions, the welding process and the procedures used. The solidified weld metal is a mixture of melted base metal and deposited weld filler metal. The HAZ is next to the weld and includes those regions heated to greater than 1350°F (700°C). The third component in a welded joint is the base metal and its weldability and chemical composition. All of the above must be taken into consideration to produce sound welds and it is the job of the welding inspector to be familiar with all of these welding conditions.

10.3 Physical Properties 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.

10.3.1 Melting Temperature 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.

10.3.2 Thermal Conductivity is the rate at which heat is transmitted through a material. In general, metals with high electrical conductivity also have high thermal conductivity and require more heat input to weld and may require a pre-heat.

10.3.4 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. Metals with a high coefficient of thermal expansion are much more susceptible to warping, distortion and thermal fatigue conditions, and result in a premature failure of the component. Welding procedures are often employed, which specify special filler metals that minimize the adverse effects caused by inherent differences between the metals being joined.

10.3.5 Density is defined as its mass per unit volume. Castings, and therefore welds, are usually less dense than the wrought material of similar composition and contain porosity and other inclusions of low density.

10.4 MECHANICAL PROPERTIES

The mechanical properties of base metals, filler metals and of completed welds are of major importance in the consideration of the design and integrity of welded structures and components. 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.

10.4.1 Tensile and Yield Strength

Tensile testing is used to determine a metals ultimate tensile strength, yield strength, elongation and reduction in area. A tensile test is performed by pulling a test specimen to failure with increasing load. The ultimate load to fracture a component divided by the cross sectional area of the component equals the tensile strength of the material.

$$\frac{\text{Ultimate Load in psi}}{\text{Cross Sectional Area}} = \text{Tensile Strength}$$

Tensile strength of a material is the maximum amount of tensile stress that it can take before failure occurs.
Yield strength is the stress a material can withstand without permanent deformation (elastic behavior).
Yield point is the exact moment when a material changes from elastic to plastic behavior.

10.4.2 Ductility

In tensile testing, ductility is defined as the ability of a material to deform plastically without fracturing. Ductility is measured in two ways:
Elongation is the increase in total length, measured after fracture of the specimen, usually expressed as a percentage of the original gage length. (Total length after fracture minus original length equals elongation)
Reduction of area is a "necking down" or reduction in diameter or thickness at the point of fracture. This reduction is measured and the reduction in area from the original area is calculated. This reduction in area is expressed as a percentage.

10.4.3 Hardness

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. In alloy steels, a high hardness measurement could indicate the presence of un-tempered martensite in the weld or heat-affected zone, while low hardness may indicate an over-tempered or annealed condition.

The Brinell test 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 result is an <u>indentation diameter</u> in the test bar and the test specimen surface. The diameters of the resulting impressions are compared and are directly related to the respective hardness's of the test bar and the test specimen.

Rockwell hardness testing differs from Brinell testing in that the hardness number is based on the measurement of the <u>depth to which an indenter is forced</u> by a heavy (major) load beyond the depth of a previously applied (minor) load and the Rockwell number then read from the dial.

Vickers and Knoop are micro-hardness testing methods. Hardness is calculated from the ratio of load to area of an indentation. A diamond shaped indenter 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.

10.4.4 Toughness

The 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 sub-size specimens, smaller than 10 mm × 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 minimum design metal temperatures based on service or location temperatures to assure that the material has sufficient toughness to resist brittle fracture.

10.5 PREHEATING

Preheating is defined as heating of the weld and surrounding base metal to a predetermined temperature prior to the start of welding. The primary purpose for preheating carbon and low-alloy steels is to reduce the tendency for hydrogen induced delayed cracking by slowing the cooling rate. However, preheating may be performed for many reasons, including:

- To be in compliance with the applicable WPS.
- Reduce shrinkage stresses in the weld and base metal, especially for joints with high restraint.
- Reduce the cooling rate to prevent hardening and reduction in ductility of the weld and HAZ.
- Maintain weld inter-pass temperatures.
- Eliminate moisture from the weld area.
- Meet the requirements of the applicable fabrication code

10.6 POST-WELD HEAT TREATMENT

Post-weld heat treatment (PWHT) is a heating operation performed after welding and is employed to improve the mechanical and metallurgical effects of welding in carbon and low-alloy steels. Time and temperature will vary 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. Another reason for post-weld heat treatment is to relieve the residual stresses caused by welding in a welded fabrication. These stresses occur due to the localized heating and severe temperature changes that occur during welding. PWHT can be applied by electrical resistance heating, furnace heating, or flame heating.

