100 Welding Fundamentals

Abstract

This section describes the welding processes commonly used for Company applications, along with the advantages, disadvantages, and typical applications for each. It discusses joint design and describes the various types of joints and welds. Weld metal composition is covered, including proper storage and handling of welding electrodes. The section describes preheat, with reasons for preheat and methods used. There is a detailed discussion of postweld heat treatment (PWHT) purposes and methods. In addition, oxyfuel gas cutting and arc cutting of metals is covered.

110 Welding Processes

The welding processes covered in this section are:

- Shielded metal arc welding (SMAW)
- Gas tungsten arc welding (GTAW)
- Gas metal arc welding (GMAW)
- Flux cored arc welding (FCAW)
- Submerged arc welding (SAW)
- Electroslag welding (ESW) and electrogas welding (EGW)
- Stud welding (SW)
- Oxyfuel gas welding (OFW), braze welding, and brazing
- Cadwelding

Several joining and spraying processes will not be discussed here because of their limited application for Company use. These processes include:

- Plasma arc welding
- Electron beam welding
- Laser welding
- Resistance welding
    - Flash welding
    - Projection welding
    - Resistance seam welding
    - Resistance spot welding
- Friction and inertia welding
- Explosion welding
- Solid state welding
- Thermal spraying
    - Flame spraying
    - Plasma spraying
    - Detonation flame spraying
- Metalizing

For brevity, the various welding processes will frequently be referred to by the standard abbreviations designated by the American Welding Society (AWS). Additional information on these and other welding processes can be found in the AWS Welding Handbooks and in Volume 6 of the American Society for Metals (ASM) Handbooks.

Arc welding is a welding process in which the heat is generated by an electric arc between an electrode and the work. In DC welding, the work is generally the positive pole with the electrode the negative pole, but reverse polarity may be used in which the work is the negative pole and the electrode is the positive pole.

111 Shielded Metal Arc Welding (SMAW)

Over half of all welding in the U.S. is done with the shielded metal arc welding (SMAW) process. SMAW is a manual arc welding process in which the heat for welding is generated by an electric arc between a flux-covered consumable electrode and the work. Figure 100-1 shows a typical welding circuit for SMAW. The electrode tip, arc, molten weld metal and the adjacent areas of the work are protected from atmospheric contamination by the gaseous shield produced by the combustion and decomposition of the electrode covering. Additional shielding is provided for the molten weld metal by the molten flux (or slag) that forms. Filler metal is supplied by the core wire of the consumable electrode, or for certain electrode types, from metal powder mixed with the electrode covering. Figure 100-2 shows the operating principles for the SMAW process.

Fig. 100-1 Typical Welding Circuit for Shielded Metal Arc Welding (SMAW)

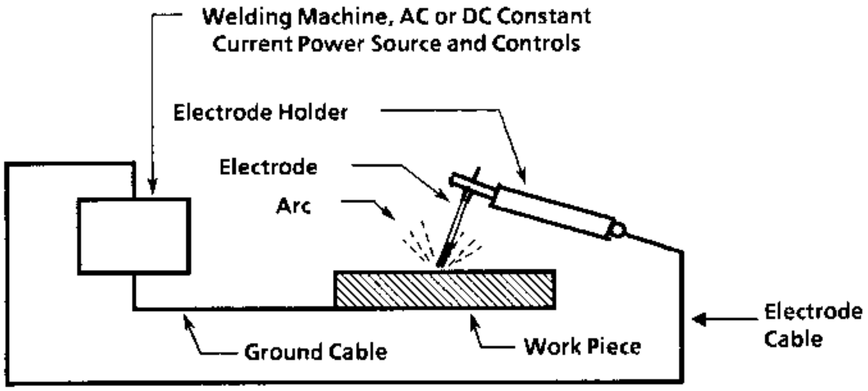
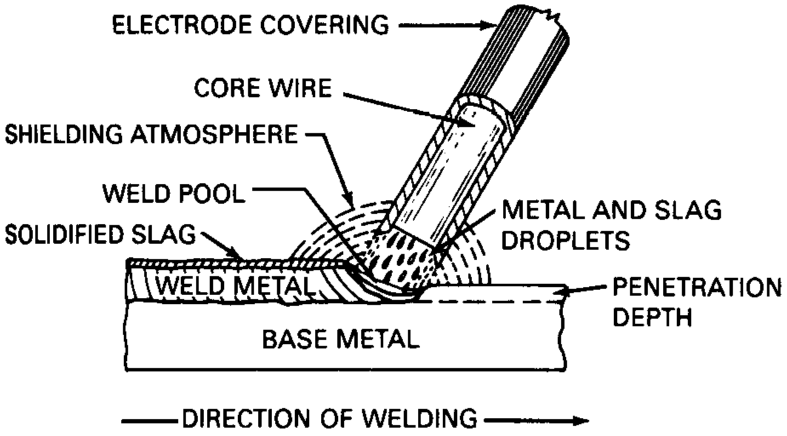


Fig. 100-2 Shielded Metal Arc Welding (SMAW) Process *(Courtesy American Welding Society)*



Advantages

SMAW is the simplest and most versatile of the arc welding processes. The simplicity and portability of SMAW equipment allow use of this process in a wide variety of applications from refinery piping to cross country pipelines, and even underwater to repair offshore structures. SMAW can be used in any position or location that can be reached with an electrode. Joints in blind areas can be welded, including the back sides of pipes in restricted areas that are inaccessible for most other welding processes, by using bent electrodes.

SMAW is used to join a wide variety of ferrous and nonferrous materials including carbon and low alloy steels, stainless steels, nickel based alloys, cast iron, and some copper alloys.

Disadvantages

Even though SMAW is a highly versatile process, it has several characteristics that make the deposition rate lower than with semi-automatic or automatic processes. Electrodes are of fixed length and welding must be stopped after each electrode has been consumed. The stub of the electrode is lost, and time is lost for changing electrodes. The slag must be removed from the weld after each pass before subsequent passes can be deposited. These steps lower welding efficiency by about 50%.

Smoke and fumes present a problem with SMAW, and ventilation is required in confined spaces. The view of the weld puddle is somewhat obscured by the protective slag that covers the freezing weld metal and by the smoke. Extra welder skill is needed to make radiograph-quality welds in pipe or plate when welded from one side.

Company Applications

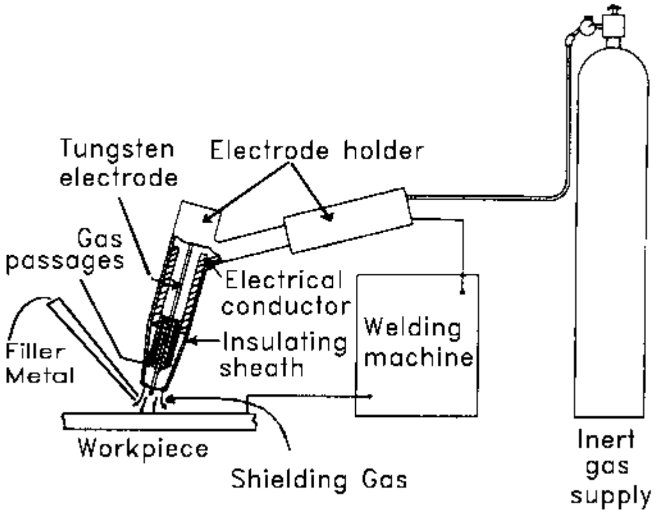
Because of its great flexibility, manual SMAW is the welding process most widely used by the Company in both maintenance work and new construction.

112 Gas Tungsten Arc Welding (GTAW)

In gas tungsten arc welding (GTAW), heat is generated by creating an arc, in an inert shielding gas, between a nonconsumable tungsten electrode and the work. GTAW melts the area of the work under the arc without melting the tungsten electrode. Figure 100-3 shows the equipment for GTAW. The GTAW process can be used either manually or automatically. It is also known by the original Linde Company trade name **Heliarc** and the acronym **TIG** (for tungsten inert gas). Filler metal can be added to the weld by introducing a bare rod into the zone of the arc. Welding techniques are similar to those for oxyfuel gas welding, but the arc and molten puddle are shielded from the atmosphere by a blanket of inert gas, usually argon, helium, or mixtures of these. Inert gas is fed through the torch and around the tungsten. Welds produced with the GTAW process have a smooth surface that is free of slag and low in hydrogen content.

One variation of the GTAW process (pulsed GTAW) uses a power source that pulses the welding current. This permits a higher average current for better penetration and

Fig. 100-3 Equipment for Gas Tungsten Arc Welding (GTAW) *(Courtesy of the American Welding Society)*



weld puddle control, particularly on root passes. Pulsed GTAW is especially useful for out-of-position pipe welding on stainless steel and nonferrous materials such as nickel based alloys.

GTAW has been adapted to automatic welding. Automation of the process requires a programmed power source and controls, a wire feeder, and machine guided travel. It has been used to make high quality tube-to-tubesheet seal welds and heat exchanger tube butt welds. Butt welding of large diameter thick walled pipe at utility power plants is another successful application of automatic GTAW. When GTAW uses automatic wire feed it is also referred to as **cold wire TIG**. Another automatic version of GTAW welding is called **hot wire TIG**, which has been developed to compete with other, higher deposition rate, welding processes. With hot wire TIG, the wire is resistance heated with low voltage AC current to increase the deposition rate.

Advantages

The GTAW process produces high quality welds without slag in a variety of ferrous and nonferrous materials. With proper welding technique, all atmospheric contaminants are excluded. A major advantage of the process is that it can be used to make high quality root passes from one side on a wide range of materials. Consequently, GTAW is used extensively for pipe welding. Welding current can be controlled over a wide range, from about 5 to 300 amps, providing greater ability to compensate for changing joint conditions such as root gap. For example, on thin walled (below 0.20-inch) pipe and sheet metal, the current can be adjusted low enough to control penetration and prevent burn-through more easily than can be done with processes that use coated electrodes. The lower speed of travel as compared to SMAW provides better visibility and makes it easier to control the weld metal during deposition and fusion.

Disadvantages

The main disadvantage of GTAW is its lower deposition rate compared with other processes such as SMAW. In addition, GTAW requires closer control of joint fit-up to produce high quality welds from one side. GTAW also needs better joint cleaning to remove oil, grease, rust, and other contaminants in order to avoid porosity and other weld defects.

GTAW must be carefully shielded from air movements above about 5 mph in order to maintain the inert gas shield over the molten puddle.

Company Applications

GTAW is excellent for thin wall pipe and small diameter tubing of stainless steel, nickel alloys, copper alloys, and aluminum. On heavier wall piping, it is frequently used for the root pass on welds requiring high quality, such as for high pressure, high temperature hydrogen piping and return bends in furnace coils. It is also used for root passes where a smooth inside diameter surface is required, such as on piping in acid service. Because of the inert gas protection of the weld and excellent process control, GTAW is frequently used on reactive metals such as titanium and magnesium.

On thin wall pipe, 0.125 inch and less, a square edge preparation that is butted tight can be used. The root pass is made without filler metal addition (this is called an autogenous weld). On thicker pipe, the joint edges are beveled, fitted up with a gap (called an open root) and filler metal is added during welding of the root pass. In lieu of adding filler metal, consumable insert rings can be fitted into the joint and fused into the root (to make the filler metal addition). Welding with consumable inserts requires careful control of fit-up.

Backup Gas Purge

A backup gas purge is used for materials that are sensitive to contamination from air on single welded joints that are not backgouged (e.g. piping and closing seams). Backup gas is needed for certain chrome-moly steels (≥3% chromium), stainless steels, high nickel alloys, copper alloys, and titanium. A gas purge is not necessary for welding carbon steel or low alloy steels containing less than 3% chromium. Either argon or helium can be used for purge gas. As an alternate, nitrogen may used for the purge gas for welding austenitic stainless steels, copper and copper alloys. Nitrogen is not suitable for most other materials because it acts as a contaminant.

The best results for stainless steels and high nickel alloys are obtained when they are purged to oxygen levels of less than 1%. Purging with four to ten times the required volume is needed to obtain the relatively inert atmosphere. Where uncertainty exists regarding the adequacy of the purge, a mine safety oxygen analyzer can be used to check the oxygen level in the purge gas being exhausted from the weld area.

Initial gas purging is usually done at a high flow rate (e.g. 30 to 90 CFH) to flush the system, then reduced to a low flow rate (about 5 to 8 CFH) for welding. Particular care should be taken to ensure that the backup gas pressure is not excessive when welding the root pass, otherwise weld blow out or root concavity can occur. Adequate venting or exhaust is important to prevent excessive pressure buildup during welding. The area of the vents for exhausting backup gas should be at least equal the area of the opening used to admit the backup gas to the system. After completion of the root and several fill layers, the backup gas purge can be discontinued. The number of fill layers required before discontinuing the gas purge will depend upon layer thickness and penetration

113 Gas Metal Arc Welding (GMAW)

Gas metal arc welding (GMAW) uses a continuous solid or tubular electrode of the desired composition on a spool or coil. This is fed continuously through a gun or torch while maintaining an arc between the end of the electrode and the base metal.

Figure 100-4 shows GMAW equipment, and Figure 100-5 illustrates the GMAW process. The GMAW process is also known by the acronym **MIG** (for metal inert gas). MIG is no longer descriptive of GMAW because not all of the shielding gases used with the process are inert. In GMAW, the electrode is generally solid and all of the shielding gas is supplied by an external source.

Fig. 100-4 Equipment for Gas Metal Arc Welding (GMAW) *(Courtesy of the American Welding Society)*

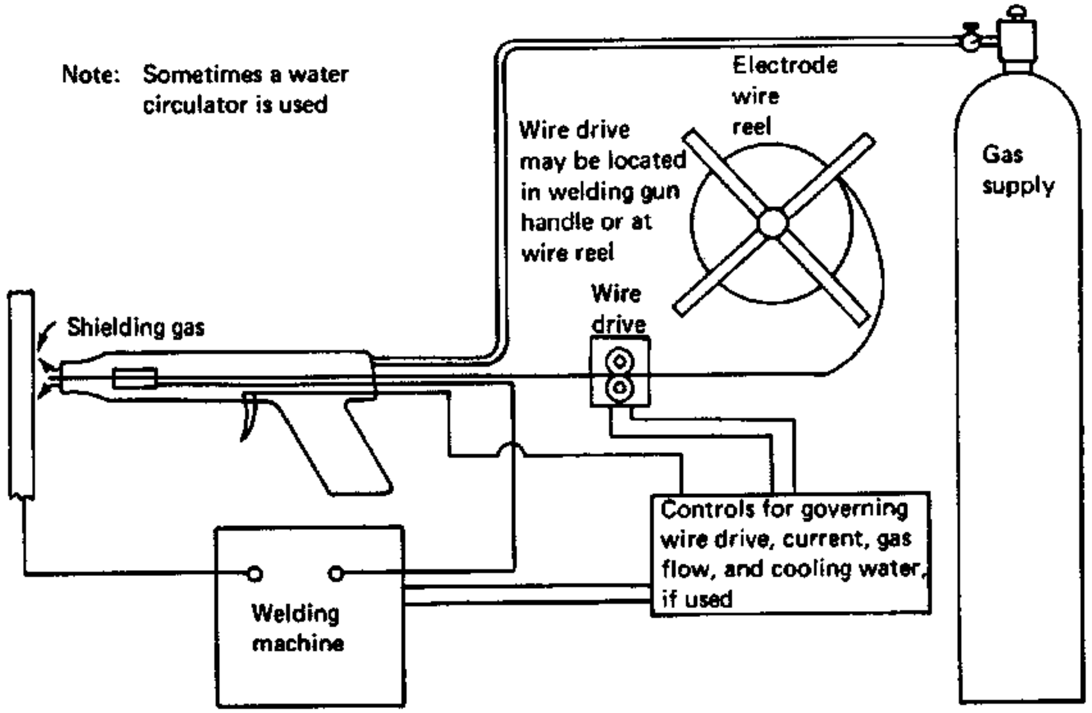
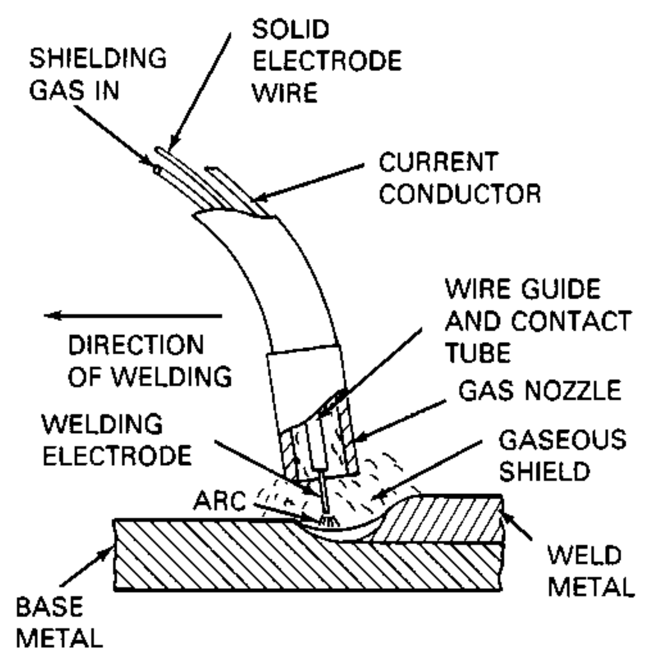


Fig. 100-5 Gas Metal Arc Welding (GMAW) Process *(Courtesy of the American Welding Society)*



There are three variations of the GMAW process that are significant to the Company:

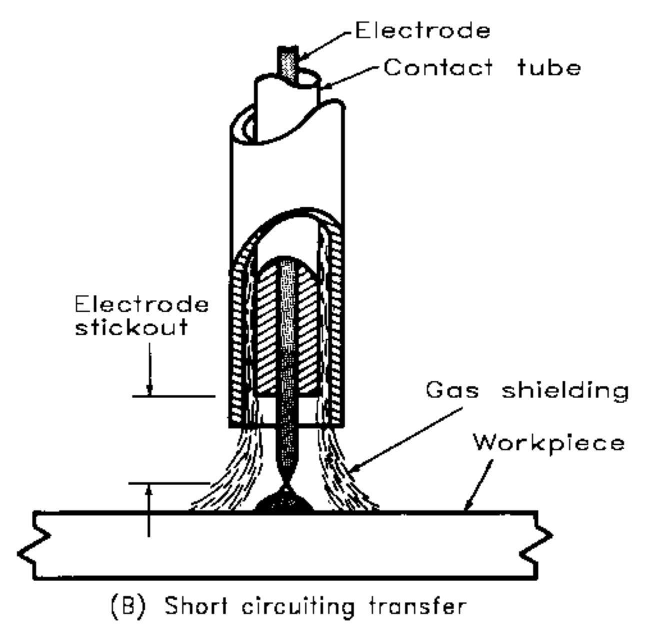
- Short-circuiting (GMAW-S)
- Spray or globular transfer GMAW
- Pulsed arc (GMAW-P)

Short-circuiting (GMAW-S)

Short-circuiting refers to the arc transfer mode (also called **short arc** or **dip transfer**). In this variation of GMAW, molten metal at the tip of the electrode wire contacts the molten weld pool, creating a short-circuit. At the start of the short-circuit cycle, the end of the electrode melts into a small globule of liquid metal, which moves toward the workpiece. As the molten metal makes contact with the workpiece, short-circuiting occurs. Then the globule is pinched from the wire, severing the molten bridge between the electrode wire and workpiece. The arc re-ignites and the cycle repeats. Metal is transferred only during short-circuiting, which occurs 20 to 200 times per second. See Figure 100-6 for an illustration of the GMAW-S process. GMAW-S uses small diameter (0.030-, 0.035-, or 0.045-inch) solid wire electrodes. It can be either semi-automatic or machine guided (i.e., mounted on a travel fixture).

During GMAW-S welding, the arc and molten puddle are shielded by a gas or gas mixture. For carbon steel, the shielding gas is commonly CO_2 or a mixture of argon and CO_2. A 75% argon and 25% CO_2 gas mixture is frequently used because it has better welding characteristics. Other proprietary gas mixtures are available that

Fig. 100-6 GMAW-S—Short-Circuiting Transfer *(Courtesy of the American Welding Society)*



contain helium as well. Shielding gas composition is selected to provide the desired welding characteristics, such as bead shape, penetration and spatter. Higher levels of CO_2 are more economical, but they result in greater penetration and weld spatter and increase manganese and silicon losses.

All-position welding capability and ease of control make GMAW-S suitable for root pass welding of piping and for thin gage strip lining attachment welds. GMAW-S is used on a variety of materials, including carbon steel, chrome-moly steels, stainless steel and nickel based alloys. Company specifications restrict the use of GMAW-S because of the risk of nonfusion and cold lap defects in the fill passes on piping welds. As a result, piping fill passes are restricted to being made in the flat position only.

Spray Transfer Or Globular Transfer

In **spray transfer GMAW**, metal transfers across the arc as a stream of small droplets (diameters equal to or smaller than the electrode-wire diameter), as shown in Figure 100-7. Spray transfer occurs only in high-argon gas shielding (80% argon or greater). Transfer occurs above a minimum current, called the transition current, which depends (among other factors) on the filler metal composition and diameter. For example, the transition current for 0.045-inch diameter steel filler metal is 220 amps. When the current is below the transition current, droplet size increases to larger than the electrode wire diameter, and it becomes **globular transfer**. Globular transfer GMAW is always done using CO_2 gas shielding. Figure 100-8 illustrates **globular transfer GMAW.**

Fig. 100-7 GMAW—Spray Arc *(Courtesy of the American Welding Society)*

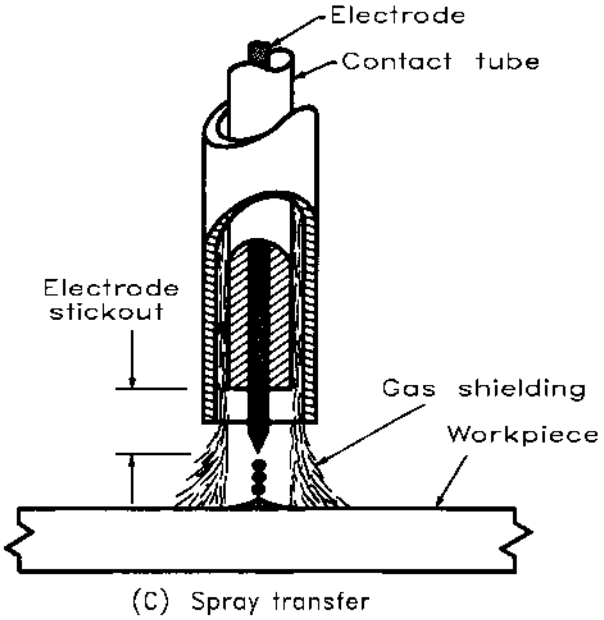
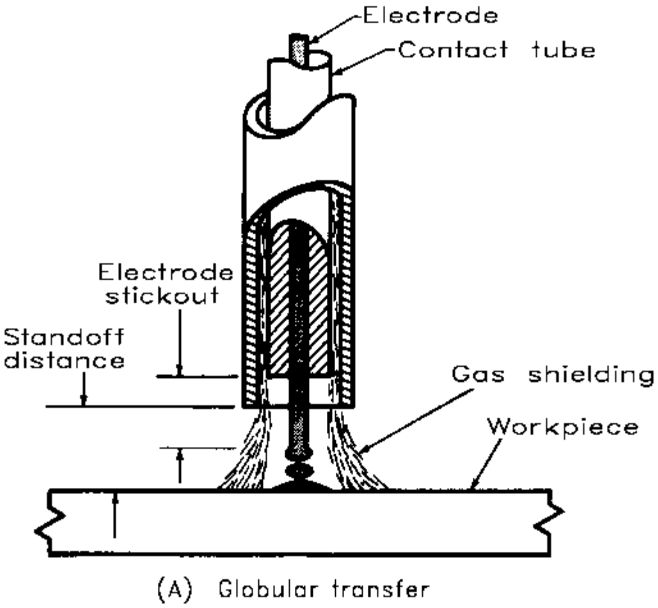


Fig. 100-8 GMAW—Globular Transfer *(Courtesy of the American Welding Society)*



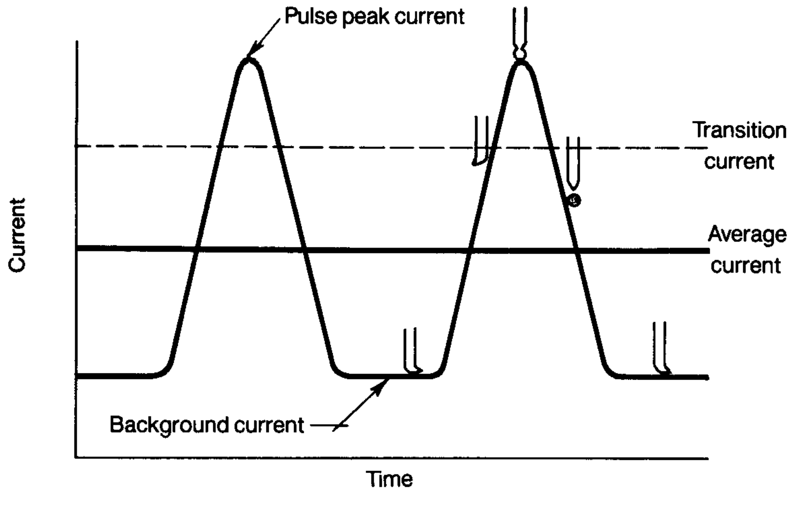
Spray transfer GMAW produces the least spatter of any mode of metal transfer. High heat input results in good penetration and the deposition rate is high, but application of the spray transfer process is limited to mostly flat and horizontal welding. The large droplets of the globular transfer mode of GMAW make out-of-position welding even more difficult and the weld spatter greater.