10.7 HARDENING

Hardening is typically induced by quenching and depends primarily on the carbon content of the material and is strongly affected by the presence of alloying elements, such as chromium, molybdenum, vanadium and to a lesser extent by nickel, copper and silicon. Welding variables, such as heat input, inter-pass temperature and size of the weld bead being applied all affect the cooling rate of the base metal HAZ which in turn affect the hardness.

The hardness limits currently recommended for steels in refinery process service are listed in the table shown.

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

Hardness values obtained in excess of these indicate that PWHT should be specified in the WPS to avoid stress corrosion cracking.

There is a direct relationship to hardenability and weldability. Higher hardness indicates more difficulty in welding.

10.8 MATERIAL TEST REPORTS

Materials test reports are notarized statements and are legally binding. There are typically two types of test reports:

1. a heat analysis (mill certificate) is a statement of chemical analysis and weight percent of elements present in an ingot or a billet
2. a product analysis is a statement of the chemical analysis of the end product and is supplied by the manufacturer of the material.

The product analysis is more useful to the inspector and engineer since it provides a more reliable identification of the actual material being used. The material test report is necessary for the inspector to review to insure accurate applicability of products for service and may include:

a. Manufacturer of the heat of material.
b. Date of manufacture.
c. Heat Number of the material.
d. Applicable National Standard(s) to which the heat conforms (ASTM, ASME or MIL-STD)
e. Heat treatment, if applicable.
f. Chemistry of the heat.
g. Mechanical properties
h. Supplemental information or testing requested by the purchaser regarding:
  - Impact strength.
  - Ductile to brittle transition temperature determination.
  - Fracture toughness.
  - Elevated mechanical property testing (i.e., tensile, hot ductility or creep testing).
  - Hardenability.
  - Hardness.
  - Response to heat treatment
  - Microstructural analysis, such as grain size evaluation.
  - Non-destructive examination, such as ultrasonic testing.

10.9 WELDABILITY OF STEELS

The weldability of metals is often presumed to be sufficient. AWS 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 service.” Weldability is related to many factors including the following:

a. The metallurgical compatibility of metals, alloys and fillers being welded;
b. The specific welding processes being used to join the metal;
c. The mechanical properties of the metal, such as strength, ductility and toughness;
d. The ability to produce a weldment with sound mechanical properties; and
e. Weld joint design.

10.9.1 Metallurgy and Weldability

The most significant factor affecting weldability of metals and alloys is their chemical composition. It controls the range of mechanical properties in steel and has the most influence on the effects of welding on the material. The single element that has the highest impact on weldability is carbon. Carbon content has the greatest effect on mechanical properties, such as tensile strength, ductility and toughness in the base metal heat affected zone and weldment. On the downside, carbon is mon-metallic and content influences the susceptibility of the metal to delayed hydrogen cracking and makes the metal more difficult to weld.

Other alloying elements such as manganese, chromium, nickel and molybdenum are added to alloy steels to provide increased strength, toughness, and corrosion resistance. It is an important function of the welding inspector to evaluate the weldability of carbon and alloy steel using the carbon equivalent (CE) equation. This function calculates a theoretical carbon content of the metal and takes into account carbon and those alloying and tramp elements. Welding codes vary in their expression of carbon equivalent and the specific formula used. One common equation is:

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

Typically, steels with a CE less than 0.35 require no preheat. Steels with a CE of 0.35 – 0.55 usually require preheating, and steels with a CE greater than 0.55 require both preheating and a PWHT.

10.9.2 Weldability Testing

Determining weldability of a metal or combination of metals is typically accomplished by procedural testing of welds using techniques that evaluate the strength and ductility of the weld. Tests used to evaluate welds include weld tension tests, shear strength, hardness, ductility, fracture toughness tests and bend tests. One of the most common applications of weldability testing is the establishment of WPS procedure qualification testing through the use of a PQR.

10.10.1 Austenitic Stainless Steels

Austenitic stainless steels are iron-based alloys that typically contain low carbon, chromium between 15% – 32% and nickel between 8% – 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.

The most common measure of weldability and susceptibility to hot cracking is the ferrite number of the weld metal. A number of resources recommend a minimum of 5% – 20% ferrite to prevent cracking. Welding can also reduce the corrosion resistance of the base metal especially in the HAZ of some stainless steels.

The most critical temperature range for stainless steels is between 800°F – 1650°F (427°C – 900°C). Exposure to the metal for a long enough time may cause carbon and chromium to precipitate and form chromium carbides at the grain boundaries. This formation results in a loss of corrosion resistance due to chromium depletion. Mitigation can be achieved by using low-carbon content stainless steels, such as Type 304L or 316L, or stabilized grades of stainless steels, such as Type 321 and 347.

Another detrimental condition experienced when welding stainless steel occurs on the backside of welds made without proper shielding. Welding open grooves or thin material without purge protection of the backside of the joint can also be detrimental to the corrosion resistance of austenitic stainless steels. Back purging can make fabrication more difficult but is essential in preventing a reduction in corrosion resistance.

10.10.2 Nickel Alloys

Nickel alloys, such as Inconel and Hastelloy (C276 or 625), are considered to have less weldability than austenitic stainless steels and tend to have more dense weld puddles and slower response to manipulation. Significant oscillation and wider beads are required to reduce the tendency for convexity, lack of fusion, undercut and trapped slag. As is the case for welding stainless steels, a serious by product of welding nickel alloys is the production of hexavalent chromium which is a carcinogenic, often invisible fume. Supplied air or air freshening devices should be worn when welding stainless and nickel alloys.

11 Refinery and Petrochemical Plant Welding Issues

11.2 Hot Tapping and In-Service Welding

Hot tapping and in-service welding involves tying into live, pressurized and flowing piping components. In do so, two primary concerns exist when welding on in-service piping and equipment:

1. Burn through - Burn through will occur if the un-melted area beneath the weld pool can no longer contain the pressure within the pipe or equipment.
2. Cracking. 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.

11.2.1 Electrode Considerations

Hot tapping 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 CE greater than 0.43% or where there is potential for hydrogen assisted cracking (HAC) such as cold worked pieces, high strength, and highly constrained areas.

Many pipeline welding procedures involve the use of cellulosic type electrodes (e.g., E6010, E6011 or E7010) especially for root and hot passes. Although these electrodes are easier to use they present a higher risk of burn through and hydrogen cracking. For the critical applications of hot tapping and in-service welding, low-hydrogen electrodes are preferred to reduce the risk of burn through because the amount of heat directed to the base metal is less than when using cellulosic type electrodes. It should be noted that cellulosic electrodes have the following adverse effects on the integrity of the weldment:

a. Deep penetration, therefore higher risk of burn-through than low-hydrogen electrodes; and
b. High diffusible hydrogen, therefore higher risk of hydrogen assisted cracking.

11.2.2 Flow Rates

In most applications of in-service welding, product will be flowing inside of any material being welded. Often this is required to avoid shutting down the line but it also helps to dissipate the heat and to limit the metal temperature during the welding operation, thereby reducing the risk of burn through.

To insure welding conditions do not overheat or burn through the pipe wall, a welding procedure should be developed based on experience in performing welding operations in similar conditions. The WPS should detail 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. To minimize burn through, the first weld pass to equipment or piping less than 1/4 in. (6.35 mm) thick should be made with 3/32 in. (4.76 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 bead should also be avoided as this increases the heat input.

11.2.4 Inspection

Inspection and surveillance techniques associated with hot tapping and in-service welding differ and may be more rigorous than typical welding fabrications and should include:

a. Verifying that sufficient wall thickness exists by using UT or RT.
b. The qualification of welding procedures specifically for hot taps and in-service welding.
c. Verifying flow conditions.
d. Specifying the sequence of welding full encirclement sleeves and fittings
e. Verifying fit-up of the hot tap fitting.
f. Auditing welding to assure the welding procedure is being followed.
g. Perform NDE of completed welds. Including:
    - VT before, during, after welding
    - UT shear wave (welds) longitudinal wave (thickness)
    - MT or PT, repairs, roots, fittings
h. Witness leak testing of fittings, completed components

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 will burn 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	Stress corrosion cracking due to high hardness of non-PWHT's weld.
(Wet H2S)	Hydrogen embrittlement. Pyrophoric scale.
Hydrofluoric Acid	Hazardous substance.
Oxygen	Combustion/metal burning.
Propylene	Explosion or unstable reaction.
Propylene	Oxide Explosion or unstable reaction.
Steam	Pressurization, leaks can blow out.