Pulsed Arc (GMAW-P)

Most welding is performed with a constant voltage (CV) power supply. With CV power supply, the amperage automatically adjusts to melt off the wire at the rate it is advancing towards the work. If the arc length shortens or lengthens, the power source changes the current output to increase or decrease the electrode burnoff and maintain constant arc length and voltage.

Pulsed arc welding is a spray transfer process that uses a special power supply (pulsed or synergic MIG) that switches the welding current between a high pulse current and a low background current level many times per second. During pulsation, weld metal transfers across the arc. Figure 100-9 shows the spray transfer mode occurring with the average current below the transition current of the filler metal. The background current sustains the arc, while each current pulse supplies enough power to free one drop from the wire tip. Metal transfer occurs during the high-current pulse, when droplets of molten metal (≤1 wire diameter in size) cross the arc at lower average current than required for conventional or spray transfer.

Fig. 100-9 Pulsed-arc Welding Diagram *(From* Welding Design & Fabrication*, a Penton Publication, © 1988. Reprinted by permission.)*



Recommended Shielding Gases

The recommended shielding gases for GMAW and FCAW-G are listed in the Alloy Fabrication Data in Appendix A, under the alloy to be welded.

Advantages

The GMAW process may be used semi-automatically or it can be machine guided for automatic welding.

Smoke and spatter are less with short-circuiting GMAW than with SMAW, and there is no slag to clean after welding. Welding speeds and deposition rates are equal to or greater than with SMAW. Weld dilution is generally lower because of less penetration of GMAW. With the low heat input and penetration of GMAW, thin sections are easily joined and wider root gaps are more easily welded. For shop fabrication of piping, high quality root passes can be made faster in any position and generally at lower cost.

Spray transfer and globular transfer GMAW produce a highly visible weld puddle, similar to the puddle of short-circuiting arc but without a slag covering. Because there is no flux and relatively small amounts of deoxidizers are added to the wire, there is very little cleaning needed after welding (as opposed to coated electrode welding). Uniform arc length is maintained by the constant voltage power supply. GMAW produces higher deposition rates on both ferrous and nonferrous alloys; the process is suitable for both groove welds and corrosion-resistant overlay welding for stainless steel, nickel-based alloys and copper alloys such as aluminum bronze.

Disadvantages

GMAW welding equipment is more expensive and complicated to set up and maintain than the equipment for SMAW. The cost of wire and shielding gas can be greater than the cost of coated electrodes, but this is offset by higher productivity and less wastage.

The gas shielding in GMAW welding can be disrupted by external air currents, so precautions must be taken to avoid wind velocities that exceed about five miles per hour. Wind shields or enclosures can be used to block air currents or reduce them to velocities low enough to maintain adequate gas shielding. Increasing gas flow rates to compensate for excessive wind may make the problem worse by creating turbulence around the arc and drawing in air.

GMAW requires greater access to the work because of the size of the welding gun and nozzle. Generally, the wire feeder must be positioned close to the work.

Short-circuiting welding can be used without restriction for root passes in butt welds or branch connections but should be strictly controlled if used for fill passes because of the risk of nonfusion or cold laps. For fill passes in piping butt welds, it should only be used where welding progression is uphill between 10 o’clock and 2 o’clock, whether the pipe is in the fixed position (5G) or rotated (1G). It is not suitable for fillet welds where material thickness exceeds 1/4 inch, and is generally not used in the fabrication of pressure vessels, tanks or structural members.

Lack of fusion between weld layers is difficult to detect by radiography and where there has been poor control of the short-circuiting process, the problem of lack of fusion has been severe enough on occasion to cause some fabricators to abandon using the short-circuiting process. Compared to coated electrode welding, short-circuiting welding requires better joint cleaning, fit-up and grinding of the tack welds to obtain good root pass quality.

Lack of fusion is not a problem with higher heat input spray transfer or globular transfer GMAW. For spray transfer GMAW, there is more arc radiation. This is more uncomfortable for the welder and makes the process more suited to automatic welding for some applications. Spray transfer GMAW welding is limited to flat and horizontal position welding because of the larger weld puddle.

Company Applications

The short-circuiting GMAW process can save time on applications such as root pass welding on pipe welds and installing alloy strip lining in pressure vessels.

Both spray transfer and globular transfer GMAW are used on pipe and pressure vessel fabrication for other than root passes. Both spray and globular transfer GMAW are used for corrosion-resistant overlays. Spray transfer is used on butt welds of stainless steels, nickel alloys and copper alloys. Pulsed arc welding can be used in similar applications but has the advantage of all-position welding capability. Spray transfer welding is not preferred on carbon steel if submerged arc welding (SAW) can be used, but is used on copper and nickel alloys.

114 Flux Cored Arc Welding (FCAW)

Like GMAW, FCAW uses a continuous solid or tubular electrode of the desired composition on a spool or coil. The electrode is fed continuously through a gun or torch while maintaining an arc between the end of the electrode and the base metal. FCAW uses a flux-containing electrode rather than a solid or fabricated electrode (metal powders in a sheath). The core ingredients may supply some or all of the shielding gas needed (in contrast with GMAW, where all of the shielding gas comes from an external source). FCAW may also use auxiliary gas shielding, depending on the type of electrode, the material being welded, and the nature of the welding involved.

There are two variations of FCAW, which are given separate designations depending upon the method of gas shielding:

- Gas shielded (FCAW-G)
- Self-shielded (FCAW-SS)

The gas shielded process (FCAW-G) requires an external shielding gas (usually CO_2 or argon-CO_2) as shown in Figure 100-10. The self-shielded process (FCAW-SS) generates it own shielding gas (e.g., Lincoln Innershield), as shown in Figure 100-11. FCAW can be used as either a semi-automatic or automatic welding process, but has widest application as a semi-automatic process.

Fig. 100-10 Gas Shielded Flux Cored Arc Welding (FCAW-G) *(Courtesy of the American Welding Society)*

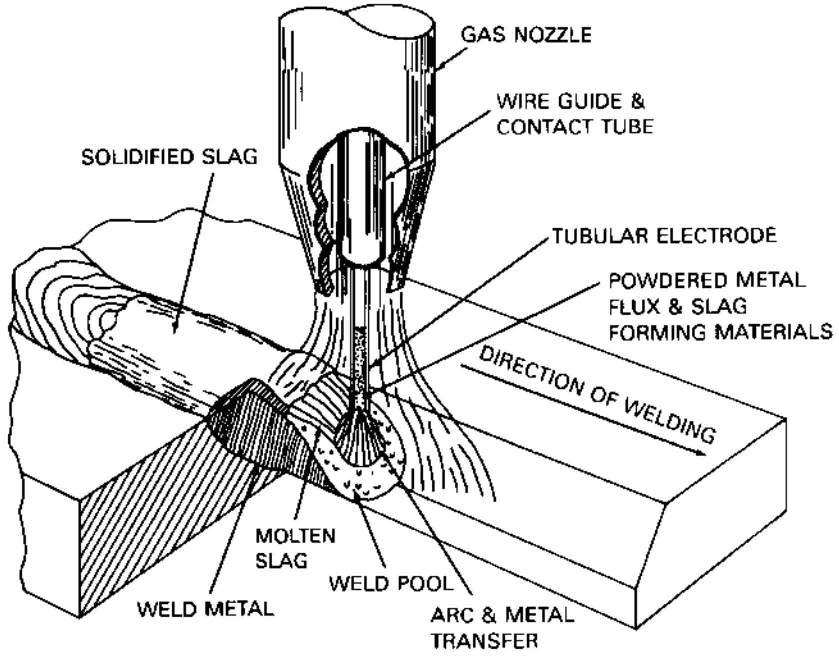
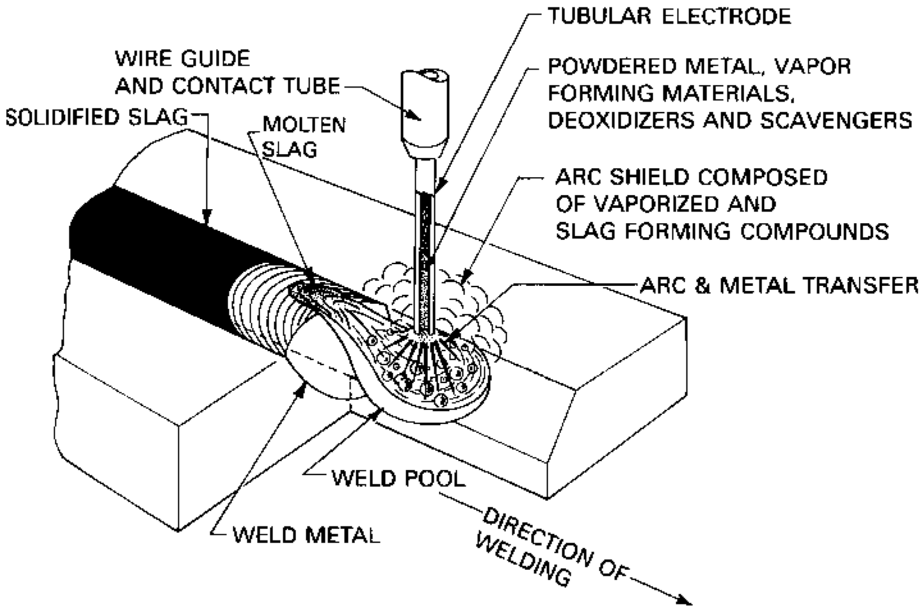


Fig. 100-11 Self-shielded Flux Cored Arc Welding (FCAW-SS) *(Courtesy of the American Welding Society)*



Gas Shielded Flux Cored Arc Welding (FCAW-G)

FCAW-G electrodes are available for welding carbon steels, low alloy steels, and stainless steels. AWS designations for electrodes used for FCAW welding are discussed in Section 133. For carbon and low alloy steels, T-1 (acid slag), T-2 (single pass welding) and T-5 (basic slag) type flux cored electrodes are generally used.

T-1 type electrodes have good welding characteristics, but the acid slag does not help keep weld metal low in hydrogen unless specially formulated. Only a limited number of flux cored electrodes meet low hydrogen requirements (i.e., less than 10 ml/100 g weld metal), and these are most commonly available in the T-1 type. The T-1 type can be used with either CO_2 or argon-CO_2 shielding gas. T-1 electrodes have a smoother arc and less spatter with argon-CO_2, although the weld is slightly higher in manganese and silicon. EX0T-1 electrodes are designed for flat and horizontal position welding only. All-position welding can be performed with EX1T-1 electrodes in diameters up to 1/16 inch. Vertical welding is generally done in the uphill direction.

The T-2 type electrodes are designed for single pass welding on rusty materials, and are higher in the deoxidizers manganese and silicon. T-2 type electrodes should never be used for multipass welds because the additional manganese and silicon cause the undiluted weld tensile strength to increase sufficiently (to above 100 ksi) to cause cracking problems either during welding or in sour service.

T-5 type electrodes use a basic slag that has lower weld metal hydrogen and promotes good impact properties and resistance to cracking. However, it also has poorer welding characteristics than T-1 type electrodes. Newer T-1 electrodes have been developed that incorporate the best of both types of electrodes; as a result, T-5 electrodes are less often used.

Self-Shielded Flux Cored Arc Welding (FCAW-SS)

EX1T-8 electrodes are FCAW-SS electrodes (Lincoln Innershield) for welding carbon and low alloy steels that are of greatest interest for Company applications. These can be used in all positions, have good notch toughness and are generally low in hydrogen (less than 10 ml/100 g weld metal). These electrodes are used in sizes from 0.068- to 3/32-inch diameter. All-position welding is done with 5/64-inch diameter or smaller electrodes, while the larger diameter wires are used only for flat or horizontal welding. Downhill welding is generally not done except when using electrodes that are specially formulated for pipeline welding. Self-shielded electrodes have denitrifiers added to them to prevent porosity caused by nitrogen picked up during welding. Aluminum is generally used for denitrifying the weld; a weld deposit of up to 1% aluminum is not considered harmful.

Welds made with the FCAW-SS process in critical applications, such as T-Y-K joints (T-, Y-, and K-shaped joints and their combinations) for offshore platforms, require special welder training and strict adherence to established welding procedures, as well as attention to electrode stickout, weave width, pass thickness, and preheat.

Advantages

The FCAW-G process has the advantage of deeper penetration and higher deposition rates than the SMAW process. As a result, it can be more economical in many shop applications. Alloying elements can be added to the flux core to provide a wide variety of compositions, including many low alloy and stainless steels. The flux provides good protection of the molten puddle by generating both a protective gas blanket and a slag covering. However, the process will not tolerate air currents exceeding about 5 mph without excessive porosity. FCAW-G is suitable for all-position welding without the problems of lack of fusion associated with GMAW short-circuiting welding.

FCAW-SS filler metals eliminate the need for external shielding gas and tolerate more severe wind conditions without excessive porosity. The process is considered to be equal to coated electrode processes in tolerance to wind. With good welder training and careful supervision, FCAW-SS can be used for single-sided T-Y-K joints on offshore structures in lieu of coated electrodes. FCAW-SS can also be used for all-position fill passes on butt or fillet welds. Welders need training in special procedures but the process is easy to use. FCAW-SS welding applications include heavy sections, pipelines, and weld overlay.

Disadvantages

Both FCAW-G and FCAW-SS produce a slag that has to be removed from the weld between passes. Neither FCAW-G nor FCAW-SS are low hydrogen processes; filler metals should be purchased only from electrode manufacturers who will furnish them to low hydrogen requirements. Welds made with these processes can have poor notch toughness. Filler metals should be used that are manufactured to impact testing requirements, such as T-1, T-5, and T-8 electrodes. These electrodes are also generally lower in hydrogen, and they have specific chemistry requirements for more consistent properties. The FCAW-G process should not be used where the wind exceeds about 5 mph because of the risk of excessive porosity. Increasing gas flow to overcome excessive wind is not a solution, as it may make conditions worse by creating turbulence that draws in additional air.

The FCAW-G process produces more smoke than solid wire GMAW. FCAW-SS wires produce even larger amounts of smoke, so for shop applications it requires good ventilation and sometimes special smoke removal equipment at the welding gun. The fume rate for stainless steel FCAW-SS or FCAW-G wires is about the same as for stick electrodes, and is less than for carbon steel self-shielded wires. Welds made with FCAW-SS wires require strict control of bead thickness and width and of electrode stickout to obtain high toughness properties.

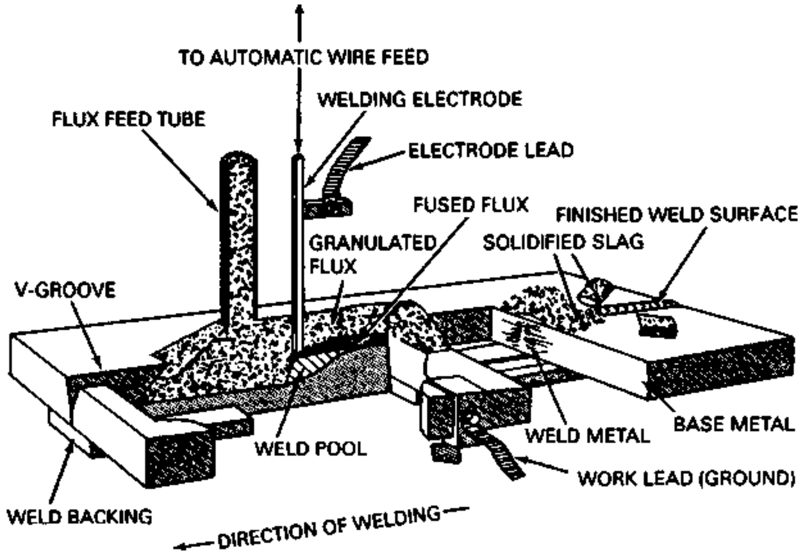
Company Applications

The FCAW-G process can be used in all positions on structural, piping, or pressure vessel butt and fillet welds. The FCAW-SS process is particularly advantageous for structural work, such as for buildings and offshore platforms where field locations or complexity of structures make the use of submerged arc equipment impractical and SMAW less competitive. Self-shielded wires can be used for root and fill passes for single-sided T-Y-K joints on offshore platforms if the Contractor demonstrates that he has experience with the process, trained welders and inspectors, and qualified welding procedures.

115 Submerged Arc Welding (SAW)

In **submerged arc welding** (SAW), the arc and molten weld metal are shielded by an envelope of molten flux and a layer of unfused granular flux particles as shown in Figure 100-12. The welding arc is not visible. A consumable electrode is continuously fed from a coil in a manner similar to the GMAW process. The heat of the arc melts the base metal, electrode, and flux to produce a molten puddle of weld metal covered by a layer of liquid slag. The slag protects the puddle until it solidifies. Because the arc is not visible, the weld is made without the intense radiation that characterizes the open arc processes and it produces very little fumes.

Fig. 100-12 Submerged Arc Welding (SAW) *(Courtesy of the American Welding Society)*



The most common use of SAW has been for shop applications where the work can be positioned for flat position welding to take advantage of the higher deposition rates of the process. SAW has also been used in the field for welding horizontal girth seams in oil storage tanks using special 3 o'clock welding equipment, and on sphere plates that are sub-assembled on site and positioned for flat position welding.

Due to the deep penetration of SAW, it is not suitable for root pass welding without some form of backup to support the weld. The backup can be either temporary or permanent. One-sided welds can be made with temporary backing materials such as copper backup bars, flux backup, or special backup tapes using flux or ceramics. Other temporary materials are steel backup bars, which are also used for fit-up of the weld joint. These are removed before welding the second side.

Weld joints for SAW are generally designed with a heavier land and without a gap in order to support the weld during welding of the first side. With the greater penetration of SAW, the second side can often be welded without backgouging. An example of this is **double submerged arc welding** (commonly referred to as DSW), used by pipe manufacturers.

SAW can be used with either direct current (DC) or alternating current (AC), but DC is preferred because of easier arc starting and greater penetration. One variation of SAW is **tandem arc welding**, which uses two electrodes, and can be run either DC-AC or AC-AC. SAW is usually employed as an automatic welding process. It can be operated semiautomatically with a hand-held gun but the deposition rate is less favorable. SAW flux should be stored in a warm, dry area and reconditioned if it becomes damp (per the manufacturer's instructions). Wire for SAW also requires dry storage.

Advantages

The SAW process can be used for welding carbon steel, low alloy steels, stainless steels and some high nickel alloys. It is used extensively for making corrosion resistant overlays using strip electrodes (e.g., 0.5 mm thick by 60 mm wide). Both higher welding currents and multiple electrodes can be used with the process to achieve deposition rates from two to ten times that of SMAW. The deep penetration characteristics of the SAW process allow use of smaller weld grooves, which decreases both the number of passes required and the welding time. The slag covering the weld provides excellent protection of the molten weld metal, resulting in high quality weld deposits.

SAW does not have the intense radiation of an open arc process, and this gives it greater welder appeal. SAW is a low hydrogen welding process, but the hydrogen level depends on the type of flux selected and its dryness. SAW heat affected zones (HAZs) tend to be lower in hardness because the higher heat input results in slower cooling rates. The generally smooth bead appearance of SAW welds makes for easier visual inspection for defects caused by operator error or equipment malfunction.

Disadvantages

For most applications, SAW requires additional handling and setup time to position work so welding can be done in the flat position. The lack of visibility of the arc and molten puddle during welding makes it harder to keep the weld positioned in the joint, although this is generally not a problem. Setup time for welding is usually greater for SAW than for SMAW and GMAW, so the process is not as cost effective on smaller jobs. Where higher heat input is used, grain coarsening can occur in the HAZ. This can cause a loss of impact properties, which may not be acceptable in some applications. For multipass welds, wire/flux combinations have to be selected that will avoid manganese and silicon buildup in the weld, since buildup of these elements increases hardness, lowers toughness, and can cause cracking problems in sour service.

Common welding defects include:

- Porosity due to weld contamination. This results from inadequate cleaning of rust and mill scale from the joint.
- Slag entrapment due to excessive convexity or undercut. This happens when slag is trapped along the edge of the weld and is not removed during normal cleaning.

- Centerbead weld cracks due to improper bead shape. This occurs in welds that are deeper than they are wide.

Considerations for Choosing Wire/Flux Combinations

Alloying elements may be added to either the electrode wire or the flux, but better chemistry control is obtained when alloys are added to the wire and a neutral flux is used. Base metal dilution is greater with SAW than with most other welding processes because of increased penetration. Base metal dilution can have a significant effect on weld metal chemistry and should be considered when selecting wire/flux combinations, particularly for thinner materials. Postweld heat treatment (PWHT) reduces weld metal hardness but also lowers tensile strength. PWHT is particularly significant for higher temperatures and longer holding times. The effect of PWHT on tensile strength must be considered in choosing wire/flux combinations. As a result, careful attention has to be paid to selecting wire/flux combinations that will produce weld metal compositions with both proper chemistry and strength.

Company Applications

Most Company installations do not use automatic SAW because there is not enough welding demand to justify the equipment. Even where equipment is available for hand-held semi-automatic welding, the SAW process is less favored than GMAW because GMAW is more versatile.

Most SAW is used on purchased equipment and for field welding of storage tanks and spheres. Because of this, there is more interest in controlling weld quality than in actual welding techniques. SAW is used extensively by our vendors for large structures such as tanks, pressure vessels, ships, and offshore platforms, including subsea drilling equipment. It is also used for weld overlay cladding (for such applications as tube sheets) with either a strip or wire electrodes.

116 Electroslag Welding (ESW) and Electrogas Welding (EGW)

Electroslag Welding (ESW)

ESW is a high deposition rate automatic welding process used primarily for welding sections 2 inches and thicker in a vertical position. Typical applications are pressure vessels, shipbuilding, and structural welding. There are two variations of the ESW process:

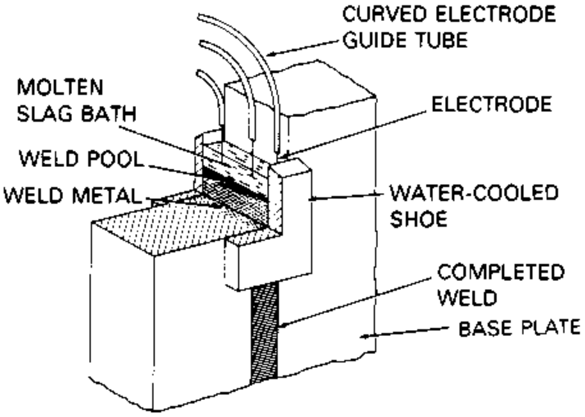
- Conventional (nonconsumable guide) method
- Consumable guide method

These two methods use different equipment and filler metal forms. For both variations of ESW, square edged plates are first positioned vertically with a gap of about one inch between them, then are welded vertically up. A starting tab is used on the bottom of the joint and runoff tabs are used on the top of the joint.

For **conventional ESW**, movable water-cooled copper shoes are used on the front and back side of the joint to hold the molten metal in place until it has solidified.

The process is started by initiating an arc between an electrode wire and the bottom starting tab in the cavity formed between the gapped plate edges and the copper shoes. Granular flux is placed in the cavity. The electric arc initiated at the beginning of the process continues until a conductive slag is formed. Once the slag becomes conductive, the arc extinguishes and the slag is kept molten by resistance heating from current passing between the electrode and the work. During the welding process, flux is added periodically to maintain an adequate slag covering over the pool of molten metal. The resistance heating of the slag melts the filler wire and plate edges to form the molten weld pool, which is retained by the copper shoes. As solidification progresses, the shoes are automatically moved up the plate surfaces. One or more wires are employed, depending on plate thickness.
Figure 100-13 shows a heavy plate electroslag system that uses three wires and is suitable for pressure vessels.

Fig. 100-13 Conventional Electroslag Welding (ESW) Using Three Electrodes *(Courtesy of the American Welding Society)*



Consumable guide ESW uses a consumable guide tube for positioning the electrode wire in the joint, and fixed water-cooled copper shoes. The guide tube does not move but is consumed during welding. This permits the weld pool to rise in the groove. The consumable guide tube adds filler metal to the weld and may also provide the flux for the conductive slag from an outside coating (like a large hollow coated electrode). More than one consumable guide tube may be used to permit welding on thicker material.