11.3 Lack of Fusion with GMAW-s Welding Process

A large quantity of ASTM A 106, Grade B Pipe, 4 in. through 10 in. was found to have lack of fusion (LOF) after being fabricated using the GMAW-S welding process. This piping was in normal fluid service and required 5% radiographic examination. Initially the radiographic film was read acceptable, but LOF it is not easily interpreted by most radiographers. For this reason, most codes will not allow RT to be used to qualify procedures and require that mechanical testing to be used.

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.

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.

Due to this inherent nature of the welding process the BPV Code Section IX, restricts this process by:

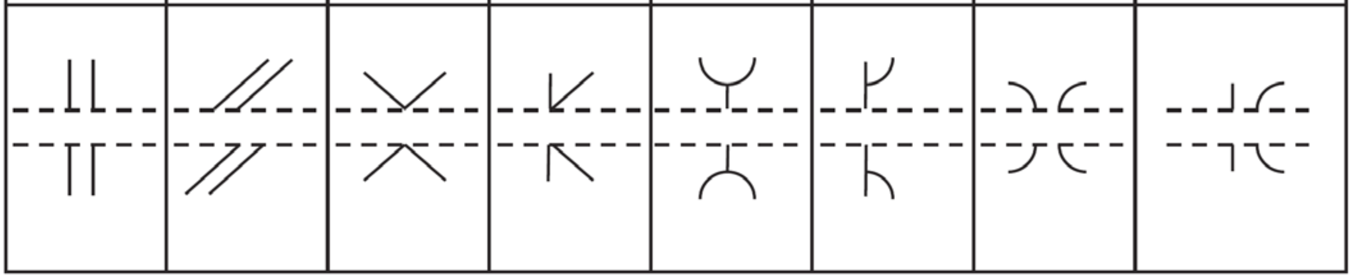
a. Requiring welders qualify with mechanical testing rather than by radiographic examination.

b. Limiting the base metal thickness qualified by the procedure to 1.1 times the test coupon thickness for coupons less than 1/2 in. thick (12.7 mm) per variable QW-403.10.

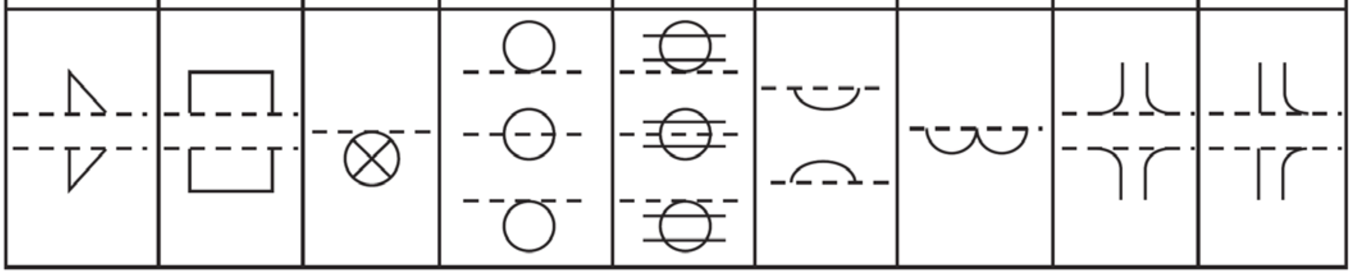
c. Limiting the deposited weld metal thickness qualified by the procedure to 1.1 times the deposited thickness for coupons less than 1/2 in. thick (12.7 mm) per variable QW-404-32.

d. Making variable QW-409.2 an essential variable when qualifying a welder for the GMAW-S process.

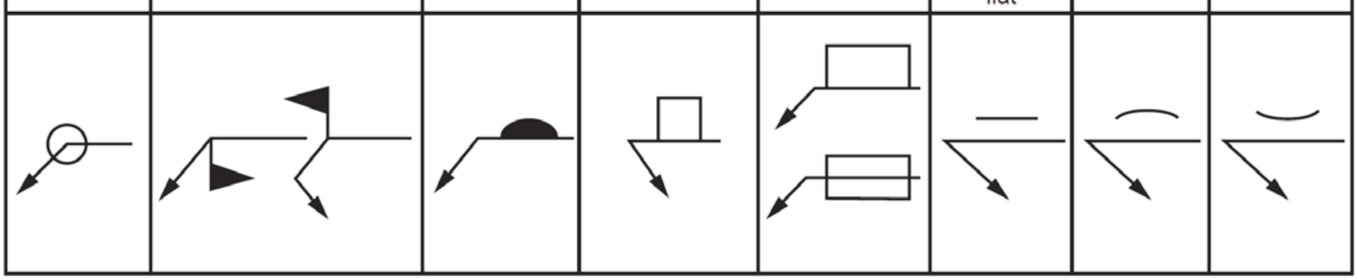
Groove							
Square	Scarf	V	Bevel	U	J	Flare-V	Flare-bevel