Electrogas Welding (EGW)

EGW is performed in the vertical position in a manner similar to ESW, but it differs in that an arc is maintained between a flux cored electrode and a molten weld pool. The molten weld pool is covered with a thin liquid slag and is shielded with CO_2 or argon-CO_2 gas. EGW is limited to thinner sections, usually less than 2 inches. It is commonly used with one movable shoe, which forms the surface of the weld on the front side. The back side of the weld is formed by a fixed copper backup bar or by a root pass made with a manual or semi-automatic process. The weld joint for EGW can be either square edges with a gap or the standard vee groove weld bevels used with other welding processes.

Advantages

The major advantage of the ESW and EGW welding processes is their ability to make vertical welds of various thicknesses in less time than is required for other welding processes. ESW is primarily used for heavy sections in the shop, while EGW can be used either in the shop or in the field. Joint preparation for either process is simple and there is less distortion from welding than with other methods.

Disadvantages

Both the ESW and EGW processes are limited to joining carbon or low alloy steels in the vertical position. Setup time for these processes is very high but is offset by higher deposition rates. The significance of setup time decreases with increasing thickness of the weld. Electroslag welds are sensitive to bead shape control. Centerline cracking can occur when the form factor (weld pool width divided by weld pool depth) is low. An example of a low form factor that is crack sensitive (i.e., unity) is a weld pool as deep as it is wide. Both ESW and EGW are very high in heat input. ESW has the highest heat input, producing large coarse-grained welds and a HAZ low in notch toughness. ESW welds require a grain refinement heat treatment after welding (such as normalizing) to restore notch toughness. The need for normalizing after welding usually prevents the use of ESW for field welding.

The heat input with EGW is not as great as with ESW, but there is some degradation of properties in the HAZ. This limits application of EGW to materials with poorer notch toughness. This limitation has led one contractor to restrict the use of EGW on field storage tanks to those that have minimum service temperatures of +30°F or above.

Company Applications

The most common application of ESW in the Company has been for the longitudinal seams in shell rings for heavy wall carbon steel and low alloy pressure vessels. EGW has been used for the vertical seams of oil storage tanks.

117 Stud Welding (SW)

Stud welding is a relatively easy process to apply. It is commonly used to attach insulation pins and refractory anchors. This process employs a special welding gun and automatic timing control. Welding heat is generated by drawing an arc between a metal stud and the base metal. Once the end of the stud and the surface of the base metal under the stud are molten, the stud is forced against the base metal under pressure, and solidification occurs. A full-strength fusion weld with a narrow weld and heat affected zone is produced.

Stud welding can be accomplished using either drawn-arc or capacitor discharge welding equipment. Drawn-arc stud welding employs a conventional DC welding machine on straight polarity, an automatic timer, and a hand-held gun. Capacitor discharge stud welding employs the rapid discharge of capacitor-stored electrical energy as the source of heat. Studs can be attached by SMAW if automatic stud welding equipment is not available. Surface preparation prior to welding is important to get consistent quality stud welds. Mill scale and rust should be removed prior to welding. This is accomplished by either grinding or abrasive blasting.

Company Applications

Drawn-arc or capacitor discharge welded studs are used extensively for fastening insulation and refractory anchors to piping, pressure vessels and tanks, and for attaching heat conductors on furnace tubes. Stud weld quality should be checked at the start of each shift to determine if the procedure (gun and timer settings) and surface preparation are satisfactory. Visual examination of stud welds (to check for 360 degrees of flash around the base) and bending selected studs approximately 15 degrees from their axis are accepted methods of determining whether the studs are adequately attached. Studs that do not show flash for 360 degrees or break during bending can be repair welded using the SMAW process. The *Insulation and Refractory Manual* contains additional information on selection, installation and inspection of anchors for refractory systems.

118 Oxyfuel Gas Welding (OFW), Braze Welding, and Brazing

Oxyfuel Gas Welding (OFW)

Oxyfuel gas welding (OFW) utilizes the heat of a gas flame to melt the base metal and produce fusion, usually with the addition of filler metal in the form of a wire of the proper composition. The oxyacetylene torch is the most commonly used method, with a flame temperature of about 5600°F. Propane, natural gas, and other alternatives to acetylene fuel gas are not used in gas welding because their heating rate is too slow. Instead, they are used for cutting, preheating and brazing, where the demand on flame characteristics is not as great. Gas welding has generally been replaced by SMAW and newer welding processes. However, OFW is still used for fillet and butt welds in small diameter (2 inch and less) thin wall pipe where GTAW is the only alternative. Gas welding is also used in foundries for repair of iron castings. Figure 100-14 shows details of OFW equipment. Figure 100-15 shows the oxyacetylene flame used for OFW.

Advantages

OFW is used primarily because of its flexibility, portability, and lack of power requirements. Equipment is simple and low cost and can be used for related operations such as cutting, bending, preheating, and brazing. Its effectiveness depends on the skill of the welder in controlling the flame composition, heat input, and torch angle (which affects molten puddle size). Gas welding with a carburizing flame produces highest hardness in hardfacing deposits.

Disadvantages

OFW is slow and builds up localized heat that causes distortion problems. Coarse-grained, brittle structures are common in carbon steel welds because of the high heat input and slow speed of welding. Either carburization or decarburization of the weld

Fig. 100-14 Oxyfuel Gas Welding Equipment *(Courtesy of the American Welding Society)*

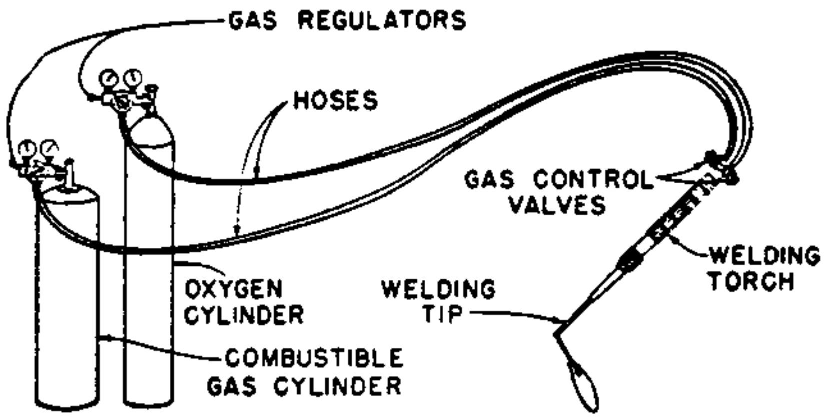
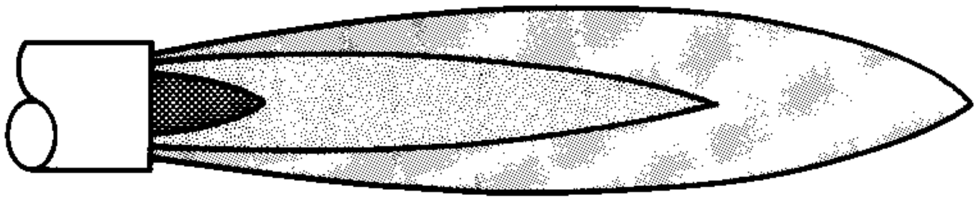


Fig. 100-15 Oxyacetylene Flame *(Courtesy of the American Welding Society)*



	Neutral flame	Oxidizing flame	Reducing flame
▩	White blue cone	White cone	Intense white cone
▨	Nearly colorless	Orange to purplish	White or colorless
░	Bluish to orange		Orange to bluish

and adjacent base metal may occur if the flame is adjusted incorrectly. This can be very damaging to the corrosion resistance of chromium steels and higher alloys.

Braze Welding and Brazing

These joining processes use a gas torch as with OFW, but involve melting of the filler metal only, not the parent metal. Brazing and braze welding use filler metals that melt above 840°F (450°C). Soldering uses filler metals that melt below 840°F (450°C). Silver brazing, formerly called silver soldering, uses a silver-copper alloy for general purpose applications.

In **braze welding**, heat is applied to a weld joint to raise its temperature above the melting point of the filler rod, but not above the melting point of the base metal. The filler metal is then flowed onto the hot surface where, in the presence of a suitable flux, it forms a bond. This process is used for repairing cast iron with a brass filler metal. Brazing is not used on containers used for flammable fluids since it can melt in a fire.

Brazing uses capillary action to cause molten brazing alloy to flow between the closely fitted members of a joint. Butt, lap or socket joints with about two to six mils clearance between parts develop the highest strength. Weaker joints result when fit-up tolerances are not controlled to avoid excessive gaps. However, too small a gap or no gap will prevent brazing alloy from flowing into the joint and can also result in a weak or leaking joint.

119 Cadwelding

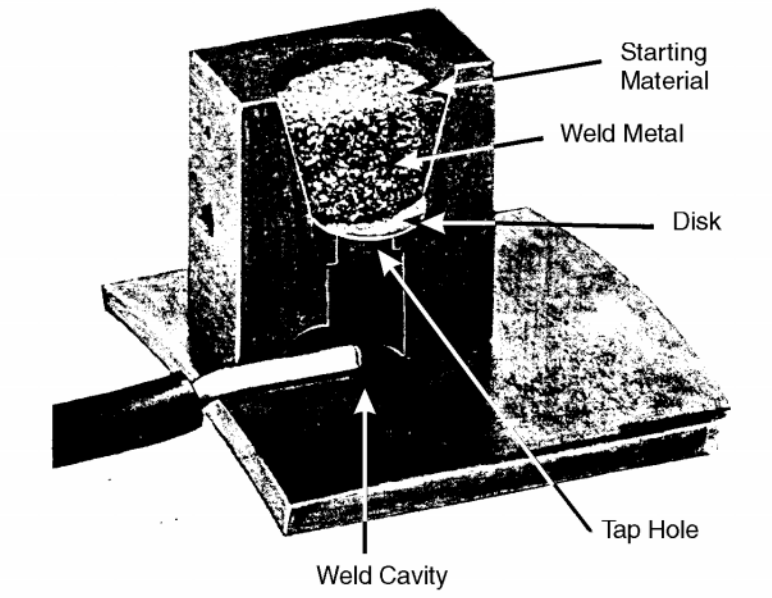
Cadwelding is the trade name for a thermit welding process used for attaching copper electrical connections and ground leads to pipelines and structures. One important pipeline application is the attachment of sacrificial anode wires and test leads for cathodic protection.

The setup for making a Cadweld connection is shown in Figure 100-16. The process consists of exothermically melting a copper alloy powder charge in a reusable graphite mold. The powder charge is supported on a thin metal retaining disk. As the copper alloy becomes molten, it melts through the metal disk, flows through the tap hole into the weld cavity and solidifies on the surfaces of the materials to be joined. Mold types differ for each application. The mold used for bonding small diameter lead wires (typically #4 or less) to pipelines is illustrated in the figure.

The Cadweld powder (F-33) used for attaching cathodic protection leads and test wires to pipelines is a mixture of copper oxide and aluminum with a small amount of vanadium. The powder is furnished in 15 gram (CA15) and larger cartridges. However, the powder charge is limited to 15 grams for ANSI/ASME B31.4 and B31.8 piping systems. A quantity of starting powder is also packed in each cartridge so that the starting powder lies on top of the mixture when the contents are poured into the mold. The charge is ignited using a flint spark igniter and the powders react to produce a melted copper alloy containing aluminum and vanadium. This alloy melts through the metal disk and solidifies on the electrical leads and base metal, bonding them together. A light aluminum-oxide slag is produced which remains on the nugget and walls of the mold. The slag is easily removed by chipping and must be removed from the mold before it can be reused.

Research studies have shown that the metallurgical effects of Cadwelding to pipelines are not deleterious for most API 5L line pipe grades (X-65 and below) in thicknesses of 0.2 inch and greater. Cadweld applications on thicknesses less than 0.2 inches should be evaluated individually. The evaluation should include the pipeline fluid (gas or liquid), temperature, pressure, and flow rate. The primary concerns are the reduced wall strength during welding, increased depth of heat-affected zones, and increased copper penetration.

Fig. 100-16 Cadweld Setup Used For Joining Electrical Lead Wires To Pipe.



Other Welding Processes

Several joining and spraying processes will not be discussed here because of their limited application for Company use. These processes include:

- Plasma arc welding
- Electron beam welding
- Laser welding
- Resistance welding
  - Flash welding
  - Projection welding
  - Resistance seam welding
  - Resistance spot welding
- Friction and inertia welding
- Explosion welding

120 Weld Joint Design

121 Joint Design Considerations

Proper joint design is important because it can affect the method of joint preparation, welding sequence, joint efficiency, and productivity. Each application should be evaluated in terms of welding process, position, accessibility for welding and inspection, distortion control, and design requirements to determine the proper joint detail. The best results can only be obtained if the joint is properly prepared and the fit-up is correct. As a minimum, consult the applicable code for guidance in joint design.

Much Company welding involves the containment of hazardous fluids (in pressure vessels, storage tanks, and piping) or is for structural welding of critical joints in offshore platforms. For these applications, it is important that the welds have adequate strength and toughness, and that they be free of discontinuities and crevices where corrosive substances can concentrate.

Full penetration butt welds with chemical composition and mechanical properties matching the base metal are generally required because they provide the best service performance and resistance to fatigue, corrosion, and brittle fracture. Partial penetration welds and fillet welds are used only where service and stresses are less severe. For example, fillet welds are used on oil storage tanks for lap welded bottoms and roof plates because they are more economical than butt welds and they have a history of successful use in this application. On the other hand, tank shell seams, which have much higher stresses, are joined with full penetration butt welds.

Standard welding symbols for welding, brazing, and nondestructive examination are described in detail in ANSI/AWS A2.4-86. A chart showing basic AWS welding symbols is provided in Figure 100-37, and in Appendix E.

122 Joint Details

Commonly used joint details suitable for shielded metal arc welding (SMAW) of plate and pipe are described.

Square Butt Joints

For the SMAW process, the square butt joint (Figure 100-17) is practical for single welded pipe joints up to 1/8 inch thick and for double welded plate joints with thicknesses up to 5/16 inch. Full penetration girth welds on pipe can made by welding from one side, but greater skills are required and only cellulosic electrodes can be used. For plate welds, backgouging is required to achieved full penetration for thicknesses from about 1/8 inch to 5/16 inch. Square butt joints are the easiest joints to prepare because no beveling is required. Joints can be prepared by oxyfuel gas cutting, machining, or shearing.

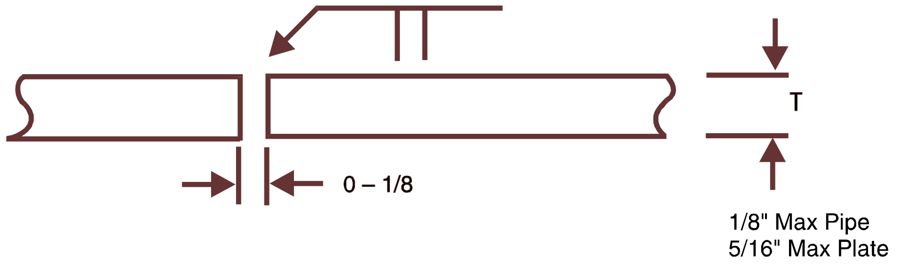
Single Vee Joints

With the SMAW process, the single vee joint design (Figure 100-18) is commonly used for single welded pipe joints and double welded plate joints with thicknesses up to about 3/4 inch. This type of joint can be prepared by oxyfuel gas cutting or by machining.

Double Vee Joints

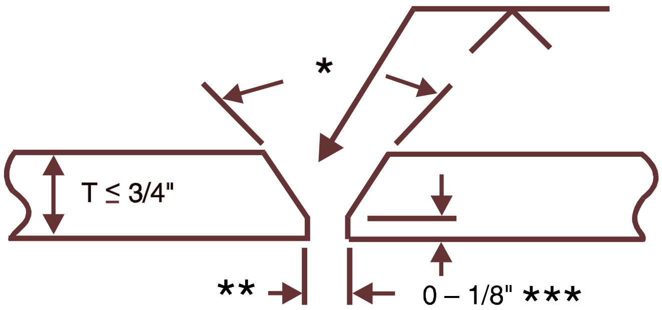
Double vee joints (Figure 100-19) are more economical for welding plate thicknesses from 3/4 inch to 2-1/2 inches with SMAW because the volume of weld metal required is less than for a single vee joint. Backgouging the root after welding from the first side is necessary to obtain complete penetration. Better distortion control

Fig. 100-17 Square Butt Joint *(Courtesy of the American Welding Society)*



Note: For single welded pipe joints use 1/16" gap.

Fig. 100-18 Single Vee Joint *(Courtesy of the American Welding Society)*



* 60° for plate; 75° for pipe

** Use 0 gap for plate and 1/16 – 1/8" gap for pipe.

*** Use 3/32" max. land for pipe welded downhill.

can obtained with welding from both sides of the joint because the weld on the second side helps balance the weld on the first side. For double bevel joints having **unequal** depths, the first side welded is the normally the deepest side (e.g., 0.67T) because backgouging will tend to balance the weld depths. For joints having **equal** depths, either side can be welded first. This type of joint can be prepared by oxyfuel gas cutting or by machining.

Modified Joints for Pipe Welding

When welding pipe over 3/4 inch thick with SMAW, either a modified vee joint or a single U joint (see Figure 100-20) can be used instead of the standard single vee pipe joint. Since preparation for these modified joints must be by machining, they can be more expensive than single vee joints. However, the weld volume is less and their use can reduce welding time.

Fig. 100-19 Double Vee Joint *(Courtesy of the American Welding Society)*

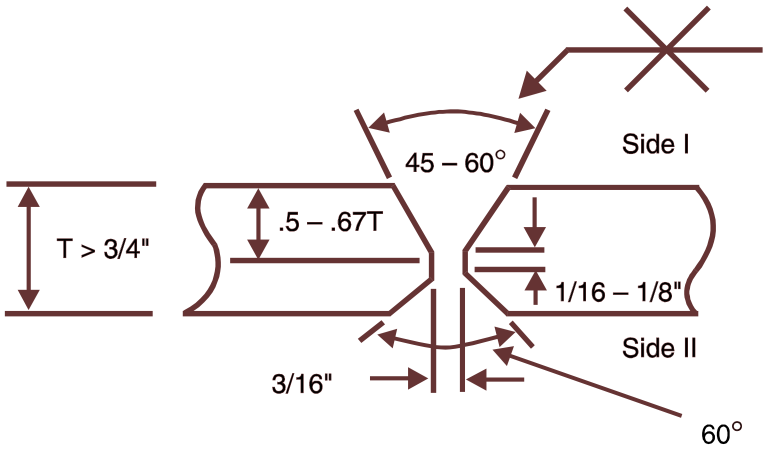
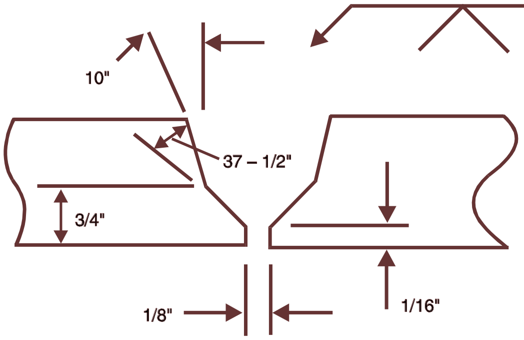
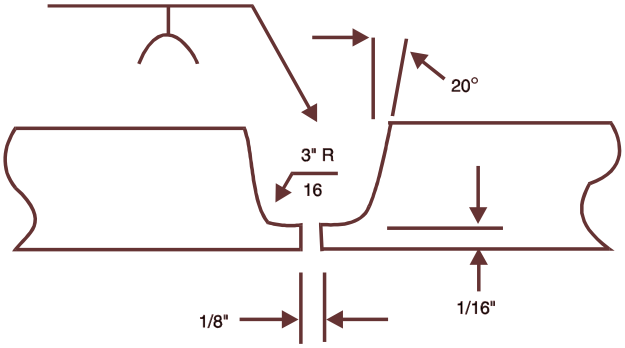


Fig. 100-20 Pipe Joints for Heavier Wall Thicknesses *(Courtesy of the American Welding Society)*



(A) Modified Vee Joint

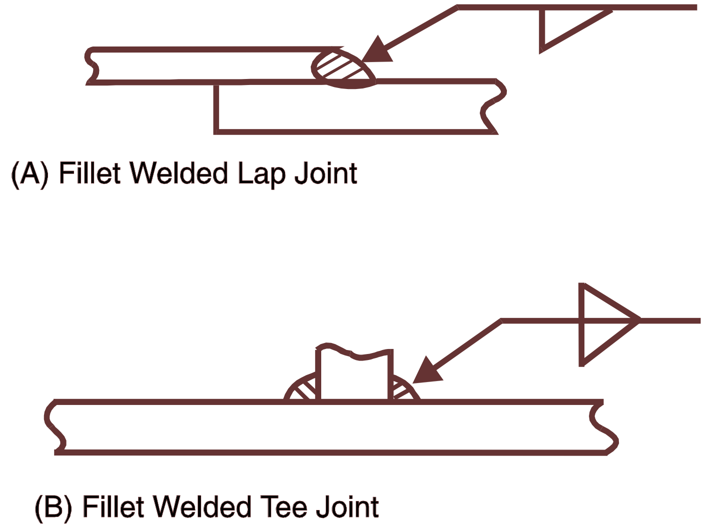


(B) Single U Joint

Fillet Welds

Fillet welds (see Figure 100-21) require a minimum of joint preparation. Fit-up of lap or tee joints must be relatively close (generally within 1/16 inch) or the effective throat of the fillet weld will not be developed. Wider gaps require either increasing the size of the fillet or weld buildup of one edge to compensate for the gap.

Fig. 100-21 Fillet Welds *(Courtesy of the American Welding Society)*

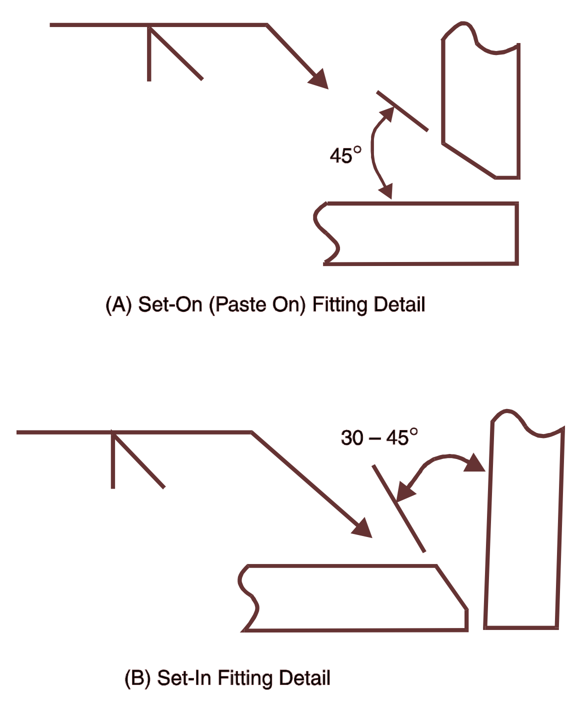


Weld Joint Details for Fittings

Attachment welds for fittings may be either set-on (paste on) or set-in (see Figure 100-22). Set-on details are generally used for small diameter fittings (2 inches or less) that are welded from one side. These may be couplings, weldolets, or small forgings that are bored out after welding.

Set-in details are used for larger diameter fittings, and are generally full penetration welds that require welding from both sides. Reinforcement for loss of area is often required and may require a pad plate or reinforcement of the fitting itself. Consult the appropriate code for specific design details.

Fig. 100-22 Fitting Weld Joint Details *(Courtesy of the American Welding Society)*

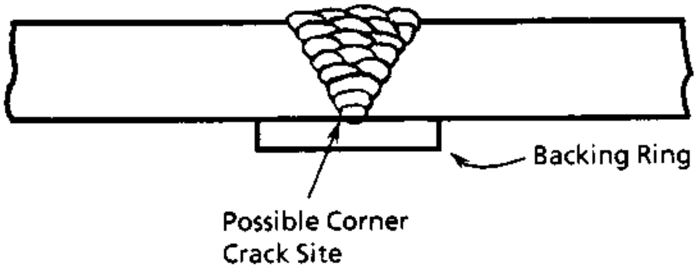


123 Backing Rings and Consumable Inserts

Permanent Backing Rings

Permanent backing rings are used to support the molten weld metal (see Figure 100-23). They are generally not permitted for process piping because they provide sites for corrosive sludge to build up, foster crevice corrosion, and block internal cleaning tools. They can also promote root cracking if service conditions are cyclic and reversing stress conditions occur at the root. For applications where these factors are not a problem, backing rings can facilitate consistent root pass quality with less welder skill.

Fig. 100-23 Backing Ring *(Courtesy of the American Welding Society)*



Consumable Inserts

Consumable inserts, unlike backing rings, are consumed or fused into the root pass of the joint during welding. They are used for making radiograph quality root passes on pipe welds that require better bead shape and fewer repairs and rejects. Consumable inserts come in several designs. They are frequently called by name of the originator of their design or by their shape, such as:

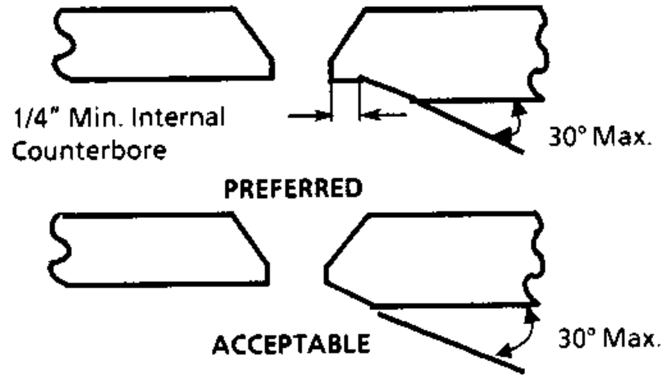
- Grinnell inserts (flat rectangular section)
- "Y" ring inserts
- EB (electric boat) inserts (formed ring type)
- Kellogg inserts (flattened round wire)

Weld joints using consumable inserts require closer control of tolerances for machining and fit-up in order to avoid incomplete fusion of the insert. Typical tolerances for fit-up and land preparation are ±0.010 inch. Consumable inserts are generally acceptable because they are fully consumed during welding and are usually of the same chemical composition as the filler metal. Welders need experience or training in welding with consumable inserts in order to obtain complete melting and fusion of the inserts. Detailed dimensions and requirements for consumable inserts are given in AWS A5.30.

124 Thickness Variations

Sometimes the thickness of abutting portions of a joint are different. A common example is the joining of different schedules of pipe, such as Schedule 80 elbows to Schedule 40 pipe, where the thicker elbow must be tapered to match the thinner pipe in order to obtain acceptable root quality. The taper will vary for different codes. Figure 100-24 illustrates two methods for matching a thicker pipe to an abutting thinner pipe.

Fig. 100-24 End Preparation for Pipe of Unequal Wall Thickness *(Courtesy of the American Welding Society)*



Seamless pipe can have significant variations in wall thickness when the inside diameter and outside diameter are not concentric. Poor fit-up may be encountered when the thicker portion of the wall of one pipe is matched with the thinner portion of the other. Counterboring can be used to match the bores as long as minimum wall thickness or required stress level is not violated.

The codes generally do not permit abrupt changes in the abutting thicknesses of butt welded joints, because of increased stress concentration. Additionally, single welded joints in pipe or plate must fit essentially flush on the back side to avoid root defects such as incomplete penetration.

For pressure vessels having wall thicknesses that are unequal, a taper should be provided if thicknesses differ by more than one-fourth the thinner section, or if thicknesses differ by more than 1/8 inch, whichever is less. (See Figure 100-25.) The transition may be formed by any process that will provide a uniform taper, such as weld buildup, grinding, or flame beveling. The length of the required taper may include the width of the weld.

125 Code and Company Requirements

The codes followed by the Company are:

- ASME Code for boilers and pressure vessels
- ANSI/ASME B31.3 Code for piping
- ANSI/ASME B31.4 Code, B31.8 Code and API Std. 1104 for pipelines
- API Std. 12D, 620, 650, 653 for storage tanks
- AWS D1.1 for structures

Various Company publications are available for additional information as outlined below.

Pressure Vessels

Pressure vessel welding is covered by the ASME Code Section VIII, Division 1.

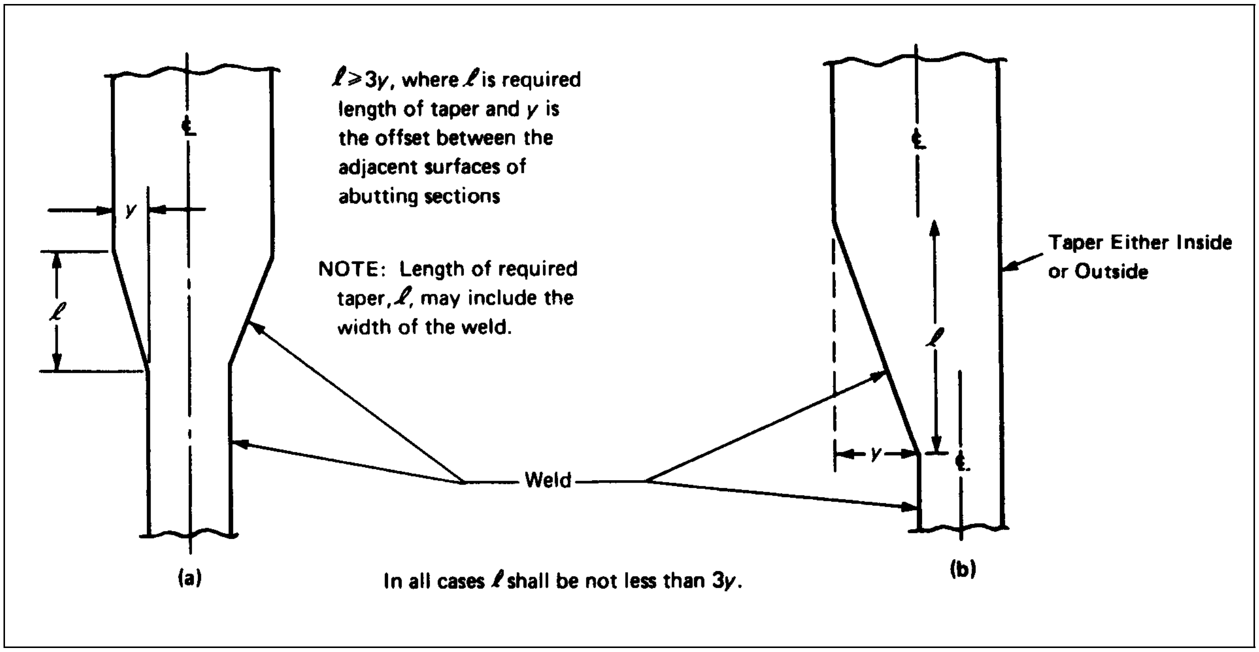
Joint design must provide the access, dimensions, and shape that will obtain the required fusion and penetration.

See Figure 100-25 for the preparation of joints of unequal thickness. Vessels made up of two or more courses should have the longitudinal welds in adjacent courses staggered by a distance of at least five times the thickness of the thicker plate.

Nozzles or reinforcements to pressure vessels should be attached with sufficient welding to develop the full strength of the reinforcing parts. Nozzle necks must be attached to vessel walls by a full penetration groove weld. Nozzle necks inserted through a hole cut in the vessel wall can be attached by a full penetration groove weld or by partial penetration welds; however, full penetration welds are preferred.

Root valves should be bridge welded if required by Standard Drawing GD-L1057 in the *Piping Manual.*

Fig. 100-25 End Preparation for Plate Edges of Unequal Thickness—Pressure Vessels *(Courtesy of the American Welding Society)*



Additional requirements are given in Specifications PVM-MS-1322, PVM-MS-4748, PVM-MS-4749, PVM-MS-4750, and Standard Drawings GA-C1030, GF-C14311, GF-C87280, and others as applicable. These specifications and standard drawings may be found in the *Pressure Vessel Manual.*

Tanks

Tank construction follows API Standards 12D, 620 or 650. The latter two references and other helpful information may be found in the *Tank Manual,* and Specification TAM-MS-967 should be used.

Piping

Chemical plant and petroleum refinery piping is covered by ANSI/ASME B31.3.

When the internal misalignment of pipe ends exceeds 1/16 inch, the thicker wall piece should be counterbored or taper bored so that the internal surfaces are approximately flush. A 4:1 bevel is recommended, but the bevel should not be greater than 30 degrees. This reduces stress concentration, facilitates root pass welding, and improves inspection of the joint when using radiography. Counterboring or tapering should not violate the minimum wall thickness.

Transition pieces may be used between pipes of different thickness, especially where the yield strengths are also different. See Section 600 of the *Pipeline Manual* for a discussion of transition pieces.

Pipelines

Pipeline welding is covered by ANSI/ASME B31.4 and B31.8 in the U.S.A., and by CSA Z183 and Z184 in Canada. Refer to the *Pipeline Manual* for further discussion.

Structural

Structural welds may be either full or partial penetration depending upon the intended service. Structural welding is covered by the Structural Welding Code, AWS D1.1, and is further described in Specification CIV-MS-398 in the *Civil and Structural Manual*.

126 Stresses in Butt Welds and Fillet Welds

Figure 100-26 illustrates the terminology used for fillet welds.

Figures 100-27 through 100-31 give equations for the simple calculations that are used for determining the stresses in butt welds and fillet welds. Consult the applicable code and Company specifications for specific design requirements for each application.

Standard Terms

The standard terms used in calculating the stresses in the weld joints in the following examples are:

S = normal stress, psi

Ss = shear stress, psi

M = bending moment, in.-lb

P = external load, lb

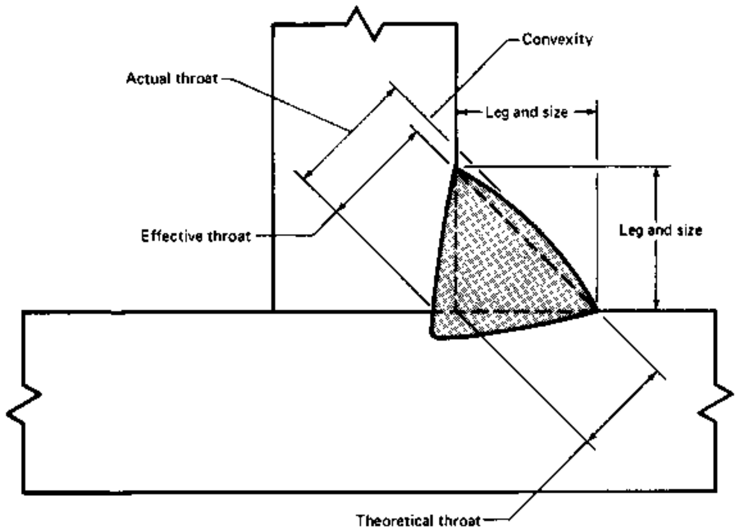
L = length of weld, in.

h = size of weld, in.

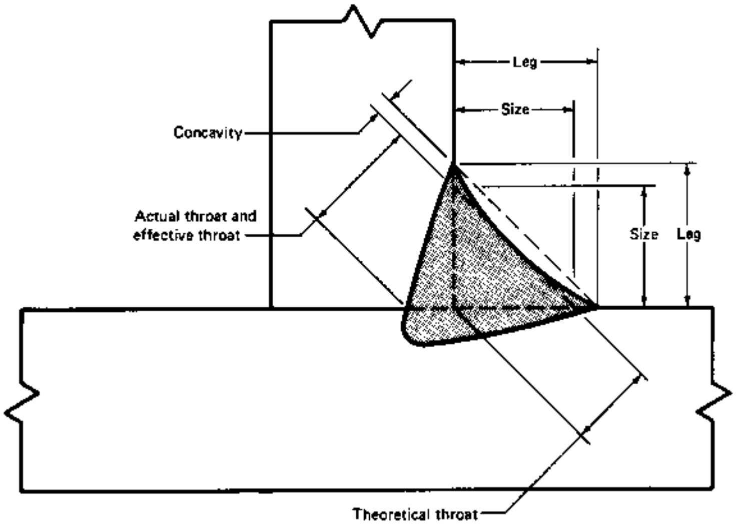
For fillet welds, h = fillet size

For butt welds, h = weld throat size excluding reinforcement

Fig. 100-26 Field Weld Terminology *(Courtesy of the American Welding Society)*

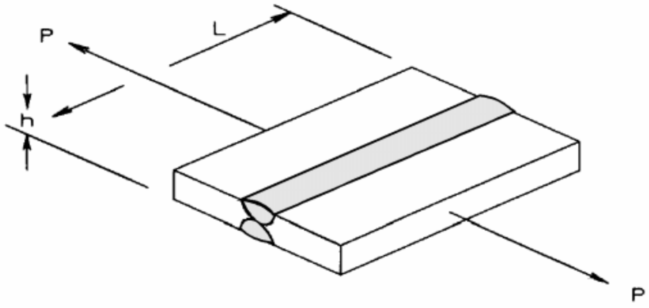


(A) Convex fillet weld



(B) Concave fillet weld

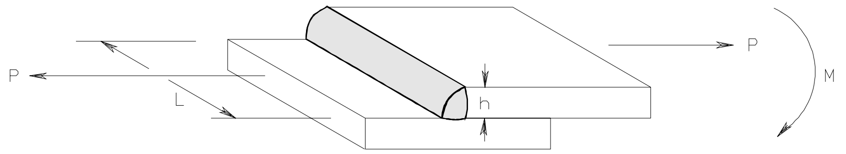
Fig. 100-27 Butt Weld with Direct Loading Stresses In Fillet Welds *(Courtesy of the American Welding Society)*



To calculate stresses
in butt welds with direct loading:

$S = \frac{P}{hL}$ $Ss = \frac{P}{2hL}$ (Eq. 100-1)

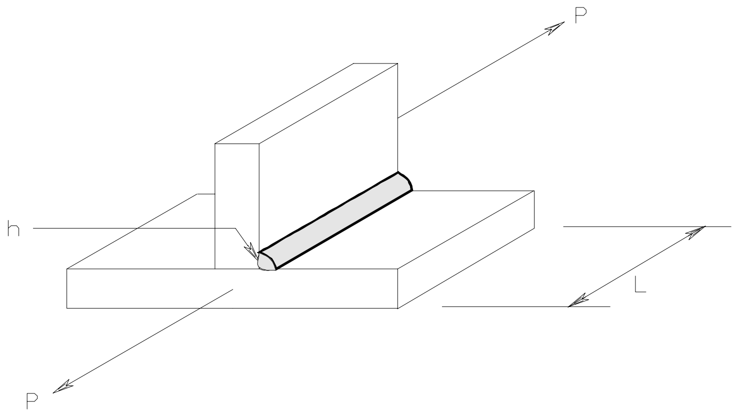
Fig. 100-29 Bending Moment in a Fillet Weld *(Courtesy of the American Welding Society)*



To calculate stress caused by bending:

$$S = \frac{3\,P}{hL} \qquad \text{(Eq. 100-3)}$$

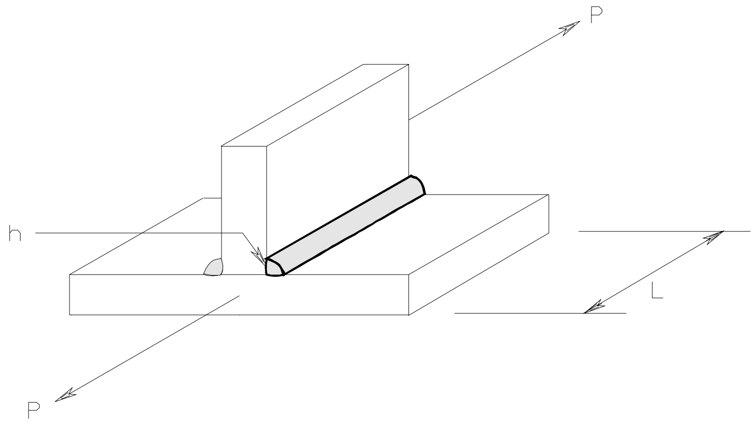
Fig. 100-30 Single Fillet Weld with Parallel Loading *(Courtesy of the American Welding Society)*



To calculate shear stress in a single fillet weld with parallel loading:

$$Ss = \frac{1.414\,P}{hL} \qquad \text{(Eq.100-4)}$$

Fig. 100-31 Double Fillet Weld with Parallel Loading *(Courtesy of the American Welding Society)*



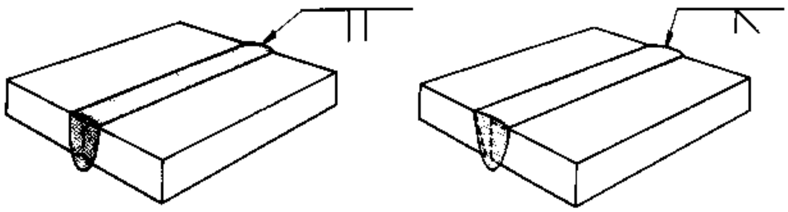
To calculate shear stress in a double fillet weld with parallel loading:

$$Ss = \frac{0.707\ P}{hL} \qquad \text{(Eq.100-5)}$$

127 Joint Terminology and Welding Symbols

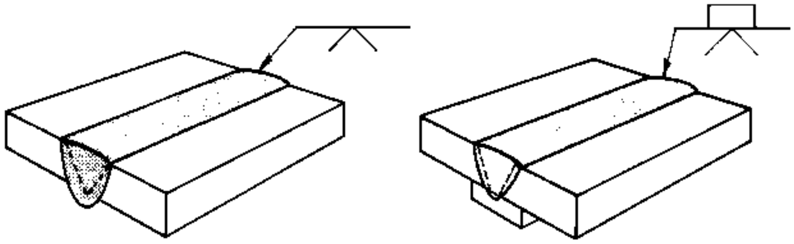
This section (Figures 100-32 through 100-37) shows AWS descriptions and terminology for single groove weld joints and double groove weld joints, along with welding positions for groove welds, fillet welds, and pipe welds. It also shows standard welding symbols used for describing weld joint requirements.

Fig. 100-32 Single Groove Weld Joints *(Courtesy of the American Welding Society)*



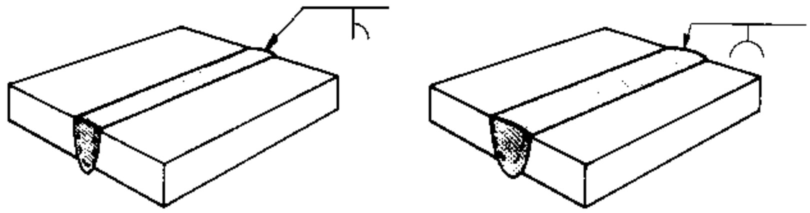
(A)
Single-square-groove weld

(B)
Single-bevel-groove



(C)
Single-V-groove weld

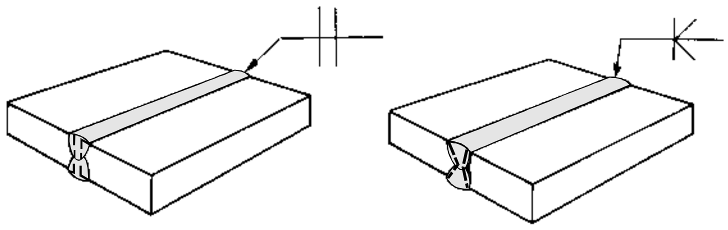
(D)
Single-V-groove weld



(E)
Single-J-groove weld

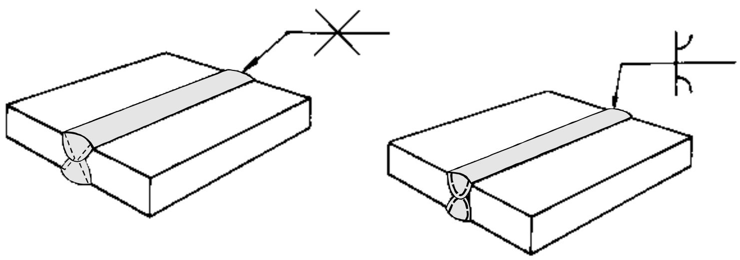
(F)
Single-U-groove

Fig. 100-33 Double Groove Weld Joints *(Courtesy of the American Welding Society)*



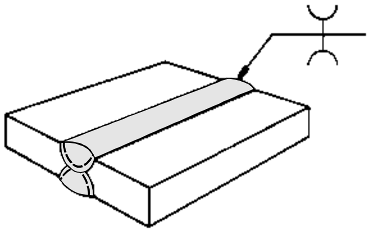
(A)
Double-square-groove weld

(B)
Double-bevel-groove



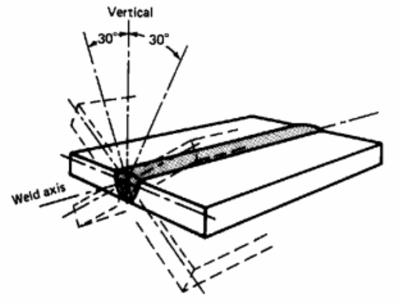
(C)
Double-V-groove weld

(D)
Double-J-groove weld

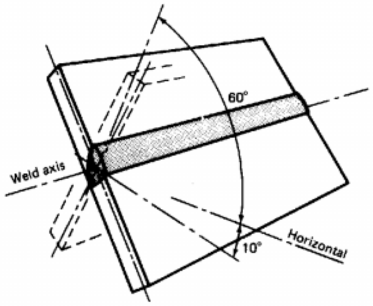


(E)
Double-U-groove weld

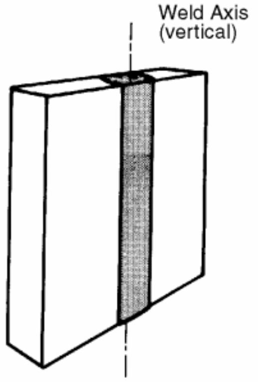
Fig. 100-34 Welding Positions for Groove Welds *(Courtesy of the American Welding Society)*



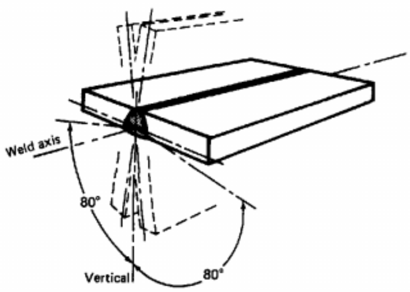
(A) Flat position
1G position



(B) Horizontal position
2G position

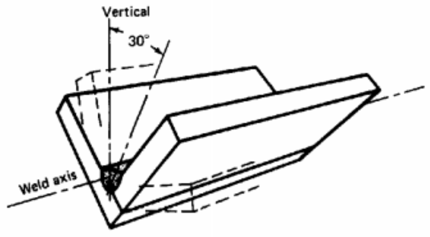


(C) Vertical position
3G position

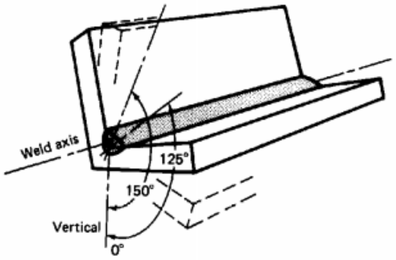


(D) Overhead position
4G position

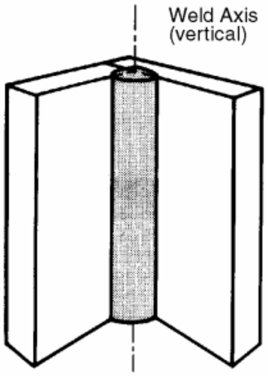
Fig. 100-35 Welding Positions for Fillet Welds *(Courtesy of the American Welding Society)*



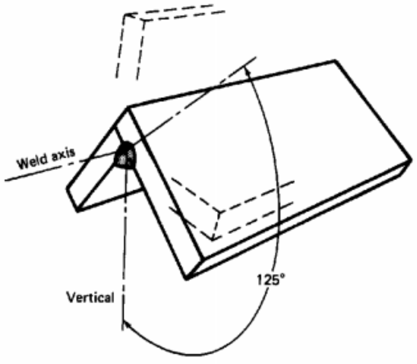
(A) Flat position
1F position



(B) Horizontal position
2F position

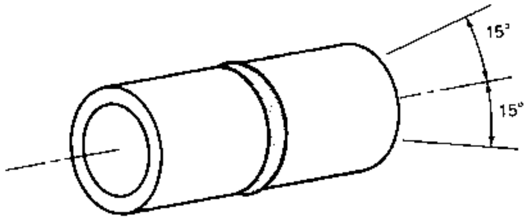


(C) Vertical position
3F position

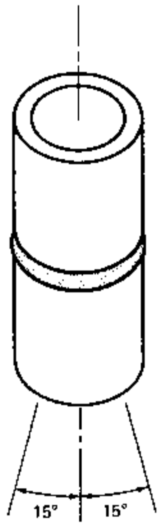


(D) Overhead position
4F position

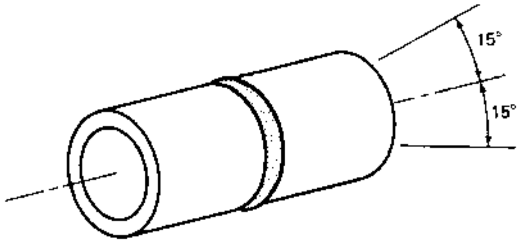
Fig. 100-36 Welding Positions for Pipe Welds *(Courtesy of the American Welding Society)*



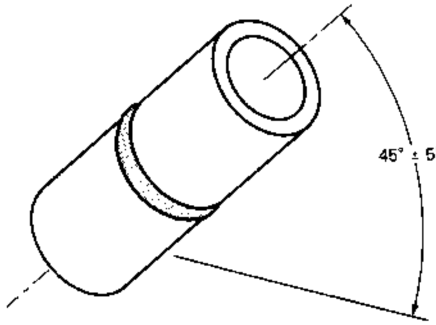
(A) Horizontal rolled position
1G position
(Weld deposited in flat position)