Fillet	Plug or slot	Stud	Spot or projection	Seam	Back or backing	Surfacing	Flange	
							Edge	Corner



Weld all around	Field weld	Melt through	Consumable insert (square)	Backing or spacer (rectangle)	Contour		
					Flush or flat	Convex	Concave



References:
AWS A2.4 Standard for Welding Symbols

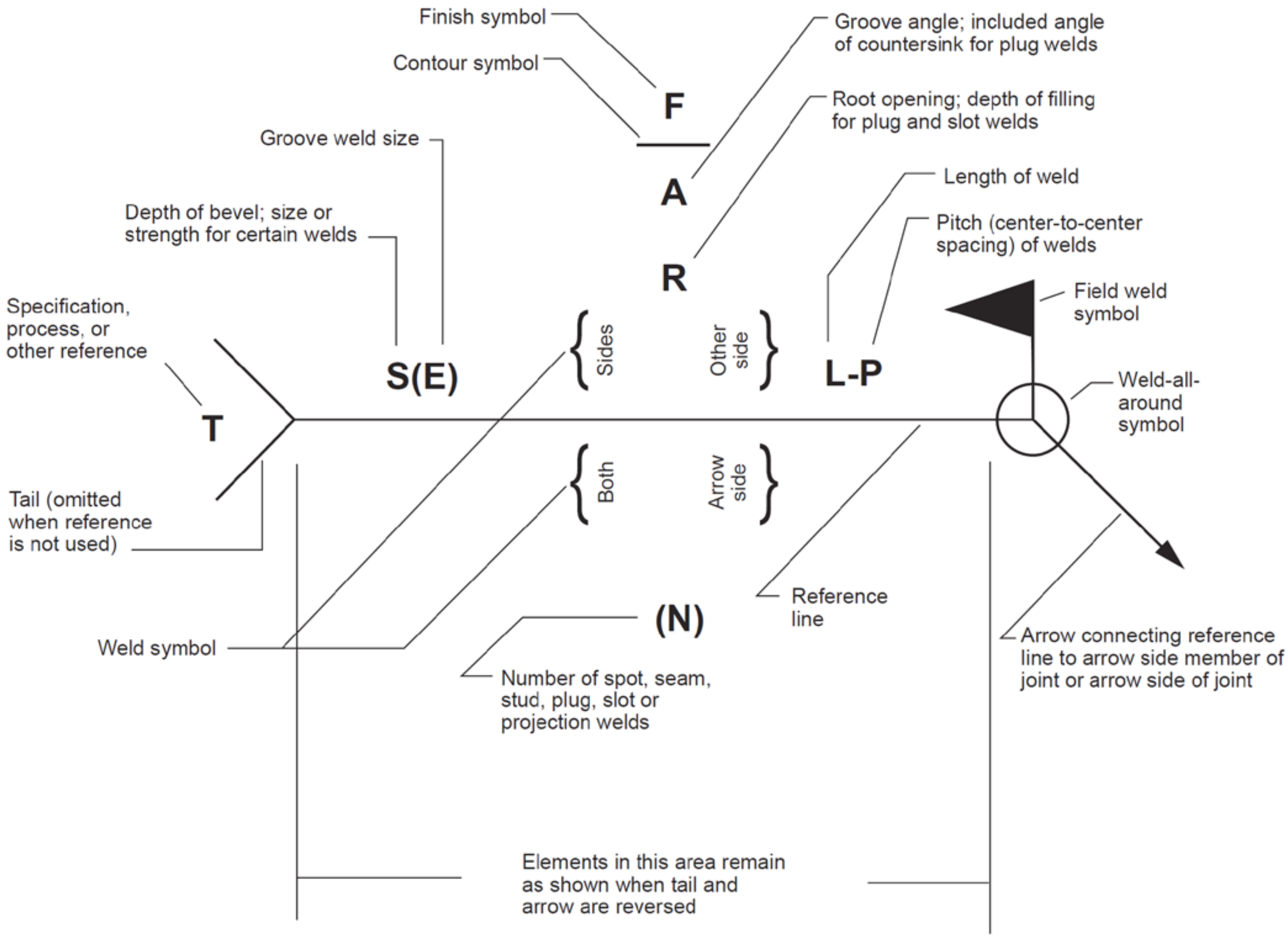
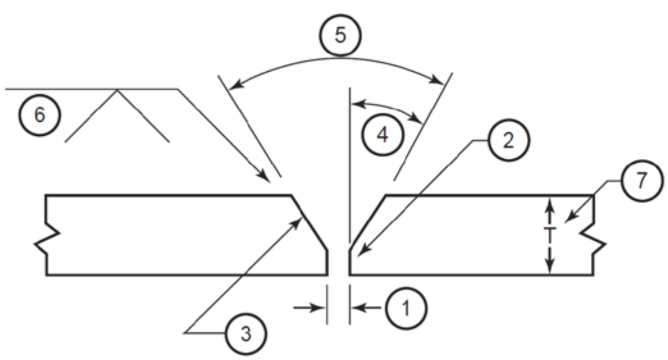