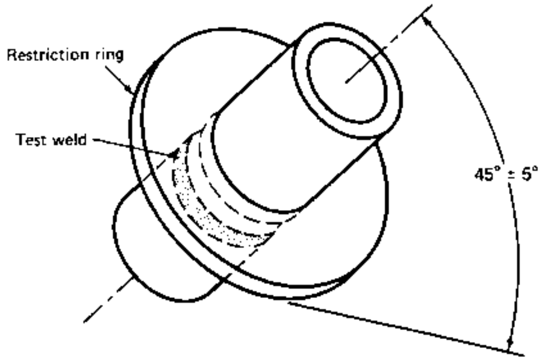


(B) Vertical position
2G position
(Welded in horizontal position)



(C) Horizontal fixed position
5G position
(Weld deposited in flat, vertical, and overhead positions)





(D) Inclined position
6G position
(Weld in flat, vertical, horizontal, and overhead positions)

(E) Inclined position with restriction ring
6GR position

Fig. 100-37 American Welding Society Standard Welding Symbols *(Courtesy of the American Welding Society)* (1 of 2)

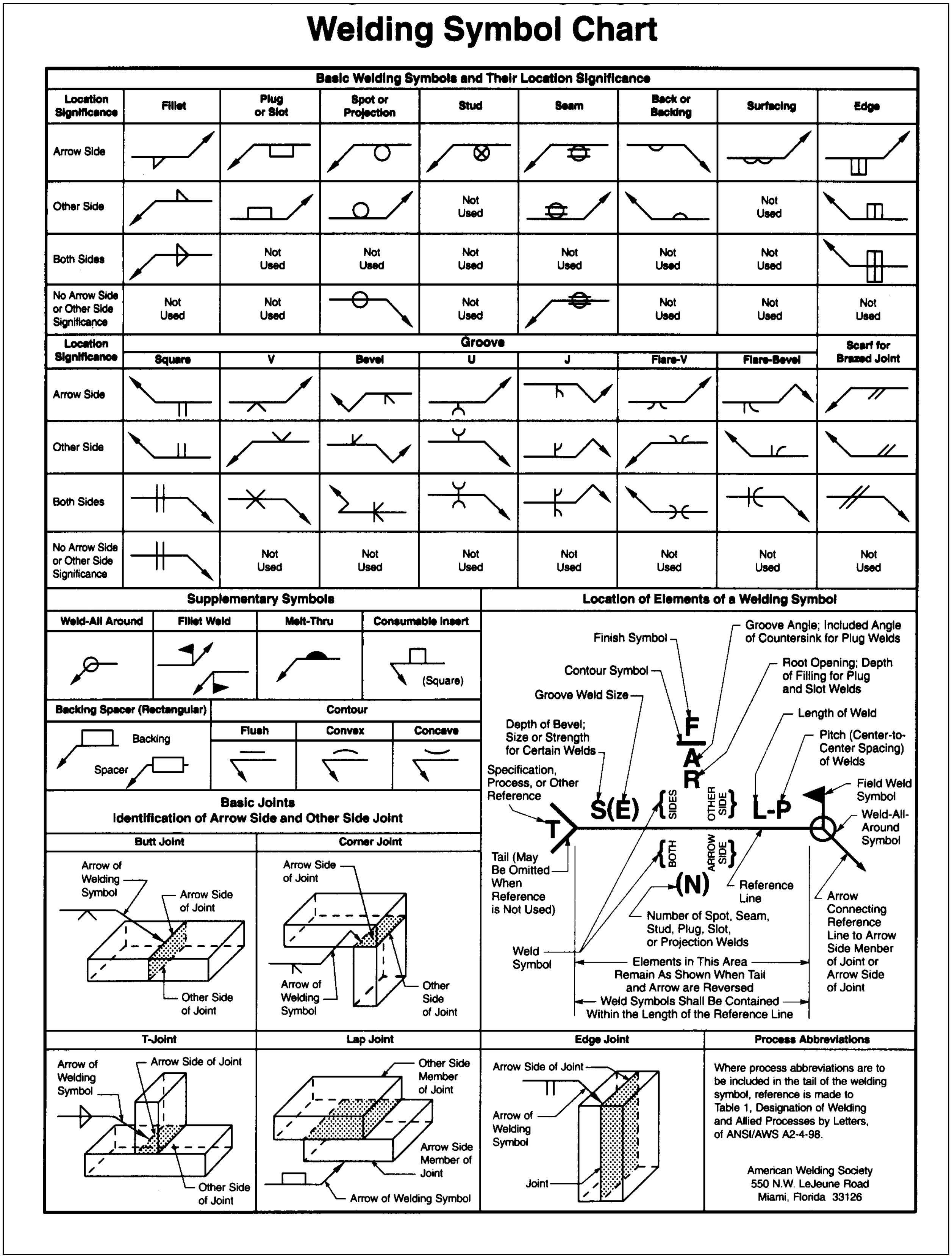
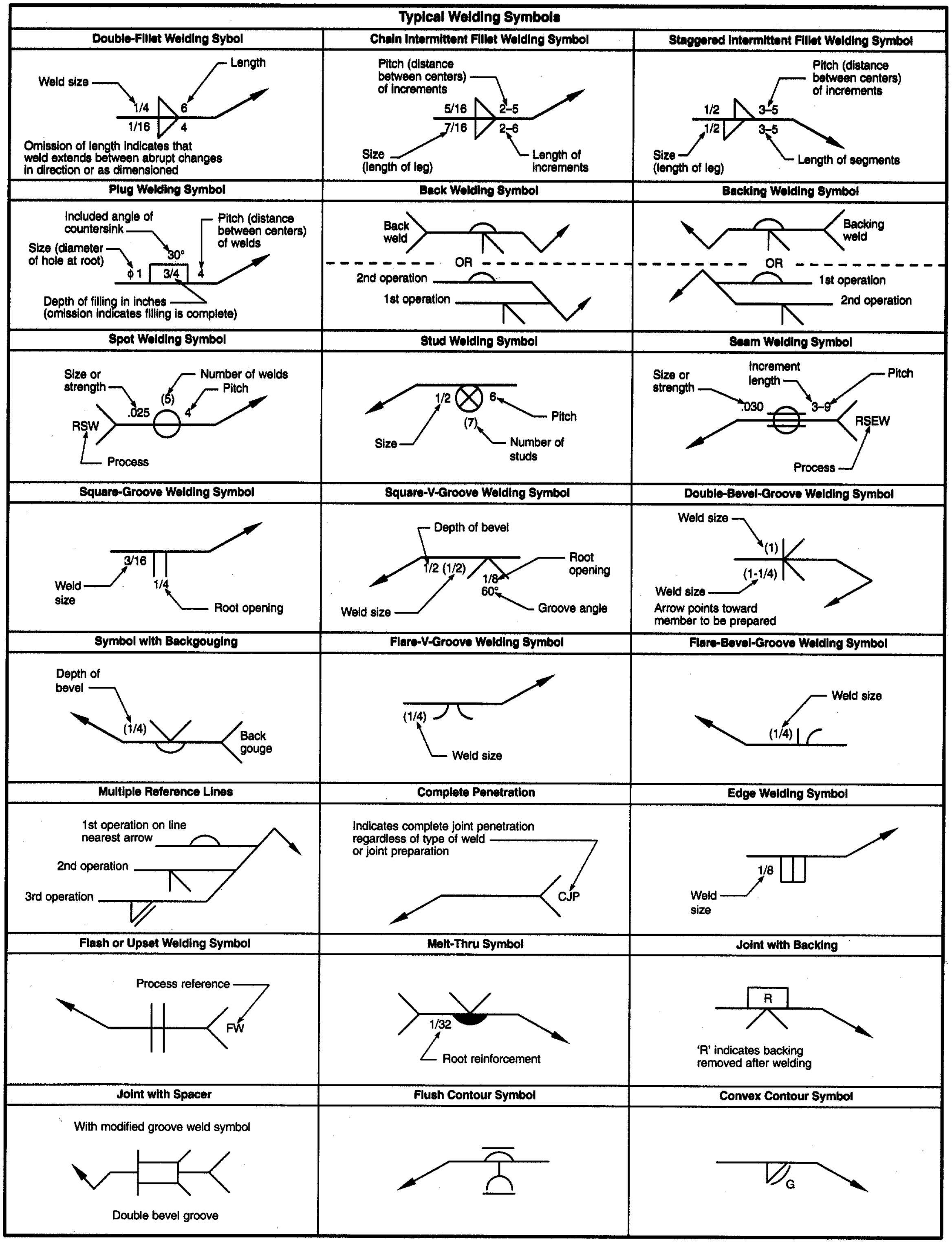


Fig. 100-37 American Welding Society Standard Welding Symbols *(Courtesy of the American Welding Society)* (2 of 2)



*It should be understood that these charts are intended only as shop aids. The only complete and official presentation of the standard welding symbols is in A2.4.

130 Weld Metal Composition

In general, all the steels and alloys permitted by the various codes and standards and used by the Company can be welded when using the proper welding procedures. Data sheets for many of these alloys are given in the Alloy Fabrication Data in Appendix A. The data sheets summarize the applicable ASTM and ASME specifications, give the range of chemical composition and mechanical properties, and give welding requirements such as preheat, heat treatment, welding processes and filler metal selection. Other information on filler metal selection is also covered in Section 300, Welding Practices.

131 Filler Metals

Filler metals are usually selected to be similar to the parent material in composition and mechanical properties, but weld metal composition may vary where:

- Difficult to weld materials are encountered (e.g., welding 13 Cr material with austenitic or Ni-Cr-Fe electrodes)
- Special mechanical properties are required (e.g., carbon steel in low temperature applications where low Ni electrodes are used)
- Dissimilar metal combinations are involved (e.g., welding carbon steel to stainless steel with Ni-Cr-Fe electrodes)

The American Welding Society has thirty-one specifications covering filler metals. There are specifications covering nonconsumable tungsten and carbon electrodes, and for fluxes for brazing, SAW and ESW. The specifications are periodically updated and a two-digit suffix indicating the year issued is added to the specification number. Figure 100-38 shows the welding process or processes discussed for which each specification is intended.

ASME also issues filler metal specifications in Section II, Part C of the Boiler and Pressure Vessel Code. These are identical with the AWS specifications. ASME filler metal specifications are identified by the prefix letters SF added to the AWS specification number (e.g., SFA5.1).

The AWS classification system for filler metals uses the following prefixes to indicate the product form, the joining process, or both:

Indicates an arc welding electrode that carries the welding current. The electrodes can be flux covered, bare, composite or flux cored and are used for SMAW, GMAW, FCAW, GTAW, and SAW welding.

R– Indicates a welding rod that is heated by means other than by carrying the arc welding current.

ER– Indicates a filler metal that may be used either as an arc welding electrode (carrying the current) or as a welding rod.

EW–Indicates a tungsten electrode (nonconsumable).

B– Indicates a brazing filler metal.

RB– Indicates a filler metal that may be used as a welding rod or as a brazing filler metal or both.

RG– Indicates a welding rod to be used in oxyfuel gas welding.

F– Indicates a flux for use in SAW.

IN– Indicates a consumable insert.

Fig. 100-38 AWS Filler Metal Specifications and Respective Welding Processes *(Courtesy of the American Welding Society)*

Spec.	Specification Title	OFW	SMAW	GTAW	GMAW	SAW
A5.1	Carbon steel covered arc welding electrodes		X			
A5.2	Iron and steel gas welding rods	X				
A5.3	Aluminum and aluminum alloy arc welding electrodes		X			
A5.4	Corrosion-resisting chromium and chromium-nickel steel covered welding electrodes		X			
A5.5	Low alloy steel covered arc welding electrodes		X			
A5.6	Copper and copper alloy covered electrodes		X			
A5.7	Copper and copper alloy welding rods	X		X		
A5.8	Brazing filler metal					
A5.9	Corrosion-resisting chromium and chromium-nickel bare and composite metal cored and standard arc welding electrodes and rods			X	X	X
A5.10	Aluminum and aluminum alloy welding rods and bare electrodes	X		X	X	
A5.11	Nickel and nickel alloy covered welding electrodes		X			
A5.12	Tungsten arc welding electrodes			X		
A5.13	Surfacing welding rods and electrodes	X		X		
A5.14	Nickel and nickel alloy bare welding rods and electrodes	X		X	X	X
A5.15	Welding rods and covered electrodes for welding cast iron	X	X			
A5.16	Titanium and titanium alloy bare welding rods and electrodes			X	X	
A5.17	Bare carbon steel electrodes and fluxes for submerged-arc welding					X
A5.18	Carbon steel filler metals for gas shielded arc welding			X	X	
A5.19	Magnesium alloy welding rods and bare electrodes	X		X	X	
A5.20	Carbon steel electrodes for flux cored arc welding				X(1)	
A5.21	Composite surfacing welding rods and electrodes	X	X	X		
A5.22	Flux cored corrosion-resisting chromium and chromium-nickel steel electrodes				X[1]	
A5.23	Bare low alloy steel electrodes and fluxes for submerged arc welding					X
A5.24	Zirconium and zirconium alloy bare welding rods and electrodes			X	X	
A5.25	Consumables used for electroslag welding of carbon and high-strength low alloy steels					
A5.26	Consumables used for electrogas welding of carbon and high-strength low alloy steels				X(2)	
A5.27	Copper and copper alloy gas welding rods	X				
A5.28	Low alloy steel filler metals for gas-shielded arc welding			X	X	
A5.29	Low alloy steel flux cored welding electrodes				X[1]	
A5.30	Consumable inserts			X		

(1) Flux cored arc welding (FCAW).

(2) Electrogas welding (EGW).

132 SMAW Electrodes

The covered electrode for SMAW provides both the filler metal and the shielding gas. Covered electrodes have various core wire compositions and a wide variety of flux coating types. The core wire provides the filler metal for the weld. The flux coating performs one or all of the following functions, depending on the type of electrode:

- Provides shielding gas to prevent contamination of the arc stream and weld metal by oxygen and nitrogen in the atmosphere.
- Forms a slag blanket over the molten puddle and solidified weld.
- Provides ionizing elements for smoother arc operation.
- Provides deoxidizers and scavengers to refine the grain structure of the weld metal.
- Provides alloying elements such as molybdenum, nickel, and chromium for low alloy steels.
- Provides iron powder for higher deposition rates.

For **carbon steel electrodes,** a four digit system is used. See Figure 100-39 for a list of AWS A5.1 SMAW carbon steel electrodes. The first two digits indicate the approximate minimum as-welded tensile strength of the weld metal in ksi (e.g., E60XX or E70XX). The third and fourth digits indicate the electrode coating type. The coating type determines usable welding positions, welding characteristics, and the type of power supply required. For example, E6010 is a 62,000 psi minimum tensile strength electrode with a cellulosic coating. It can be used in all positions, it has a strong deep penetrating arc, and is used on DC reverse polarity. E7018 is a 72,000 psi minimum tensile strength electrode with a low hydrogen, iron powder coating. It can be used in all positions, it has a smooth arc with medium penetration, and is used on DC reverse polarity.

Low alloy steel electrodes are covered by AWS Specification A5.5, which uses a classification system similar to that for carbon steel with the addition of a suffix for chemical composition. See Figure 100-40 for an abbreviated list of AWS A5.5 SMAW low alloy steel electrodes. Higher strength electrodes, with a minimum tensile strength of 100,000 psi and above, use five digits (e.g., E10018-D2). The first three digits stand for tensile strength. The minimum tensile strength can be for either the as-welded or PWHT condition, depending on the classification. The suffix can be a letter and number designation or a letter only, and designates the chemical composition that it must meet. For example, E8018-B2 is a low hydrogen, iron powder electrode with a nominal composition of 1-1/4 Cr-1/2 Mo, and E8010-G is a cellulosic electrode with a general classification that is required only to have the minimum amount of one of the elements listed (the actual composition is left to the electrode manufacturer).

Stainless steel electrodes are covered by AWS Specification A5.4 (for compositions of 5 Cr and above) and are classified according to the AISI designation for the composition of the deposited weld metal and the type of coating (in the last two

Fig. 100-39 AWS A5.1—SMAW Electrodes for Carbon Steel *(Courtesy of the American Welding Society)*

Classification	Coating Type	Position	Current	Strength, ksi		Elongation, min. percent	Characteristics
				Tensile	Yield		
E6010	Cellulose-sodium	all	DCep	62	50	22	Strong, deep-penetrating arc. Thin slag chips off. Fillets are flat. Spatter at high amperages.
E6011	Cellulose-potassium	all	AC, DCep	62	50	22	Same as E6010, but usable AC. Less penetration with DCep. Spatter at high amperages.
E6012	Titania-sodium	all	AC, DCen	67	55	17	Medium penetration. Dense slag. Fillets are convex. Weld metal less ductile, stronger than for E6010 and E6011. Little spatter at high amperages.
E6013	Titania-potassium	all	AC, DCep, DCen	67	55	17	Easier slag removal than for E6012, smoother arc.
E6027	Iron-oxide, iron-powder	flat, horizontal fillet	AC, DCen	62	50	22	Iron-powder cover. Medium penetration, low spatter loss. Heavy slag peels off. High amperage.
E7014	Iron-powder titania	all	AC, DCep, DCen	72	60	17	Similar to E6012 and E6013 with iron-powder addition for higher deposition. Higher amperages. Medium penetration. Slag peels off.
E7016(1)	Low hydrogen, potassium	all	AC, DCep	72	60	22	Low hydrogen. Medium penetration. Slag chips off. Convex weld face.
E7018[1]	Low hydrogen, potassium, iron-powder	all	AC, DCep	72	60	22	Iron-powder covering. Low hydrogen. Smooth arc.
E7024[1]	Iron-powder, titania	flat, horizontal fillet	AC, DCep, DCen	72	60	17	High iron-powder content. Low penetration. Quiet arc.
E7028	Low hydrogen, potassium, iron-powder	flat, horizontal fillet	AC, DCep	72	60	22	Similar to E7018, but heavy iron-powder content in coating. Slag chips off.

(1) -1 following the designation indicates Charpy V-notch requirement of 20 ft-lb at -50°F; for E7024, at 0°F with 22% minimum elongation.

Fig. 100-40 AWS A5.5—SMAW Electrodes For Low Alloy Steel *(Courtesy of the American Welding Society)* (1 of 2)

Classification	Coating Type	Current	Composition, Percent						
			C	Mn	Si	Ni	Cr	Mo	V
Carbon-molybdenum									
E7010-A1	Cellulose-sodium	DCep	0.12	0.60	0.40	—	—	0.40-0.65	—
E7018-A1	Iron-powder, low hydrogen	AC, DCep	0.12	0.90	0.80	—	—	0.40-0.65	—
Chromium-molybdenum									
E8018-B2	Iron-powder, low hydrogen	AC, DCep	0.05-0.12	0.90	0.80	—	1.0-1.5	0.40-0.65	—
E8018-B2L	Iron-powder, low hydrogen	AC, DCep	0.05	0.90	0.80	—	1.0-1.5	0.40-0.65	—
E9018-B3	Iron-powder, low hydrogen	AC, DCep	0.05-0.12	0.90	0.80	—	2.0-2.5	0.90-1.2	—
E9018-B3L	Iron-powder, low hydrogen	AC, DCep	0.05	0.90	0.80	—	2.0-2.5	0.90-1.2	—
E8015-B6 E8016-B6 E8018-B6 (Old E502-XX)(1)	Low hydrogen, lime Low hydrogen, potassium Iron-power, low hydrogen	DCep AC, DCep AC, DCep	0.05-0.10	1.0	0.90	0.40	4.0-6.0	0.45-0.65	—
E8015-B6L E8016-B6L E8018-B6L (Old E502-XX)[1]	Low hydrogen, lime Low hydrogen, potassium Iron-power, low hydrogen	DCep AC, DCep AC, DCep	0.05	1.0	0.90	0.40	4.0-6.0	0.45-0.65	—
E8015-B7 E8016-B7 E8018-B7 (Old E7Cr-XX)[1]	Low hydrogen, lime Low hydrogen, potassium Iron-power, low hydrogen	DCep AC, DCep AC, DCep	0.05-0.10	1.0	0.90	0.40	6.0-8.0	0.45-0.65	—
E8015-B7L E8016-B7L E8018-B7L (Old E7Cr-XX)[1]	Low hydrogen, lime Low hydrogen, potassium Iron-power, low hydrogen	DCep AC, DCep AC, DCep	0.05	1.0	0.90	0.40	6.0-8.0	0.45-0.65	—
E8015-B8 E8016-B8 E8018-B8 (Old E505-XX)[1]	Low hydrogen, lime Low hydrogen, potassium Iron-power, low hydrogen	DCep AC, DCep AC, DCep	0.05-0.10	1.0	0.90	0.40	8.0-10.5	0.85-1.20	—

Fig. 100-40 AWS A5.5—SMAW Electrodes For Low Alloy Steel *(Courtesy of the American Welding Society)* (2 of 2)

Classification	Coating Type	Current	Composition, Percent						
			C	Mn	Si	Ni	Cr	Mo	V
E8015-B8L	Low hydrogen, lime	DCep	0.05	1.0	0.90	0.40	8.0-10.5	0.85-1.20	—
E8016-B8L	Low hydrogen, potassium	AC, DCep							
E8018-B8L	Iron-power, low hydrogen	AC, DCep							
(Old E505-XX)[1]									
Nickel steel									
E8016-C1	Low hydrogen, potassium	AC, DCep	0.12	1.25	0.60	2.0-2.75	—	—	—
E8018-C1	Iron-powder, low hydrogen	AC, DCep							
E8018-C2	Iron-powder, low hydrogen	AC, DCep	0.12	1.25	0.80	3.0-3.75	—	—	—
E8016-C3	Low hydrogen, potassium	AC, DCep	0.12	0.40-1.25	0.80	0.80-1.10	0.15	0.35	0.05
E8018-C3	Iron-powder, low hydrogen	AC, DCep							
Manganese-molybdenum									
10018-D2	Iron-powder, low hydrogen	AC, DCep	0.15	1.65-2.0	0.80	—	—	0.25-0.45	—
Other(2)									
E7010-G	Cellulose-sodium	DCep	—	1.00 min	0.80 min	0.50 min	0.30 min	0.20 min	0.10 min
E8010-G	Cellulose-sodium	DCep	—	1.00 min	0.80 min	0.50 min	0.30 min	0.20 min	0.10 min
E8018-G	Iron-powder, low hydrogen	AC, DCep	—	1.00 min	0.80 min	0.50 min	0.30 min	0.20 min	0.10 min
E9018-G	Iron-powder, low hydrogen	AC, DCep	—	1.00 min	0.80 min	0.50 min	0.30 min	0.20 min	0.10 min

(1) Formerly classified in AWS A5.4

(2) Requires minimum as specified of only one of the elements listed. "G" indicates a special or proprietary electrode of composition specified by the supplier.

digits). The electrode coating types are either lime (-15) or titania (-16). Both coatings are low hydrogen, but they differ in welding characteristics. This affects their usable welding positions and the type of welding current that can be used with them. Lime-coated or basic electrodes (-15) have a less fluid slag, are generally more crack resistant, and are suitable for welding in all positions. Titania-coated electrodes (-16) produce a smoother weld deposit with a tendency to be concave in shape. They are generally only suitable for the flat and horizontal positions. There are also hybrid electrodes that exhibit the bead appearance of titania-coated electrodes and the all-position welding characteristics of lime-coated electrodes. These hybrids are sometimes called DC-titania electrodes.

An example of a coated stainless steel electrode is E316-15. This electrode deposits Type 316 stainless steel weld metal. It has a lime coating that is suitable for all-position welding using DC reverse polarity. An E410-16 electrode deposits a 12% Cr stainless steel weld metal. It has a titania coating that is generally not suitable for all-position welding but may be used on either DC reverse polarity or AC. See Figure 100-41 for an abbreviated list of AWS A5.4 SMAW stainless steel electrodes.

A complete listing of manufacturers' types and trade names of coated and bare electrodes is given in the AWS FMC (Formerly A5.0) Filler Metal Comparison Charts. For composition and properties, consult the AWS specifications referred to in these filler metal comparison charts.

SMAW Electrode Coatings

Low hydrogen electrodes have coatings that absorb moisture when exposed to the atmosphere, so they must be purchased in hermetically sealed containers and properly stored in a heated rod oven after opening to prevent moisture absorption. Under no circumstances should electrodes be allowed to become wet or damp. Electrodes with moisture resistant coatings (called MR electrodes) are now available from several manufacturers. These new electrodes greatly resist moisture pickup and should be used whenever possible.

Absorption of moisture into low hydrogen electrodes can cause hydrogen-induced underbead cracking. The risk of underbead cracking increases with the tensile strength of the electrode. Figure 100-42 gives the recommended maximum atmospheric exposure times (after removal from a sealed container or a heated storage oven) under moderate conditions (70% relative humidity at 70°F) for low hydrogen electrodes of various strength levels.

Electrodes that have been exposed to the atmosphere for times exceeding those shown in Figure 100-42 should either be reconditioned in an oven to remove the moisture in the coating or they should be discarded. Figure 100-43 gives recommended temperatures for storing and reconditioning commonly used electrodes.

Fig. 100-41 AWS A5.4—SMAW Electrodes for Stainless Steel *(Courtesy of the American Welding Society)* (1 of 2)

AWS A5.4—Chemical Composition Requirements for Weld Metal (1),(2)											
AWS Class-ification(3)	**C(4)**	**Cr**	**Ni**	**Mo**	**Cb plus Ta**	**Mn**	**Si**	**P**	**S**	**N**	**Cu**
E209[e]	0.06	20.5-24.0	9.5-12.0	1.5-3.0	—	4.0-7.0	0.90	0.03	0.03	0.10-0.30	0.75
E219	0.06	19.0-21.5	5.5-7.0	0.75	—	8.0-10.0	1.00	0.03	0.03	0.10-0.30	0.75
E240	0.06	17.0-19.0	4.0-6.0	0.75	—	10.5-13.5	1.00	0.03	0.03	0.10-0.20	0.75
E307	0.04-0.14	18.0-21.5	9.0-10.7	0.5-1.5	—	3.3-4.75	0.90	0.04	0.03	—	0.75
E308	0.08	18.0-21.0	9.0-11.0	0.75	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E308H	0.04-0.08	18.0-21.0	9.0-11.0	0.75	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E308L	0.04	18.0-21.0	9.0-11.0	0.75	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E308Mo	0.08	18.0-21.0	9.0-12.0	2.0-3.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E308MoL	0.04	18.0-21.0	9.0-12.0	2.0-3.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E309	0.15	22.0-25.0	12.0-14.0	0.75	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E309L	0.04	22.0-25.0	12.0-14.0	0.75	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E309Cb	0.12	22.0-25.0	12.0-14.0	0.75	0.70-1.00	0.5-2.5	0.90	0.04	0.03	—	0.75
E309Mo	0.12	22.0-25.0	12.0-14.0	2.0-3.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E310	0.08-0.20	25.0-28.0	20.0-22.5	0.75	—	1.5-2.5	0.75	0.03	0.03	—	0.75
E310H	0.35-0.45	25.0-28.0	20.0-22.5	0.75	—	1.5-2.5	0.75	0.03	0.03	—	0.75
E310Cb	0.12	25.0-28.0	20.0-22.0	0.75	0.70-1.00	1.5-2.5	0.75	0.03	0.03	—	0.75
E310Mo	0.12	25.0-28.0	20.0-22.0	2.0-3.0	—	1.5-2.5	0.75	0.03	0.03	—	0.75
E312	0.15	28.0-32.0	8.0-10.5	0.75	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E316	0.08	17.0-20.0	11.0-14.0	2.0-3.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E316H	0.04-0.08	17.0-20.0	11.0-14.0	2.0-3.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E316L	0.04	17.0-20.0	11.0-14.0	2.0-3.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E317	0.08	18.0-21.0	12.0-14.0	3.0-4.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E317L	0.04	18.0-21.0	12.0-14.0	3.0-4.0	—	0.5-2.5	0.90	0.04	0.03	—	0.75
E318	0.08	17.0-20.0	11.0-14.0	2.0-2.5	6 × C, min to 1.00 max	0.5-2.5	0.90	0.04	0.03	—	0.75
E320	0.07	19.0-21.0	32.0-36.0	2.0-3.0	8 × C, min to 1.00 max	0.5-2.5	0.60	0.04	0.03	—	3.0-4.0
E320LR	0.035	19.0-21.0	32.0-36.0	2.0-3.0	8 × C, min to 0.40 max	1.5-2.5	0.30	0.02	0.015	—	3.0-4.0
E330	0.18-0.25	14.0-17.0	33.0-37.0	0.75	—	1.0-2.5	0.90	0.04	0.03	—	0.75
E330H	0.35-0.45	14.0-17.0	33.0-37.0	0.75	—	1.0-2.5	0.90	0.04	0.03	—	0.75
E347	0.08	18.0-21.0	9.0-11.0	0.75	8 × C, min to 1.00 max	0.5-2.5	0.90	0.04	0.03	—	0.75
E385	0.03	19.5-21.5	24.0-26.0	4.2-5.2	—	1.0-2.5	0.75	0.03	0.02	—	1.2-2.0
E349(5),(6),(7)	0.13	18.0-21.0	8.0-10.0	0.35-0.65	0.75-1.2	0.5-2.5	0.90	0.04	0.03	—	0.75

Fig. 100-41 AWS A5.4—SMAW Electrodes for Stainless Steel *(Courtesy of the American Welding Society)* (2 of 2)

AWS A5.4—Chemical Composition Requirements for Weld Metal (1),(2)											
AWS Classification(3)	**C(4)**	**Cr**	**Ni**	**Mo**	**Cb plus Ta**	**Mn**	**Si**	**P**	**S**	**N**	**Cu**
E410	0.12	11.0-13.5	0.60	0.75	—	1.0	0.90	0.04	0.03	—	0.75
E410NiMo	0.06	11.0-12.5	4.0-5.0	0.40-0.70	—	1.0	0.90	0.04	0.03	—	0.75
E430	0.10	15.0-18.0	0.60	0.75	—	1.0	0.90	0.04	0.03	—	0.75
E630	0.05	16.0-16.75	4.5-5.0	0.75	0.15-0.30	0.25-0.75	0.75	0.04	0.03	—	3.25-4.00
E16-8-2	0.10	14.5-16.5	7.5-9.5	1.0-2.0	—	0.5-2.5	0.60	0.03	0.03	—	0.75

(1) Analysis shall be made for the elements for which specific values are shown in the table. If, however, the presence of other elements is indicated by any routine analysis, further analysis shall be made to determine that the total of these other elements, except iron, is not present in excess of 0.5%.

(2) All values are weight percent. Single values shown are maximum percentages except where otherwise specified.

(3) Suffix-15 electrodes are classified with DC, electrode positive. Suffix-16 electrodes are classified with AC and DC, electrode positive. See Section A6 of the Appendix. Electrodes up to and including 5/32 in. (4.0 mm) in size are usable in all positions. Electrodes 3/16 in. (4.8 mm) and larger are usable only in the flat and horizontal-fillet positions.

(4) Carbon shall be reported to the nearest 0.01% except for the classification E320LR, for which carbon shall be reported to the nearest 0.005%.

(5) Vanadium shall be 0.10 to 0.30%

(6) Titanium shall be 0.15% max.

(7) Tungsten shall be from 1.25 to 1.75%.

Fig. 100-42 Recommended Maximum Atmospheric Exposure Times for Low Hydrogen Electrodes (EXX15/16/18)

Electrode Strength	**Maximum Exposure Time**
E70XX	9 Hours
E80XX	4 Hours
E90XX	2 Hours
E100XX	1 Hour
E110XX	½ Hour
E120XX	½ Hour

Notes:

1. The maximum exposure times are based on atmospheric exposure conditions of 70% relative humidity at 70°F. Exposure times should be reduced for more severe conditions.
2. Electrodes exposed to the atmosphere for times not exceeding those shown should be returned to a heated rod oven and held for 8 hours minimum before re-issuing.
3. Electrodes which have been exposed to the atmosphere for longer times than those shown should either be reconditioned per Figure 100-43 before re-issuing or else discarded.
4. Heated portable rod ovens should be used, where possible, for higher strength electrodes (E80XX and above) to reduce atmospheric exposure time.

Fig. 100-43 Recommended Electrode Storage and Reconditioning Procedures *(Courtesy of the American Welding Society)*

AWS Electrode Type	Recommended Storage for Unopened Boxes	Recommended Storage in a Holding Oven	Reconditioning(1)
Carbon Steel Electrodes			
EXX10 EXX11 EXX12 EXX13	Dry at room temp	Not recommended(2)	Not done
EXX14 EXX20 EXX24 EXX27	Dry at room temp	150-200°F	250-300°F for 1 Hour
E7015 E7016 E7018 E7028	Dry at room temp	225-300°F	650-750°F for 1 Hour
Low Alloy Electrodes			
E70/9015 E70/9016 E70/9018	Dry at room temp	225-300°F	650-750°F for 1 Hour
E90/12015 E90/12016 E90/12018	Dry at room temp	225-300°F	650-750°F for 1 Hour
Stainless Steel Electrodes			
EXXX-15/16	Dry at room temp	150-200°F	450°F for 1 Hour
High Alloy Electrodes			
Inconel Monel Nickel Hastelloy Copper Alloys	Dry at room temp	150-200°F	450°F for 1 Hour

(1) Reconditioning required after exceeding the recommended maximum exposure time.

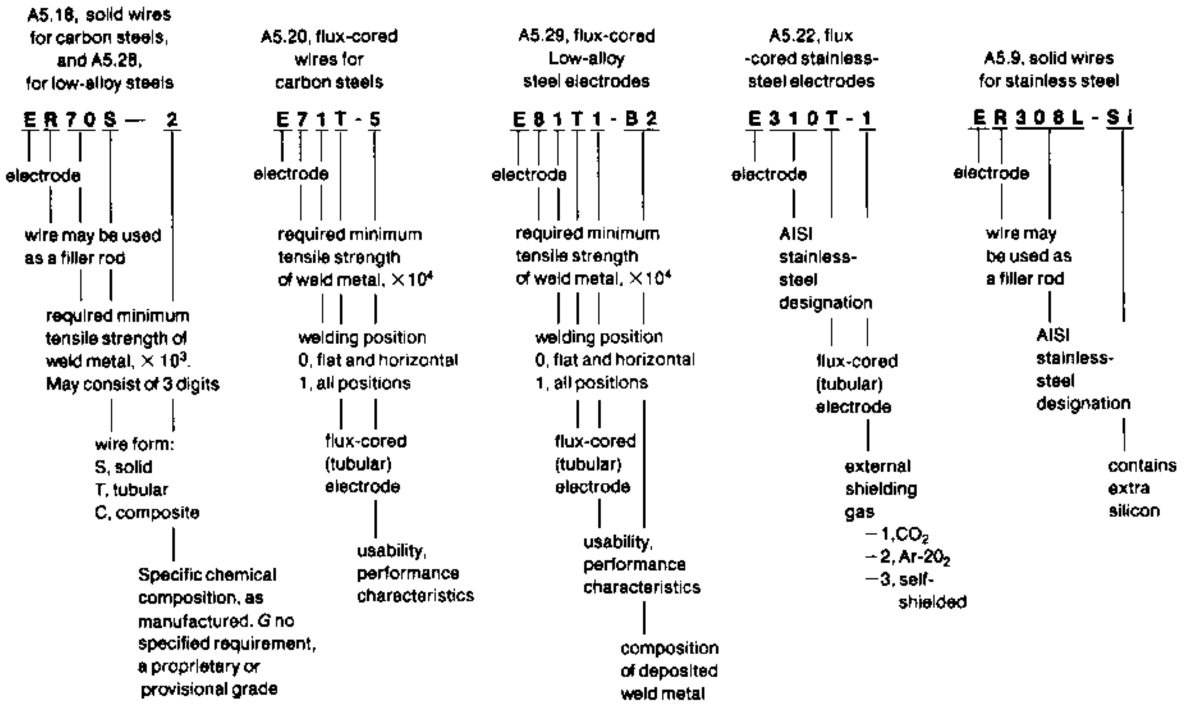
(2) Assumes that room temperature conditions are not below 40°F and the relative humidity does not exceed 70%. Otherwise, store in oven not exceeding 120°F.

133 GMAW and FCAW Electrodes

A general description of the AWS designations for carbon steel, low alloy, and stainless steel electrode wires for GMAW and FCAW is shown in Figure 100-44. The designations are similar to the system used for SMAW electrodes but with some differences.

Carbon steel and low alloy steel filler metals for GMAW are covered by AWS Specifications A5.18 and A5.28 respectively (see Figures 100-45 and 100-46).

Fig. 100-44 AWS Designations for Carbon Steel, Low Alloy and Stainless Steel Filler Metals for GMAW and FCAW *(From* Welding Design & Fabrication*, a Penton Publication, ©1988. Reprinted by permission.)*



These filler metals can also be used for GTAW, and use both an “E” and “R” (for rod) designation in their prefix.

Fig. 100-45 AWS Designations for Carbon Steel, Low Alloy and Stainless Steel Filler Metals for GMAW and FCAW *(Courtesy of the American Welding Society)*

AWS A5.18—Solid Wires For GMAW of Carbon Steel(1)						
Classification	**Composition**					
	C	**Mn**	**Si**	**Ti**	**Zr**	**Al**
ER70S-2	0.07	0.90-1.40	0.40-0.70	0.05-0.15	0.02-0.12	0.15-0.15
ER70S-3	0.06-0.15	090-1.40	0.45-0.70	—	—	—
ER70S-4	0.07-0.15	1.00-1.50	0.65-0.85	—	—	—
ER70S-5	0.07-0.19	0.90-1.40	0.30-0.60	—	—	0.50-0.90
ER70S-6	0.07-0.15	1.40-1.85	0.80-1.15	—	—	—
ER70S-7	0.07-0.15	1.50-2.00(2)	0.50-0.80	—	—	—
ER70S-G	(3)					

(1) P, 0.025; S, 0.035; Cu, 0.50, except for -G wires.
(2) If Mn content exceeds 2.0, C content drops 0.01% for each 0.05% Mn.
(3) No requirements on chemical composition, except no addition of Ni, Cr, Mo, V.

Fig. 100-46 AWS A5.28—GMAW Filler Metals for Low Alloy Steel *(Courtesy of the American Welding Society)*

Classification	Composition(1)									
	C	Mn	Si	P	S	Ni	Cr	Mo	V	Cu(2)
Chromium-Molybdenum										
ER80S-B2	0.07-0.12						1.20-1.50	0.40-0.65		
ER80S-B2L	0.05	0.40-0.70	0.40-0.70	0.025	0.025	0.20	1.20-1.50	0.40-0.65	—	0.35
ER90S-B3	0.07-0.12						2.30-2.70	0.90-1.20		
ER90S-B3L	0.05						2.30-2.70	0.90-1.20		
Nickel steel										
ER80S-Ni3	0.12	1.25	0.40-0.80	0.25	0.25	3.00-3.75	—	—	—	—
Manganese-Molybdenum										
ER80S-D2	0.07-0.12	1.60-2.10	0.50-0.80	0.025	0.025	0.15	—	0.40-0.60	—	0.50
Other(3)										
ER100S-1	0.08	1.25-1.80	0.20-0.50			1.40-2.10	0.30	0.25-0.55	0.05	0.25
ER100S-2	0.12	1.25-1.80	0.20-0.60	0.010	0.010	0.80-1.25	0.30	0.20-0.55	0.05	0.35-0.65
ER110S-1	0.09	1.40-1.80	0.20-0.55			1.90-2.60	0.50	0.25-0.55	0.04	0.25
ER120S-1	0.10	1.40-1.80	0.25-0.60			2.00-2.80	0.60	0.30-0.65	0.03	0.25
ERXXS-G(4)										

(1) As manufactured. Total other elements, 0.50.
(2) Includes coating material.
(3) Ti, Zr, Al, 0.10 each, except -G wires.
(4) Minimum 0.50 nickel, 0.30 chromium, or 0.20 molybdenum.

Carbon steel electrode wires (e.g., ER70S-2) are further described by their as-welded tensile strength (in ksi) in the first two digits, their product form by a letter ("S" for solid), and a chemistry suffix (e.g., "-2") for weld deoxidizers (Mn, Si and others) added.

Low alloy steel electrode wires (e.g., ER80S-B2) are similarly described (tensile strength can be as-welded or PWHT depending on type), except a suffix is used for chemistry as with SMAW low alloy electrodes (e.g., "-B2" for 1-1/4 Cr-1/2 Mo).

Carbon steel and low alloy steel FCAW filler metals are covered by AWS Specifications A5.20 and A5.29 respectively, shown in Figures 100-47 and 100-48. They use only an "E" designation in their prefix.

Fig. 100-47 AWS A5.20—FCAW Filler Metals for Carbon Steel *(Courtesy of the American Welding Society)*

Classification(1),(2)	Charpy V-notch, ft/lb (°F)	Shielding(3)	Current	Single/ multipass	Applications
E70T-1	20 (0)	CO_2	DCep	multi	General purpose flat and horizontal welding. Railcar fabrication, beams and girders, ships, over-the-road vehicles, storage tanks.
E70T-2	—	CO_2	DCep	single	For single-pass welds on rusted, contaminated base material. Castings, machine bases, oil field equipment, railcars.
E70T-3	—	self	DCep	single	Rapid, automated welding on thin-gage steel.
E70T-4	—	self	DCep	multi	
E70T-5	20 (-20)	CO_2	DCep	multi	Basic slag for good impact properties, low weld metal hydrogen, low crack sensitivity.
E70T-6	20 (-20)	self	DCep	multi	
E70T-7	—	self	DCen	multi	
E70T-10	—	self	DCen	single	High-speed welds on thin-gage steel.
E70T-G	—	(4)	4	4	
E71T-1	20 (0)	CO_2	DCep	multi	General purpose all-position welding. Use at low currents (150-200 A) to bridge wide gaps, at higher currents (200-250 A) for DCep penetration. Barges, oil rigs, storage vesels, earthmoving equipment.
E71T-5	20 (-20)	CO_2	DCep	multi	
E71T-7	—	self	DCen	multi	
E71T-8	20 (-20)	self	DCen	multi	
E71T-11	—	self	DCen	multi	Thin-gage material, structural steel.
E71T-GS	—	3	4	4	

(1) Electrode should deposit weld metal of plain-carbon-steel composition; types -2, -3, -10, -GS, intended for high-dilution single-pass welding, carry no composition requirements.

(2) Minimum mechanical properties, as-welded: tensile, 72,000 lb/in.^{2}; yield, 60,000 lb/in.^{2}; percent elongation, 22.

(3) Argon additions may improve weld metal properties and welding characteristics.

(4) New or proprietary wire, properties as specified by the supplier.

Fig. 100-48 AWS A5.29—FCAW Filler Metals for Low Alloy Steel *(1 of 2) (Courtesy of the American Welding Society)*

Classification[1]	C	Mn	Si	Ni	Cr	Mo	V	Al	Cu	Condition[2]	Impact Test Temp., °F[3]
Carbon-Mo steel											
E70T5-A1	0.12	1.25	0.03		—	0.40-0.65	—	—	—	PWHT	0
E80T1-A1				—						PWHT	—
E81T1-A1										PWHT	—
Cr-Mo steel											
E81T1-B1	0.12	1.25		—	0.40-0.65		—	—	—	PWHT	—
E80T1-B2			0.03	—	1.00-1.50					PWHT	—
E81T1-B2										PWHT	—
E80T5-B2							—	—	—	PWHT	—
E80T1-B2H	0.10-0.15		0.80	—						PWHT	—
E90T1-B3	0.12				2.00-2.50	0.90-1.20				PWHT	—
E91T1-B3										PWHT	—
E90T5-B3										PWHT	—
E100T1-B3										PWHT	—
Ni-steel											
E71T8-Ni1	0.12	1.50	0.80	0.80-1.10	0.15	0.35	0.05	1.8	—	AW	–20
E80T1-Ni1										AW	–20
E81T1-Ni1										AW	–20
E80T5-Ni1										PWHT	–60
E80T1-Ni2				1.75-2.75	—	—	—			AW	–40
E81T1-Ni2										AW	–40
E80T5-Ni2										PWHT	–75
E90T1-Ni2										AW	–40
E91T1-Ni2										AW	–40
E80T5-Ni3				2.75-3.75				—		PWHT	–100
Mn-Mo steel											
E91T-D1	0.12	1.25-2.00	0.80	—	—	0.25-0.55	—			AW	–40
E100T5-D2	0.15	1.65-2.25				0.25-0.55				PWHT	–40
E90T1-D3	0.12	1.00-1.75				0.40-0.65				AW	–20

Fig. 100-48 AWS A5.29—FCAW Filler Metals for Low Alloy Steel *(2 of 2) (Courtesy of the American Welding Society)*

Classification[1]	C	Mn	Si	Ni	Cr	Mo	V	Al	Cu	Condition[2]	Impact Test Temp., °F[3]
Other											
E80T5-K1	0.15	0.80-1.40	0.80	0.80-1.10		0.20-0.65	0.05	—	—	AW	–40
E90T1-K2		0.50-1.75		1.00-2.00	0.15	0.35		1.8	—	AW	0
E91T1-K2										AW	0
E90T5-K2										AW	–60
E100T1-K3		0.75-2.25		1.25-2.60		0.25-0.65		—	—	AW	0
E110T1-K3										AW	0
E100T5-K3										AW	–60
E110T5-K3										AW	–60
E110T5-K4		1.20-2.25		1.75-2.60	0.20-0.60	0.30-0.65		—	—	AW	–60
E120T5-K4										AW	–60
E120T1-K5	0.10-0.25	0.60-1.60		0.75-2.00	0.20-0.70	0.15-0.55		—	—	—	—
E61T8-K6	0.15	0.50-1.50		0.40-1.10	0.15	0.15		1.8	—	AW	–20
E71T8-K6										AW	–20
EXXXTX-G	—		(4)	0.50 min	0.30 min	0.20 min	0.20 min	1.8	—		
E80T1-W	0.12	0.50-1.30	0.35-0.80	0.40-0.80	0.45-0.70	—	—	—	0.30-0.75	AW	–20

(1) Current DCEP, except EXXT8-X which uses DCEN. P, 0.03 max; S, 0.03 max, except -G type.
(2) AW, as welded; PWHT, post-weld heat treated per A5.29.
(3) Charpy V-notch, 20 ft-lb.
(4) As specified by supplier. For electrodes not covered by other classifications.

Carbon steel FCAW electrode wires (e.g., E71-T5) are described in the first digit by their minimum as-welded tensile strength (in 10 ksi). The second digit describes usable welding positions ("1" for all positions, "0" for flat and horizontal). The "T" stands for tubular electrode, and the last digit ("1," "2," or "5") is for the type of slag the flux produces. The slag affects usability and performance characteristics (see FCAW in Section 110, Welding Processes, for a discussion of preferred electrode types).

Low alloy FCAW electrode wires (e.g., E81T1-B2) are similarly described except a suffix is used for chemistry as with SMAW electrodes (e.g., "-B2" for 1-1/4 Cr-1/2 Mo).

Stainless steel GMAW and FCAW filler metals are covered by AWS Specifications A5.9 and A5.22 respectively. **GMAW stainless steel filler metals** (e.g., ER308Si) can also be used for GTAW and use both an "E" and "R" (for rod) designation in their prefix. The stainless type is indicated as the AISI number (e.g., "308"). An "Si" suffix is used when the filler metal contains high silicon, which is added to improve weldability. **FCAW stainless steel electrode wires** (e.g., E316T-

1) use an “E” prefix, the AISI stainless type (e.g., “316”), “-T” for tubular, and a suffix for the shielding gas required (e.g., “-1” for CO_2, “-3” for self-shielded).

140 Preheat

The following guidelines are for determining preheat, using both traditional methods and methods developed for new steel-making practices.

141 Reasons for Preheat

Preheating is done to prevent cracking of welds. Preheat is also sometimes used for reducing residual stress, improving toughness, and controlling the metallurgical properties of the heat affected zone (HAZ).

Welds sometimes crack soon after being completed. **Hydrogen cracking** (also called **delayed cracking**, **cold cracking** and **underbead cracking**) is a common result of inadequate preheat or high plate hardenability. Figure 100-49 shows some causes of cracking, [1] and illustrates that inadequate preheat and high plate hardenability, in conjunction with other problems, can be responsible for almost half of weld cracking problems in structural welding.

Fig. 100-49 Causes of Cracking in Structural Welds *(Courtesy of the American Welding Society)*

Problem	Percentage of Cracks	Typical Cause
Plate problem	17%	High hardenability Plate lamination
Weld procedure problem	31%	Poor weld sequence Poor fit-up Inadequate preheat
Joint design problem	16%	High restraint
Structure design problem	31%	High restraint
Other	3%	

Hydrogen cracking occurs primarily in the HAZ as toe cracks or underbead cracks. It can also occur in high strength weld metal, especially in the root pass. The cracks are called delayed cracks since they occur some time after the welding has been completed. Inspection holds of 24 or 48 hours are common when delayed cracking is a potential problem. This should not be a concern with low carbon and plain carbon steels.

For hydrogen cracking to occur, three factors must be present:

- hydrogen
- high stresses
- a high base steel hardness

Hydrogen cracking can be avoided by controlling these three factors.

Hydrogen content. The hydrogen content of the completed weld is most directly related to the amount of hydrogen available in the welding process, typically measured as the **hydrogen potential** of the welding consumable. Low hydrogen electrodes, such as E7018, are commonly used to limit the amount of hydrogen entering the metal. A low hydrogen welding process is commonly defined as one which results less than 10 ml hydrogen in 100 g of metal after welding.