Figure A-4—Standard Weld Symbols



Groove Weld

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

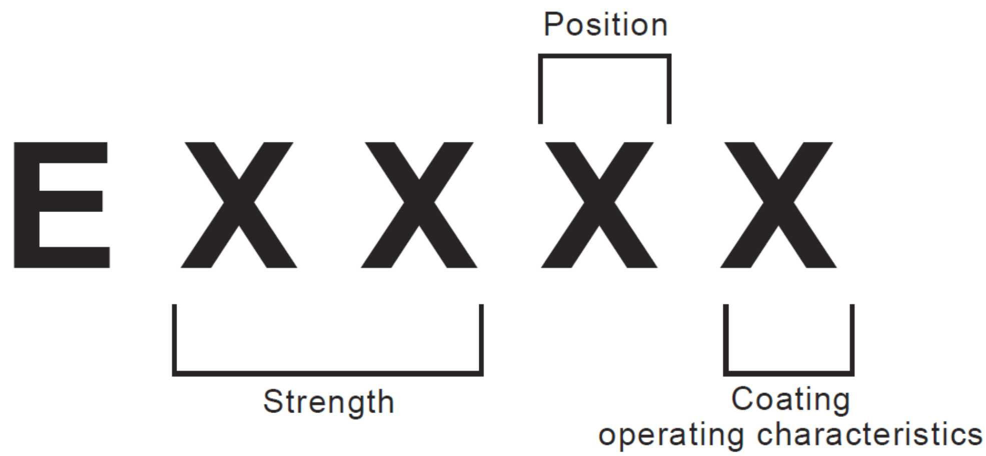


Figure A-6—SMAW Welding Electrode Identification System

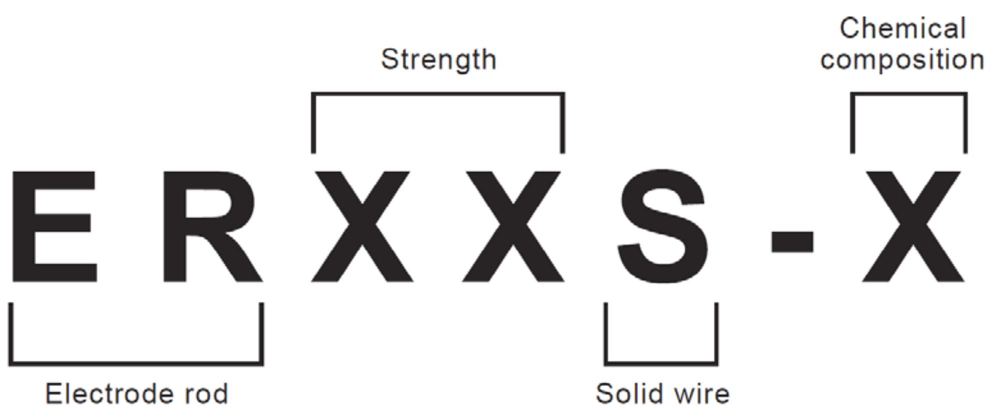


Figure A-7—GMAW/GTAW Welding Electrode Identification System

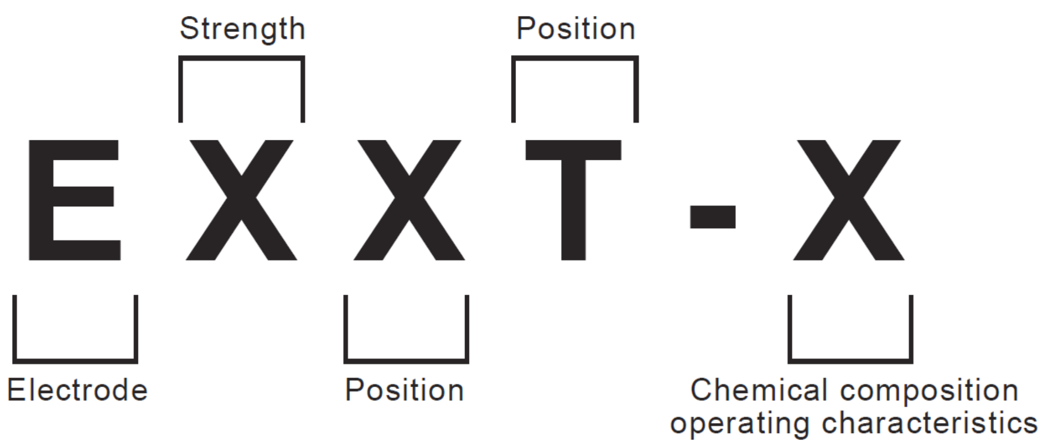
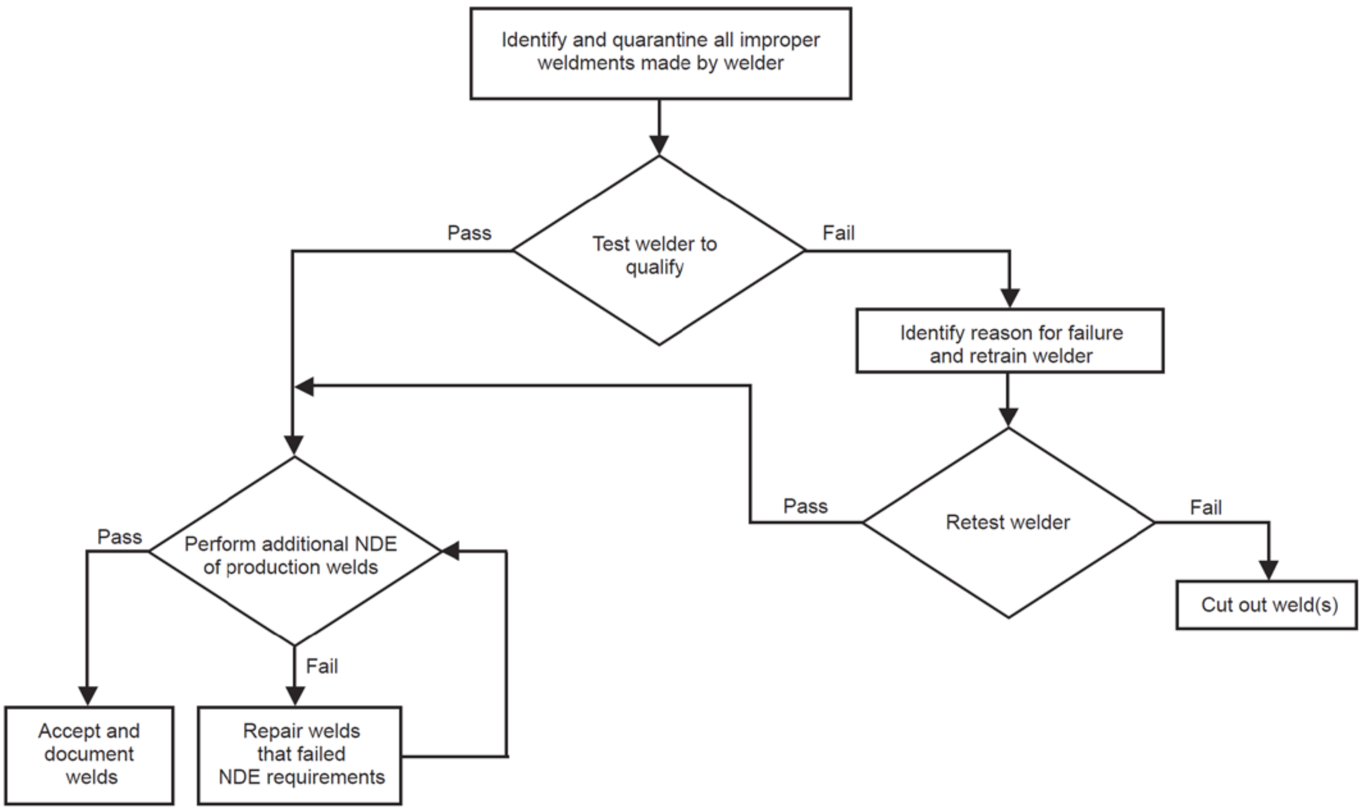


Figure A-8—FCAW Welding Electrode Identification System



Potential causes:
a. Expired qualification.
b. Not qualified in range.
c. Not qualified in method.
d. Not qualified in material.