The heat from preheating allows hydrogen to diffuse out of the weld area at a faster rate, lowering the hydrogen content and thereby lowering the likelihood of hydrogen cracking.

Stress level. The stress on the weld is determined by the restraint on the joint as the weld metal cools and shrinks, and by the yield strengths of the base metal and the weld metal. Higher restraint results in higher stresses and higher likelihood of cracking.

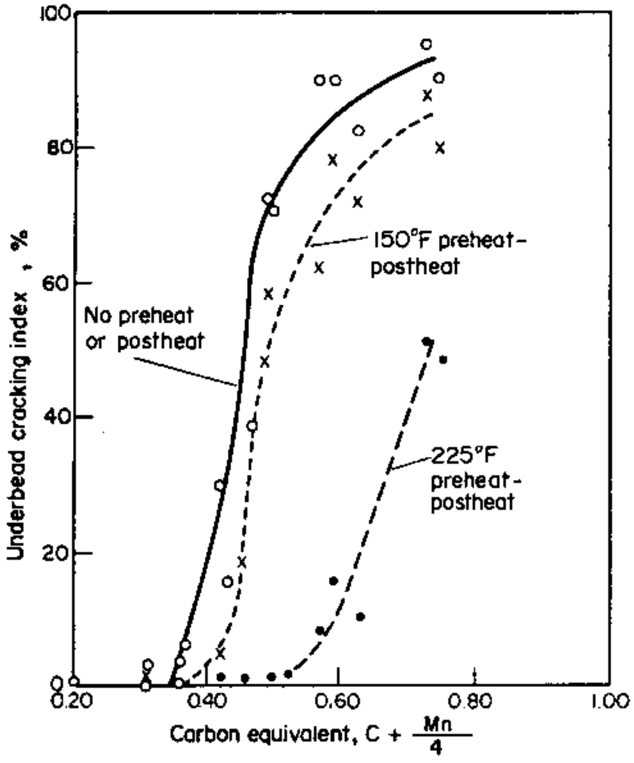
In trying to decide how much preheat is needed, the degree of restraint on the joint needs to be estimated. However, restraint is difficult to quantify; it is influenced by the size of the weld, joint geometry, thickness of the base metal, fit-up, and external constraints. The restraint estimation is often simplified by considering only the thickness of the joint to be welded. Preheat is then often increased as thickness increases, with no consideration of the complexity of the joint being welded. However, there are significant differences between a simple butt weld, a nozzle weld on a pressure vessel, and a complex T-Y-K joint with ring stiffeners on an offshore platform. More restrained joints require more preheat.

Hardness of the steel. The sensitivity of the steel HAZ to hydrogen cracking depends upon whether the HAZ has a susceptible microstructure. Susceptibility of the microstructure is usually measured simply by its hardness, with higher hardness being more susceptible to cracking. The hardness of the HAZ is controlled by restricting the steel chemistry and by controlling the cooling rate after welding with preheating.

The cooling rate after welding is influenced by the amount of preheat, with higher preheat causing slower cooling and a lower hardness microstructure. The cooling rate is also influenced by the joint geometry, the amount of heat input from the welding process, the interpass temperature, and the ambient temperature.

The effect of chemistry on hardness is measured as hardenability. For a given cooling rate, a steel with higher hardenability will have a higher HAZ hardness. Hardenability can be measured by the steel's **carbon equivalent** (C.E.). Carbon equivalent is a number that combines the hardening potency (hardenability) of various alloying elements in terms of their equivalency to the hardening potency of carbon in iron. Hardenability formulas are presented later in this section.
Figure 100-50 shows how increasing hardenability (measured here by the simplified carbon equivalent formula of $C + Mn/4$) dramatically increases sensitivity to hydrogen cracking.

Fig. 100-50 Effect of Preheat and Carbon Equivalent on Hydrogen Cracking for Bead-on-Plate Tests [5] *(From* Analysis of Welded Structures *by Dr. Koichi Masubuchi. Used by permission of the author.*)



How the Need for Preheat has Changed

Steel is an iron base alloy containing carbon and other alloying elements, notably manganese. Traditional steels are called plain carbon steels, since they have no alloying additions beyond the bare minimum. They are the simplest of steels. They are also very common, being the primary steel used for simple pressure vessels, piping, line pipe, and structural steel.

In about the 1960's, new steels called **high strength low alloy steels** or **HSLA steels** began to be developed. They offered higher strengths without steel mill heat treatment. These steels are now in common use for the same purposes as plain carbon steels. However, they introduced a problem, because their alloy content, although low, makes them more hardenable and therefore harder to weld without hydrogen cracking. They require higher preheat than plain carbon steels.

In the early 1980's this higher preheat cost led steel companies to introduce another generation of steels, called thermo-mechanically controlled process steels or TMCP steels. This is a complicated name for a simple idea. TMCP steels have significantly lower carbon and other alloy content in order to lower their hardenability. The loss of strength from lower alloying is made up for by a sophisticated rolling process in the steel mill, which quickly water cools the hot steel during rolling, locking in a highly strained microstructure. This microstructure gives the steel the additional strength needed to meet the strength grade specification.

TMCP steels are highly weldable because of their low hardenability. There are a few tradeoffs, such as loss of strength in the HAZ if weld heat input is high enough to relax the strained microstructure, but these tradeoffs are increasingly being recognized and addressed by modifications in steel-making and fabrication practices.

TMCP steels are increasingly proposed for fabrication where traditional plain carbon or HSLA steels have been used in the past. TMCP steels are being introduced so rapidly that fabrication technology has not kept pace. A common problem for the fabricator proposing a TMCP steel (proposed to save the fabricator preheating costs) is that owners' specifications still apply preheat rules based on plain carbon and HSLA steels. If owners gain familiarity and experience with TMCP steels, significant savings can be expected from elimination or dramatic reduction of preheat requirements.

142 Preheat Determination—Plain Carbon Steels

Hardenability has been measured by **carbon equivalent (C.E.)** in various forms since the early 1940's. The accepted standard for plain carbon steels is the International Institute of Welding's formula, known as the IIW formula:

$$\text{C.E.} = \text{C} + \text{Mn}/6 + (\text{Cr} + \text{Mo} + \text{V})/5 + (\text{Ni} + \text{Cu})/15$$

The IIW carbon equivalent formula was developed on steels with high carbon contents and tensile strengths of 60-100 ksi. The formula is valid for carbon contents of 0.20% or more. To assure adequate weldability of the steel, the carbon equivalent is limited to a maximum value.

Typical carbon equivalent ranges and corresponding required preheats are shown in Figure 100-51.

Fig. 100-51 Preheat for IIW Carbon Equivalents *(Courtesy of the American Welding Society)*

	IIW Carbon Equivalent, %				
Thickness, t, inches	**<0.35**	**0.35-0.45**	**0.45-0.55**	**0.55-0.65**	**>0.65**
Non-Low Hydrogen Processes					
t ≤ 1/2	ambient	ambient	ambient-200°F	200-350°F	350-450°F
1/2 < t ≤ 1	ambient	ambient-200°F	200-350°F	350-450°F	450-650°F
1 < t	ambient-200°F	200-350°F	350-450°F	450-650°F	450-650°F
Low Hydrogen Processes					
t ≤ 1/2	ambient	ambient	ambient	ambient-200°F	200-350°F
1/2 < t ≤ 1	ambient	ambient	ambient-200°F	200-350°F	350-450°F
1 < t	ambient	ambient-200°F	200-350°F	350-450°F	450-650°F

143 Preheat Determination—HSLA and TMCP Steels

The Pcm Formula

Preheat for HSLA steels has traditionally been determined using the IIW formula. However, recent trends in steel-making justify using less restrictive hardenability formulas. The IIW formula should not be used to determine preheat for TMCP steels because this eliminates the economic advantage of these steels.

A new hardenability formula was developed in the mid-1960's and early 1970's which better predicts the hydrogen cracking tendency of low carbon steels such as HSLA and TMCP steels. It is called the **Pcm carbon equivalent formula**: [1,2,3,4]

$$Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$$

The Pcm carbon equivalent formula was developed for steels with low carbon contents and with tensile strengths of 60-130 ksi. Pcm is more appropriate than the IIW carbon equivalent for steels with a carbon content less than 0.18%.

Preheat determination using Pcm involves measuring or estimating the steel chemistry, the hydrogen potential of the welding process, and the amount of joint restraint.

Limitations of the Pcm formula

The Pcm formula is applicable within the following ranges of chemical composition: [5]

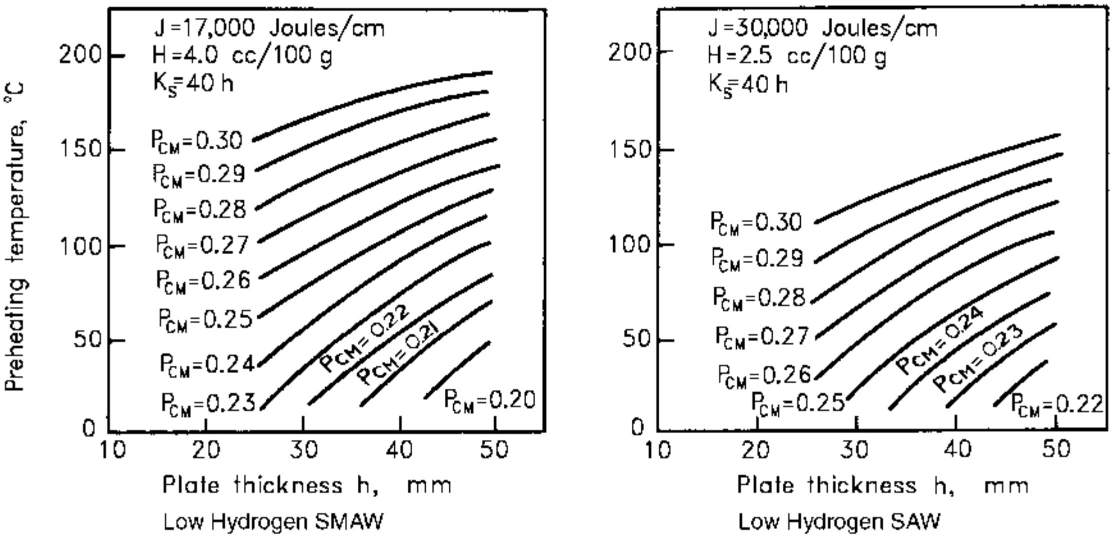
Element	Range, wt.%
C	0.07–0.22
Mn	0.40–1.40
Ni	0.0–1.20
Mo	0.0–0.70
Ti	0.0–0.05
B	0.0–0.005
Si	0.0–0.60
Cu	0.0–0.50
Cr	0.0–1.20
V	0.0–0.12
Nb	0.0–0.04

Determination of the required preheat using the Pcm method can be quite involved. Much of the "cookbook" approach of the IIW method can be lost because restraint and hydrogen potential must be estimated. Often not all the information is known or it cannot can be determined. To make Pcm useful and to realize the potential savings from eliminating preheat, reasonable assumptions are made. The assumptions include:

- Thickness from 3/4 to 2 inches
- Heat input from 17 to 30 kJ/cm
- Moderate to high weld restraint (typical of structural welding)
- Low hydrogen potential electrodes (1.0 to 5.0 ml/100g)

Figure 100-52 shows preheat requirements applicable to typical TMCP steels.

Fig. 100-52 Typical Preheat Requirements Using Pcm [5] *(From* Analysis of Welded Structures *by Dr. Koichi Masubuchi. Used by permission of the author.*)



Note: For Pcm <0.18%, preheat is unnecessary for thickness <2 inches.

Continuing Developments

The Pcm formula is just starting to be applied to common fabrication work. Steelmaking chemistry is changing at a rapid pace. As modifications of the chemical composition of HSLA steels are introduced, other Pcm correlations are being developed. For instance, boron, vanadium and niobium are particularly potent alloying elements and they are sometimes given more weight in the Pcm formula. Despite this developmental work, the increasing use of TMCP steels is leading to broad acceptance of the original Pcm formula and it should be used for selecting preheat for current technology TMCP steels. If a fabricator or steelmaker suggests using a different formula, a materials engineer in CRTC's Materials and Equipment Engineering Unit can be consulted.

144 Preheat Determination—High Alloy Steels

Chrome-moly Steels

Alloys such as 5 Cr, 7 Cr and 2-1/4 Cr-1 Mo have alloying elements added for reasons other than hardenability and the immediate strength boost this yields. For instance, chromium may be added for corrosion resistance, or chromium and molybdenum may be added for high temperature creep resistance. Because these high alloying additions lead to high hardenability, preheat is required to avoid hydrogen cracking, and postweld heat treatment (PWHT) is required to temper the HAZ.

The preheat temperatures for these high alloy steels are determined using the IIW carbon equivalent formula. Pcm is not appropriate because the alloying element content exceeds the range for the Pcm correlation; i.e., the steels are too hardenable for Pcm to be useful.

Occasionally situations come up where chrome-moly steels or chromium steels can be welded without PWHT. For instance, a furnace tube may operate hot enough in service to eliminate the need for PWHT. A procedure has been developed that allows steel to be welded without PWHT and without hydrogen cracking. The procedure is to hold the preheat temperature for an extended time (about one hour) after completion of welding so that the hydrogen in the steel can diffuse out.

Where PWHT is planned but welding of hardenable low alloy steels is interrupted before completion, preheat temperatures should be maintained for one hour before allowing the part to cool to ambient temperature, in order to avoid delayed hydrogen cracking. If the interruption is short, preheat can be maintained until welding is resumed. If the interruption is longer, an intermediate heat treatment (also called an intermediate stress relief or ISR) of the work can be performed. This is done by raising the weld temperature into the stress relief temperature range for a short time. Usually 30 minutes at 1000 to 1200°F followed by slow cooling under insulation is sufficient for intermediate stress relief.

Stainless Steels

Austenitic stainless steels (such as the 300 series and Inconels) are nonhardenable. Because they are nonhardenable, they are not susceptible to delayed hydrogen cracking and do not need preheat.

A few ferritic stainless steels (generally those containing more than 12% Cr) can harden and do need to be preheated. Preheat is determined using the IIW formula.

Cast Irons

Cast irons are iron-carbon-silicon alloys, somewhat similar to carbon steels, but the carbon content of cast irons is so high that the carbon forms graphite upon cooling from the molten condition. The carbon content of gray cast iron is about 2 to 4% carbon versus the 0.2% level of carbon steel. This high carbon content results in carbon equivalents for cast irons that are an order of magnitude higher than for carbon steels. Preheat is necessary.

145 Code and Company Requirements

Because the ASME Code avoids mandating preheat when normal engineering practice frequently calls for it, the Company must specify preheating requirements.

Company Preheat Recommendations

Figure 100-53 summarizes the Company's practice for most materials. Note that the recommended preheats are minimums and are based upon use of the IIW carbon equivalent formula, and the economic advantages of avoiding preheat for some HSLA and TMCP steels are not recognized. If use of these steels is anticipated, the IIW-based preheats are overly conservative and may result in excessively high fabrication bids. See Section 143.

Fig. 100-53 Recommended Preheat for SMAW Welding *(Courtesy of the American Welding Society)* (1 of 2)

Type of Alloy	Thickness, Inches	Minimum Preheat Temperature[1]
Plain Carbon Steels		
Mild carbon (Less than 0.35% C)	<3/4 3/4 to 2-1/2 >2-1/2	50°F 100°F/inch thickness[2] 250°F
Medium carbon (0.30 to 0.60% C)	All	Per Figure 100-51
J-55 casing	All	200°F
N-80 casing	All	300°F
HSLA Steels		
4130	≤1/2 >1/2	300°F 450°F
4140	≤1/2 >1/2	400°F 550°F, hold 1 hr after welding
4340	All	550°F, hold 1 hr after welding
T-1 & 100 ksi YS	All	100°F/inch, 300°F max.[3]
API-5LX grades	<3/4 ≥3/4	50°F[4] 200°F
Cor-Ten & 50 ksi YS	<3/4 3/4 to 2-1/2 >2-1/2	50°F 100°F/inch thickness 250°F
High Alloy Steels		
C-Mo, C-Mo-Ni	<1/2 1/2 to 2 >2	50°F 150°F/inch thickness 300°F
2-1/2 to 3-1/2% Ni	<3/4 ≥3/4	50°F 200°F
1/2 to 1-1/4% Cr-Mo	All	300°F
2 to 3% Cr-Mo	All	300°F[5]
High Alloy steels, cont.		
4 to 10% Cr-Mo	All	450°F

Fig. 100-53 Recommended Preheat for SMAW Welding *(Courtesy of the American Welding Society)* (2 of 2)

Type of Alloy	Thickness, Inches	Minimum Preheat Temperature(1)
1/2 to 10% Cr-Mo	Socket welds welded with austenitic electrodes	300°F, hold 1/2 hr. after welding
11 to 14% Cr	All ≤3/8 >3/8 ≤3/8 >3/8	Cutting—300°F Austenitic electrodes—None Austenitic electrodes—450°F E410 electrodes—300°F E410 electrodes—450°F
16 to 29% Cr	≤1/4 >1/4	50°F 300°F, 450°F max.[3]
Cast iron	All	Nickel-iron electrode—300-650°F Nickel electrode—50-300°F Oxyacetylene brazing—600-1000°F Oxyacetylene welding—800-1200°F Cutting—none
Austenitic stainless 3XX grades, Alloy 20, Incoloy 800	All	None
Nickel Alloys, Monel, Inconel, Hastelloy (all grades)	All	None

(1) Temperature listed applies to both welding and cutting unless otherwise noted.

(2) This table is based on the **IIW carbon equivalent formula**. Preheat may not be necessary for low carbon steels made to modern practices, such as TMCP steels.

(3) Preheat limited to maintain weld zone toughness. Consult Materials Engineer.

(4) Provided the hot pass is applied within 5 minutes of completion of the root pass for cellulosic electrodes.

(5) Upon interruption or completion of welding, raise temperature to 1000-1200°F and hold 30 minutes before slow cooling to ambient temperature, or raise preheat temperature to 500-600°F and hold for 30 minutes per inch of thickness.

ASME Section VIII

Section VIII of the ASME Boiler and Pressure Vessel Code does not contain mandatory preheat requirements. Nonmandatory recommendations are given in its Appendix R. The ASME Code states that mandatory preheat is not required due to the multitude of variables that affect the need for preheat, as discussed earlier in this section. ASME Section VIII, Sections UCS-56 and UHA-32, allow some relaxation of PWHT requirements when some materials are preheated.

AWS D1.1 Table 3.2

The American Welding Society's Structural Welding Code—Steel (AWS D1.1), Table 3.2 recommends minimum preheat levels by strength group and for low hydrogen and non-low hydrogen welding processes. These preheat levels are based on experience and are only appropriate for joints that do not have “excessive” restraint (as defined by experience). AWS D1.1, Table 3.2 is most appropriate for conventional normalized steels, which typically have an IIW carbon equivalent maximum of 0.45.

The Company's use of the preheats in AWS D1.1, Table 3.2 varies. For instance, welding in well known fabrication yards with normally used materials is often done with no additional requirements beyond those in AWS Table 3.2. In less familiar yards or when new or critical materials are fabricated, the Company has often required more extensive preheating than required by the AWS.

AWS D1.1 Appendix XI

AWS D1.1, Table 3.2 minimum preheats are more than should be necessary for TMCP steels. AWS D1.1 was revised in 1986 to recognize other methods of determining the minimum preheat needed to avoid hydrogen cracking in TMCP steels. The revision is in the nonmandatory Appendix XI, "Guideline On Alternative Methods for Determining Preheat." AWS D1.1 cautions the user on the need for careful consideration of assumptions and past experiences in using this guideline. The appendix also requires that preheats that are less than those specified by Table 3.2 be included in the procedure qualification.

146 Other Methods of Determining Preheat

Weldability Tests

Sometimes empirical correlations like the IIW and Pcm correlations are not enough to determine preheat. Numerous welding tests have been developed that can be used to establish accurate minimum preheat requirements. For example, these tests can be used to accurately simulate restraint. The American Petroleum Institute's Recommended Practice (API RP) 2Z provides guidance on using the Y-groove and CTS restraint tests to determine minimum preheat requirements.

Cold Weather Preheating

When the ambient temperature is below the dew point, preheat is necessary to avoid delayed hydrogen cracking and porosity caused by water picked up from the metal surface during welding. Generally no welding should be done on work that is cooler than about 50°F without first preheating. When ambient temperatures are below about 50°F, work should be preheated until warm to the touch, or about 100°F.

At ambient temperatures below about 0°F, special procedures may be necessary to maintain the preheat temperature prior to and during welding.

147 How Preheat is Applied

Size of Area to Preheat

The entire part or only the joint area may be preheated. Heat should be applied to a large enough area so that the weld area will not cool below the minimum required preheat temperature during the welding. Generally, a distance of 3 inches on either side of the weld joint is adequate for local preheating of piping, pressure vessels, and storage tanks.

Methods of Preheat:

Gas Burners. Propane or natural gas “rosebud” burners are widely used for preheating because they are simple and produce a large diffuse flame that heats a large area. However, they are not very precise in applying the heat, so inspection for proper preheat should be made by the welder prior to starting the weld. Inspection for preheat is discussed later.

In shop fabrication of pressure vessels and piping, gas burners in the shape of rings and rods are used to preheat complete seams without the constant attention of an operator.

Electric Heaters. The same electric resistance heaters that are used for localized postweld heat treatments of pipe or vessel welds can be used for preheating. This is done by making the heating coil in two halves that can be moved away from the weld and operated with reduced current to heat the weld area to the preheat temperature. After welding, the coils are moved together over the weld and covered with insulation for the postweld heat treatment. Supplemental instrumentation may be required to measure and control the preheat temperature.

Radiant Heaters. Radiant heaters are an excellent source of preheat because they produce heat without smoke, moisture or other combustion products that can get into the weld zone. Compared to torches, however, radiant heaters are expensive and cumbersome. The cost of radiant heating is justified in preheating tube-to-tubesheet welds where condensate from an open flame heater can get into the crevices and cause problems. Radiant heaters used for preheating can be electric with either quartz lamp or NiChrome electric resistance heating elements. Gas fired radiant heaters with ceramic surfaces, wire screen or porous brick are also available. Radiant heaters are seldom used for preheating other than for tube-end welding and shop operations.

Induction Heating. Induction heating coils usually used for postheating can also be used for preheating in the same manner as are resistance heating coils. The induction heaters must be turned off during welding because the rapidly changing magnetic field interferes with welding. Induction coils also induce permanent magnetism in ferritic steel parts, and the parts may need to be demagnetized before welding can be performed.

148 Preheat Inspection

Hydrogen cracks are tight and difficult to detect. Because they frequently do not appear until some time after welding has been completed, they can be missed if inspection is performed too soon after welding. Inspection holds of 24 or 48 hours are common where delayed hydrogen cracking is a concern. Holds should not be necessary for low carbon and plain carbon steels.

Tight surface cracks are most easily detected by magnetic particle inspection, or dye penetrant inspection can be used. Subsurface cracks (underbead cracks) are readily detected only by ultrasonic inspection. Radiography is not effective in finding tight cracks because of geometry alignment problems. (See Section 500 for a complete discussion of inspection procedures.)

On jobs where extensive welding will be performed, such as offshore platform fabrication, it may be reasonable to begin with a high frequency of inspection for hydrogen cracks and then to drop to a maintenance level of inspection after the fabricator has proven that his procedures produce consistently crack-free welds.

Some welds are more susceptible to cracking than others. Special attention should be paid to low heat input welds, especially tack welds. Inspection of temporary scaffolding support clip welds is often overlooked. Repair welds and gouging should receive careful attention since they may be outside the mainstream effort for preheating.

Temperature Measurement

Correct temperature measurement is an important part of preheating. Temperature indicating crayons are usually used for measuring preheat temperatures. Other methods use paints and pellets that change color or melt at specific temperatures. Contact thermometers and thermocouples can also be used. Boiling water droplets (saliva) are a good indicator of temperatures near 200°F. Surfaces comfortably warm to the touch are about 100°F.

149 Interpass Temperature Control and Line Heating

Interpass Temperature Control

Closely related to preheating is the idea of interpass temperature control—maintaining the workpiece in the proper preheat temperature range during multipass welding. It is important to keep the interpass temperature high enough to prevent delayed hydrogen cracking and to obtain the other benefits of preheating. In most cases, welding heat input is not sufficient to maintain proper temperature, so supplemental heating is required. However, closely timed passes or carefully spaced welders, such as in SMAW electrode pipeline welding, can provide enough heat input to maintain the preheat temperature within acceptable limits.

An excessively high interpass temperature can lead to undesirable microstructures and lowered hardness. This can happen in the case of multiple pass welds made by automatic SMAW on pipe welds. The high heat input may raise the temperature of the workpiece to undesirably high levels, requiring that welding be stopped to allow the work to cool. Interpass temperatures are seldom as important a concern as preheat.