Figure B-1—Suggested Actions for Welds Made by an Incorrect Welder

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Company Inc. By: Pea Green

Welding Procedure Specification No.: CS-1 Date: 01Aug87 Supporting PQR No.(s): CS-1

Revision No. ______ Date: ______

Welding Process(es): SMAW (28) Type(s): Manual (26)

(Automatic, Manual, Machine, or Semi-Auto)

JOINTS (QW-402) Details (3)

Joint Design: Single V, double V, J & U (1)

Backing (Yes): √ (2) (No): √ (2)

Backing Material (Type): weld metal (2)

(Refer to both backing and retainers.)

☒ Metal (4) ☐ Nonfusing Metal

☐ Nonmetallic ☐ Other

Sketches, Production Drawings, Weld Symbols or Written Description should show the general arrangement of the parts to be welded. Where applicable, the root spacing and the details of weld groove may be specified.

(At the option of the Mfgr., sketches may be attached to illustrate joint design, weld layers and bead sequence, e.g. for notch toughness procedures, for multiple process procedures, etc.)

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*BASE METALS (QW-403)

P-No.: 1 (8) (9) Group No.: ______ to P-No.: 1 (8) (9) Group No.:

OR

Specification type and grade: ______

to Specification type and grade: ______

OR

Chem. Analysis and Mech. Prop.: ______

to Chem. Analysis and Mech. Prop.: ______

Thickness Range

Base Metal: Groove: 1/16 in. through 3/4 in. (5) (6) (29) Fillet: ______

Pipe Dia. Range: Groove: 1 in. min. OD Fillet: ______

Other: (7) (30) (31) (32)

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*FILLER METALS (QW-404)

Spec. No. (SFA): 5.1 (14)

AWS No. (Class): E7010 (14)

F-No.: 3 (10)

A-No.: 2 (11)

Size of Filler Metals: 3/32, 1/8, 5/32 in. (12)

Weld Metal

Thickness Range

Groove: 3/4 in. max. (13)

Fillet: ______

Electrode-Flux (Class): ______

Flux Trade Name: ______

Consumable Insert: ______

Other: ______

*Each base metal-filler metal combination should be recorded individually.

QW-482 (Back)

WPS No.:________________ Rev.:____________

POSITIONS (QW-405)

Position(s) of Groove: All (15)

Welding Progression: ______ Up: X (16) Down: X (16)

Position(s) of Fillet: ____________

POSTWELD HEAT TREATMENT (QW-407)

Temperature Range: NA (19) (20)

Time Range: ____________

PREHEAT (QW-406)

Preheat Temp. Min.: 50°F min (17)

Interpass Temp. Max.: ____________

Preheat Maintenance: (18)

(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

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

ELECTRICAL CHARACTERISTICS (QW-409)

Current AC or DC: DC (21) Polarity: Rev (21)

Amps (Range): see below (22) Volts (Range): (22)

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type: ____________

(Pure Tungsten, 2% Thoriated, etc.)

Mode of Metal Transfer for GMAW: ____________

(Spray arc, short circuiting arc, etc.)

Electrode Wire feed speed range: ____________

TECHNIQUE (QW-410)

String or Weave Bead: string or weave (23)

Orifice or Gas Cup Size: ____________

Initial and Interpass Cleaning (Brushing, Grinding, etc.): (24)

Method of Back Gouging: air-arc or grinding (25)

Oscillation: ____________

Contact Tube to Work Distance: ____________

Multiple or Single Pass (per side): (60)

Multiple or Single Electrodes: ____________

Travel speed (Range): ____________

Peening: (27)

Other: ____________

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp. Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, Etc.)
Root	SMAW	E7010	3/32"	DC RP	60-120			
Fill	"	"	1/8"	"	95-150			
	"	"	5/32"	"	125-175			
			(12)	(21)	(22)			