Line Heating

Fabricators sometimes use heating torches to locally heat steel to correct distortion or to produce desired curves by using the local upsetting effect of the hot flame. This is called flame straightening or line heating. It is common in shipbuilding and in offshore platform fabrication. This procedure should be qualified prior to use because it is possible to heat the surface above the critical temperature of steel. This can cause local hardening upon cooling, which is unacceptable in many services where environmental cracking can occur at hard zones. The surface can also be hardened by carburization if the flame characteristics are wrong.

150 Heat Treatment

151 Postweld Heat Treatment (PWHT)

Several heat treatments can be applied after welding. The most frequently used heat treatment after welding is for relief of residual welding stresses. The ASME Boiler and Pressure Vessel Code refers to heat treatment after welding as postweld heat treatment (PWHT), and this is the preferred term for welded pressure vessel and piping construction. PWHT is sometimes called stress relief, and may also be referred to as tempering. PWHT may be performed on an entire weldment or to a localized portion of a weldment.

PWHT is performed for one or more of the following reasons:

- Reduce residual stresses
- Reduce weld and HAZ hardness
- Improve toughness
- Outgas hydrogen from the weld
- Remove cold work from the weld
- Increase ductility
- Improve resistance to environmental cracking and corrosion
- Increase dimensional stability during machining

Alternatives to PWHT are discussed in Section 152. Other high temperature heat treatments, including annealing, normalizing, and quenching, are discussed in Section 153.

Company Practice and Code Requirements

PWHT may be required by the ASME Boiler and Pressure Vessel Code, by the ANSI/ASME B31 Code for Pressure Piping or by Company specifications. It is based on material, thickness, toughness requirements, and end use. The Company practice for PWHT is to follow the rules of the applicable code as a minimum, and to add requirements where service experience indicates a need to be more conservative.

Figure 100-54 summarizes the ASME Pressure Vessel Code, ANSI Piping Code and Company specification requirements for preheat and PWHT requirements. Figures 100-55 and 100-56 summarize current Company practice for all heat treatments (PWHT, annealing, normalizing, and hardening) of various materials.

Fig. 100-54 Summary of ASME Pressure Vessel Codes, ANSI Piping Code and Company Specification Requirements for Preheat and PWHT (1 of 2)

Specification$^{(1)}$	Scope	Material	Min. Preheat Temp.	PWHT Temperature: Time	Max. Weld Hardness
PVM-MS-4750 Carbon Steel Pressure Vessels	1. 1-1/2" max. thickness—ASME Sect. VIII Div. 1 2. SMAW, SAW, GMAW (with restrictions), GTAW, and FCAW-G (low H_2) welding processes.	P-1 C.S.	50°F for t ≤ 1.25", 200°F for t > 1.25"	Per Code (UCS-56)*, supplements to the specification, or as specified on the vessel drawing for the service conditions.(*PWHT is required for t > 1-1/2" providing a 200°F preheat is used for 1-1/4" < t ≤ 1-1/2".)	200 BHN For sour service - if PWHT is not performed, the HAZ hardness 2 mm below the surface is limited to R_C 22 max.
PVM-MS-4749 Heavy Wall Carbon Steel and Low Alloy Steel Pressure Vessels	1. Heavy wall carbon steel (over 1-1/2" thick) 2. Low-alloy Cr-Mo (all thicknesses) 3. ASME Sect. VIII Div. 1 & 2 pressure vessels 4. SMAW, SAW, GTAW and GMAW (with restrictions) welding processes. FCAW not permitted. 5. Also covers heat exchangers per EXH-MS-4764.	P-1 C.S.	70°F for t ≤ 1.25", 200°F for t > 1.25"	1100-1200°F: Div 2, AF-402.1	200 BHN
		P-4 1 – 1-1/4 Cr-Mo	300°F	1300-1375°F: Div 2, AF-402.1$^{(2)}$	215 BHN
		P-5A 2-1/4 – 3 Cr-Mo	300°F	1300-1375°F: Div 2, AF-402.1 3 hrs min.^{2}	215 BHN
ASME Sect. VIII, Div. 1, Appendix R & UCS-56	All welding processes		(Recommended)	(Minimum Temperature)	
		P-1 C.S.	50-175°F	1100°F: time depends on thickness	None
		P-3 C-1/2 Mo	50-175°F	1100°F: time depends on thickness	None
		P-4 1–1-1/4 Cr-Mo	50-250°F	1100°F: time depends on thickness	None
		P-5A 2-1/4–3 Cr-Mo	300-400°F	1250°F: time depends on thickness	None
PIM-MS-2505-J Carbon Steel Piping Fabrication	1. Supplement to ANSI/ASME B31.1 and B31.3 2. SMAW, SAW, GMAW (with restrictions), GTAW and FCAW-G welding process. 3. Also covers furnace tubes per HTR-MS-1350	P-1 C.S.	100°F when the pipe is wet or the ambient temperature <40°F.	1100-1200°F: 1 hr min. for t >3/4" or if required by the Company.	None

Fig. 100-54 Summary of ASME Pressure Vessel Codes, ANSI Piping Code and Company Specification Requirements for Preheat and PWHT (2 of 2)

Specification[1]	Scope	Material	Min. Preheat Temp.	PWHT Temperature: Time	Max. Weld Hardness
PIM-MS-4772 Low Alloy Steel Piping Fabrication	1. Supplement to ANSI/ASME B31.1 and B31.3 2. SMAW, SAW, GMAW, GTAW and FCAW-G welding processes 3. Also covers furnace tubes per HTR-MS-1350	P-3 C-1/2 Mo	100°F when the pipe is wet or the ambient temp.<40°F.	1175-1250°F: 1 hr when required by Code or Company	215 BHN
		P-4 1 Cr-Mo	300°F	1300-1375°F: 2 hr minimum	215 BHN
		P-4 1-1/4 Cr-Mo	350°F	1300-1375°F: 2 hr minimum	215 BHN
		P-5A 2-1/4 Cr-Mo	350°F	1300-1375°F: 2 hr minimum	215 BHN
		P-5A 3 Cr-Mo	350°F	1325-1400°F: 2 hr minimum	215 BHN
		P-5B 5 - 9 Cr-Mo	450°F	1325-1400°F: 2 hr minimum	215 BHN
ANSI B31.3 Tables 330.1.1 & 331.1.1	All welding processes	P-1 C.S.	50-175°F (Recommended)	1100-1200°F: 1 hr min. (for t >3/4")	None
		P-3 C-1/2 Mo	50-175°F (Recommended)	1100-1325°F: 1 hr min. (for t >3/4")	225 BHN
		P-4 1-1/4 Cr	300°F (Required)	1300-1375°F: 2 hr min. (for t >1/2")	225 BHN
		P-5A 2-1/4 Cr	350°F (Required)	1300-1400°F: 2 hr min. (for t >1/2")	241 BHN
		P-5B 5-9 Cr	350°F (Required)	1300-1400°F: 2 hr min.	241 BHN

(1) Company specifications do not cover HSLA or API 5LX steels.

(2) **Lower PWHT temperatures for P-4 and P-5 materials having Class 2 properties:** PWHT of P-4 and P-5 materials with Class 2 properties (higher tensile strength) at temperatures below those recommended by the Company may be necessary to not over-temper the material and meet the higher tensile-strength requirements. The manufacturer should make the recommendations regarding the temperature range and minimum and maximum PWHT times. The manufacturer's recommendations should be supported by mechanical property data including tensile strength, hardness and notch toughness of the weld and heat-affected zone. The minimum temperature selected by the manufacturer must meet minimum Code requirements.

Fig. 100-55 Company Practice for Heat Treatment Times and Temperatures

Type of Alloy	PWHT Temp., °F	Time	Anneal Temp., °F	Time	Normalize Temp., °F	Hardening
Ferritic Steel						
Low carbon (to 0.30%)	1100-1200	1 hr/in	1575-1650	1 hr/in	1650-1700	
Medium carbon (0.35-0.60%)(1)	1100-1200	1 hr/in	1550-1625	1 hr/in	1600-1650	1550-1575°F quench
High carbon (over 0.60%)[1]	1100-1200	1 hr/in	1450-1600	1 hr/in	1550-1600	1475-1550°F quench
Carbon-1/2% moly	1175-1250	1 hr/in	1650-1800	1 hr/in	1650-1800	
2 to 3-1/2% nickel	1050-1150	1 hr/in	1450-1550	1 hr/in	1550-1650	
1/2 to 1-1/4% chrome-moly(2)	1300-1375	1 hr/in(3)	1650-1800	1 hr/in	1700-1800	
2-10% chrome-moly	1300-1400	1 hr/in[3]	1650-1800	1 hr/in	1700-1800	1700-1800°F quench
12% chrome (Type 410 & 416 SS)	1300-1400	1 hr/in[3]	1550-1650	1 hr/in		1800°F air cool, temper 1100°F, 2 hrs
16-27 chrome	1300-1400	1 hr/in	1400-1650			
High-strength structural	1050-1150	1 hr/in				1700°F water quench, temper 1175°F
17-4 PH	1150	4 hrs	1400 then 1150	2 hrs 4 hrs		1900°F oil quench, age 1050°F, 4 hrs
Cast Iron	900-1200	1 hr/in	1300-1400	1 hr/in		
Austenitic Stainless Steel						
304, 304L, 308, 309, 316, 316L, 310, 321, 347, Incoloy	1550-1650	1 hr/in(4)	1850-1950	1/2 hr/in		
Aluminum Alloys						
1100, 5000 series	350-400	1 hr/in	625-675	1 hr		
6061	400-450	1 hr/in	775-825	1 hr		985°F water quench, age 350°F, 8 hrs
Nickel Alloys						
Nickel	1000-1100	1 hr/in	1300-1400	1 hr/in		
Monel(5)	1100-1200	1 hr/in	1450-1550	1 hr/in		
Inconel[5]	1550-1650	1 hr/in	1800-1900	1/2 hr/in		
Copper Alloys						
Copper	375	1/2 hr	600-1200	1/2 hr		
Red Brass	450	1/2 hr	800-1350	1/2 hr		
Yellow Brass	550	1/2 hr	800-1100	1/2 hr		
Tin (phosphor) Bronze	375	1/2 hr	900-1250	1/2 hr		
Cupro Nickel	800-1000	1/2 hr	1200-1500	1/2 hr		
Nickel Silver	500	1/2 hr	1100-1500	1/2 hr		
Aluminum Bronze	600-900	1/2 hr	1100-1500	1/2 hr		
Silicon Bronze	600	1/2 hr	900-1300	1/2 hr		

(1) Such as J-55, N-80, S-90 and S-95 Oil Country tubulars.
(2) Including ANSI Type 4130 low alloy steel.
(3) 2 hrs minimum
(4) 1 hr minimum
(5) Specific grades of age hardenable Monel and Inconel should be heat treated per manufacturers' recommendations.

Fig. 100-56 Company Requirements for Postweld Heat Treatment

	PWHT Requirements		
Material and Service	**Vessels & Tanks**	**Large Piping(1)**	**Small Piping[1]**
Carbon Steel			
Hot caustic(2)	Yes	Yes	Yes
Cold caustic[2]	Heating coils only	Only if traced	Only if traced
MEA over 100°F	Yes	Yes	Yes
MEA below 100°F	(3)	Only if traced	Only if traced
DEA & MDEA over 100°F	Yes	Yes	No
DEA & MDEA below 100°F	[3]	Only if traced	No
Potassium carbonate over 150°F	Yes	Yes	No
Potassium carbonate below 150°F	[3]	Only if traced	No
Carbonate in FCC Plants	Yes	Yes(4)	Yes[4]
Anhydrous ammonia	Consult M&E Engineering	Consult M&E Engineering	No
Sour service	Yes(5)	Seamless pipe - no Welded pipe - Consult M&E Engineering.	No
Other(6)	Per ASME VIII	Per B31.3 or B31.1	No
Carbon - 1/2 Moly Steel	Same as carbon steel but do not use.	Same as carbon steel but do not use.	Same as carbon steel but do not use.
Chrome - Moly Steels(7)	Yes, per ASME Code & MS Specifications	Yes, per B31.3/31.1 and PIM-MS-4772	Yes, per B31.3/31.1 and PIM-MS-4772
Stainless Steel			
Types 304 & 316	No(8)	No(8)	No(8)
Types 304L, 316L, 321	Consider on a case-by-case basis. Also see comments under "Large Piping."	Generally yes, but not for services below 150°F, and not for chemical plants where sensitization is a greater concern.	Only in known chloride cracking service except PWHT is generally performed to first block valve.
Type 347(9)	≤ 3/4" - same as 304L, 316L & 321. > 3/4" - Consult M&E Engineering	≤ 3/4" - same as 304L, 316L & 321. > 3/4" - Consult M&E Engineering	Only in known chloride cracking service except PWHT is generally performed to first block valve.
Alloy 20, Incoloy & Inconel Alloys	Consult M&E Engineering	Consult M&E Engineering	Consult M&E Engineering

(1) "Large piping" is butt welded pipe 2" & larger. "Small piping" is socket welded pipe 1-1/2" & smaller.

(2) "Hot caustic" is over 140°F for concentrations below 30 percent (wt.) and over 110°F for concentrations above 30 percent (wt.).

(3) PWHT on-plot vessels. For tanks, PWHT is required for the heating coils only.

(4) PWHT all FCC main fractionator overhead piping at 1150-1250° F. Furnace PWHT is preferred to obtain the lowest residual stresses; however, if local PWHT is used, special consideration should be given to the PWHT procedure including heating band width, insulation thickness and runout length of insulation. See "Local PWHT Band Width for Pipe Welds" in Section 151.

(5) PWHT is strongly recommended because it has been shown to reduce wet H_2S cracking even though it may not always eliminate it.

(6) For other environments such as HF and nitrate, see the Corrosion Prevention Manual for specific recommendations regarding PWHT.

(7) Chevron MS specifications are more restrictive than the Codes.

(8) The use of standard carbon grades (0.08 C max.) of 304 and 316 stainless steels is discouraged because of the sensitization which can occur either during welding or other heating in the 800° - 1600°F temperature range (i.e., PWHT). Sensitization compromises the intergranular corrosion resistance and cracking resistance of the material.

(9) Type 347 stainless steel can be sensitive to cracking during PWHT but is less sensitive for thicknesses of 3/4" and under because of less restraint.

Controlling Environmental Cracking

Environmental cracking such as stress corrosion cracking and sulfide stress cracking is always a concern in refineries, chemical plants, and producing locations. One effective way to prevent cracking is by heat treating the metal. Figure 100-56 summarizes Company PWHT requirements for some common environments.

Hydrogen embrittlement failures such as sulfide stress cracking (SSC) and HF stress corrosion cracking are related to material strength and hardness, so they can also be prevented by control of weld metal hardness and avoidance of base metals with a high carbon equivalent (i.e., high hardenability).

Carbon steel materials clad with austenitic stainless steel are often not heat treated because the cladding has a much greater coefficient of thermal expansion. Heat treatment results in stresses being re-introduced as the clad material cools from the heat treating temperature.

Solid stainless steel vessels may or may not be heat treated. Those in chemical service often are not because heat treatment may cause sensitization, resulting in eventual intergranular attack.

Piping and vessels made of unstabilized stainless steels are almost never heat treated because of the risk of sensitizing.

Stabilized stainless steel piping is generally heat treated for prevention of external chloride cracking. The chlorides may come from a coastal environment, plant wash-down, fire water, or from insulation. Such cracking occurs only occasionally. As a result, the common practice is to obtain what protection can be achieved easily. Generally, stainless steel piping NPS 2 and larger is heat treated, while smaller lines are not. Treating only NPS 2 and larger piping eliminates roughly 80% of the hazard at 20% of the cost that would be incurred by heat treating all of the piping. It also avoids the problem of warpage and oxidation of small valves.

Reasons for PWHT

PWHT is primarily intended to reduce the residual stresses in a weldment. Residual stresses result from either weld shrinkage or cold work. Higher temperature heat treatments, such as annealing or normalizing, also reduce residual stresses, but relief of stresses is usually not the main reason for these treatments.

Where parts are to be machined to close tolerances after welding, PWHT may be used to minimize dimensional changes and distortion during machining. PWHT is also performed to reduce susceptibility to stress corrosion cracking, and can result in improvement in general corrosion resistance.

Cold worked parts such as shell and head plates for vessels or bends in piping and heat exchanger tubing often require heat treatment. Relieving the stresses from cold work improves dimensional stability, resistance to brittle fracture, and resistance to stress corrosion cracking and corrosion. ASME Section VIII, Division 1 generally requires heat treatment after cold forming if the extreme fiber elongation for carbon and low alloy steel plate is more than 5% and certain other requirements apply (i.e., lethal service, impact testing, thickness over 5/8 inch, 10% reduction in thickness, and forming temperatures causing strain aging). Section UCS-79 covers the forming requirements for shell sections and heads, and the formulas for calculating extreme fiber elongation.

PWHT also tempers and softens welds and heat affected zones (HAZs) that have become hardened by rapid cooling from high temperatures. In the case of chrome-moly steels and other hardenable steels, this tempering is the most important function of a PWHT. Tempering reduces hardness and strength, and improves ductility and toughness. The heat treating benefits of both relieving stresses and tempering act to improve resistance to sulfide stress cracking and hydrogen embrittlement.

Some structures are too large to be heat treated as a whole. It is frequently practical to fabricate the more highly stressed components as subassemblies and then apply PWHT to them to reduce residual stresses and lessen the risk of brittle fracture. An example of a field erected structure with subassemblies that are shop fabricated and postweld heat treated is openings (e.g., manways and cleanout doors) in bottom shell plates of oil storage tanks. Another example is column-to-shell (post plates) attachment welds of large storage spheres. This approach has also been used on critical components for large buildings (e.g., the Sears Tower in Chicago) and bridges.

Cautions Regarding Lower PWHT Temperatures

Both the temperature and the time at temperature must be considered in selecting PWHT procedures. For certain materials, lower temperatures can be used if holding times are increased. Section UCS-56 of ASME Section VIII specifies the following minimum holding times for decreases in normal holding temperatures for carbon steels and some low alloy steels:

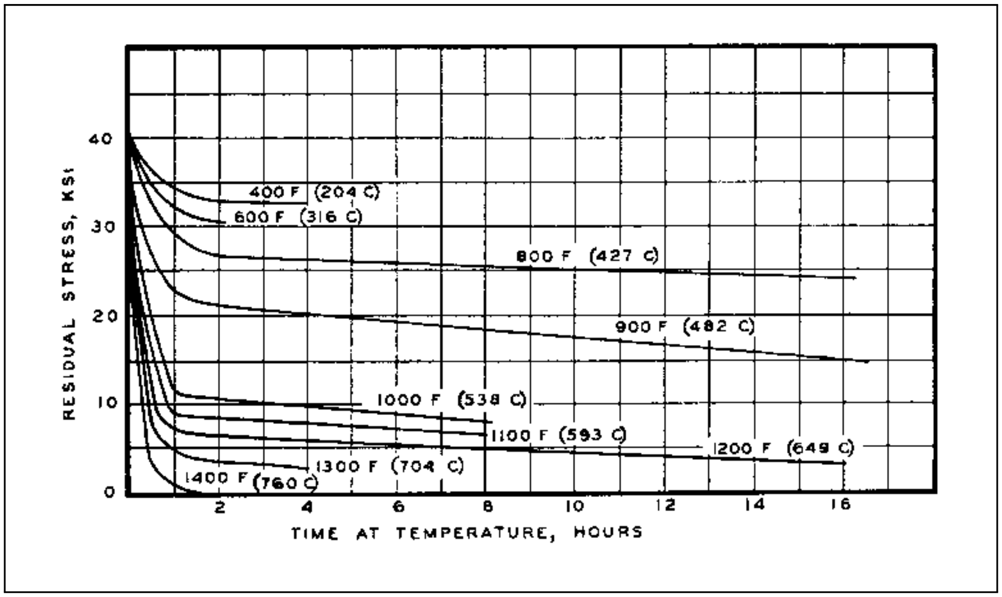
Decrease in Temperature Below Normal Holding Temperature, °F	Minimum Holding Time at Decreased Temperature, hr/in. of Thickness
50	2
100	4
150	10 *
200	20 *

* Permitted only for P-No.1, Group Nos. 1 and 2 materials (e.g., A285 Gr C and A516 Gr 70).

Although these compensations of time for temperature are permitted, the level of residual stresses in a weld after 20 hours at 900°F is still higher than after one hour at 1100°F. The reduction in residual stresses at different temperatures with time for one carbon-manganese steel is shown in Figure 100-57[6]. Because carbon steel is ductile, these low temperature postweld heat treatments are accepted even though the stress relief benefit is reduced. Lower temperatures are not acceptable where PWHT is needed to provide tempering of hardened welds and heat affected zones for resistance to hydrogen embrittlement or sulfide stress cracking.

In the case of the chrome-moly steels, there is even less relaxation of stresses at lower heat treating temperatures. This is because their high creep strength resists relaxation and their stable chromium and molybdenum carbides resist tempering. In

Fig. 100-57 Influence of Temperature and Time on Relieving Stress for Carbon-Manganese Steel *(Courtesy of American Welding Society)*



order to temper chrome-moly welds to acceptable hardness levels for pressure vessels and piping, Company procedures require heat treating in the 1300-1400°F temperature range for a minimum of two hours. This heat treatment is designed to reduce the hardness and tensile strength of welds and HAZs to below 215 Brinell and 100 ksi, respectively.

The table in Figure 100-58 gives the times at various temperatures to produce the same degree of tempering of 2-1/4 Cr-1 Mo steel. Heat treating this material at a temperature lower than 1250°F (minimum temperature required by the Code) is much less satisfactory. Note that an exposure of about one year (10,000 hours) at 1050°F is required to obtain the equivalent of tempering at 1325°F.

The tempering temperature of hardenable steels is important because when these steels are left as-welded or are postweld heat treated at a temperature too low for adequate tempering, the weld zone is inadequately softened, which leaves it susceptible to brittle fracture and hydrogen embrittlement failures such as sulfide stress cracking (SSC).

For welds between different materials, the proper heat treatment temperature is usually the higher temperature of those required for the two materials. However, some combinations, such as stainless steel to 1-1/4 Cr-1/2 Mo or C-1/2 Mo steels, should be considered individually because of the risk of overheating or loss of corrosion resistance in one of the materials. Contact CRTC Materials and Equipment Engineering Unit for assistance.

Heating and Cooling Rates for PWHT

Heating and cooling rates during PWHT of steel have little metallurgical significance. However, parts should be heated and cooled slowly enough to avoid large

Fig. 100-58 Equivalent Tempering Temperatures and Time For 2-1/4 Cr-1 Mo Steel *(Courtesy of the American Welding Society)*

Temperature, °F	Time, Hrs
1325	2.0
1300	3.5
1275	7.0
1250	14.0
1225	30.0
1200	70.0
1150	300.0
1100	1,700.0
1050	10,000.0
1000	60,000.0

temperature gradients that can cause distortion and induce high stresses. The ASME Code limits heating and cooling rates as follows:

- The heating rate above 800°F is limited to 400°F per inch of thickness per hour but not to exceed 400°F per hour.
- During heating above 800°F, the maximum variation in temperature is 250°F within any 15-foot interval of length.
- During the holding period, the difference between the highest and lowest temperatures is limited to 150°F.
- The cooling rate above 800°F is limited to 500°F per inch of thickness per hour but not to exceed 500°F per hour.

ANSI/ASME B31.3 does not limit either heating or cooling rates, since distortion is not a problem for pipe joints because of their symmetry and flexibility. This is acceptable for piping given local PWHT of circumferential seams, but when complex spools are heat treated in a furnace, give consideration to controlling temperature gradients to avoid distortion.

Local PWHT Band Width for Pipe Welds

Although local postweld heat treatment of piping girth welds is often performed in the field, PWHT of an entire piping assembly in a furnace produces the lowest residual stresses because the bending stresses from thermal expansion are not induced during heat treatment. For service environments where low residual stresses are required and furnace PWHT is not practical, the heating band width for local PWHT can be more closely controlled to obtain better results. Research work by CRTC, Edison Welding Institute, DNV, and Pascagoula regarding the carbonate cracking problem on FCC overhead piping has led to the recommendation of wider heating band widths, improved insulation, and slightly higher heat-treatment temperatures. The result is lower residual stresses in carbon steel piping welds.

From research work, the following recommendations were developed to obtain the greatest reduction of residual stresses during local PWHT of carbon steel piping welds in horizontal runs.

- The minimum heating band widths for various pipe sizes with wall thickness of 1/2 inch or less are shown in Fig. 100-59. The minimum band width for all pipe sizes and wall thicknesses can be calculated as follows:

$$BW = 2 \times \{[2.06 \times (R \times t)^{1/2}] + 1\}$$

where:

BW = band width

t = pipe wall thickness

R = pipe radius to mid wall

- To control the PWHT temperature of pipe welds 12 inches and over, two heating zones are recommended with the control thermocouples placed at 12 o'clock and 6 o'clock. For single zone heating, the control thermocouple is located at 12 o'clock. Thermocouples should be placed at the center of the weld and should not be insulated from the resistance heaters.

Fig. 100-59 Minimum heating band widths and number of thermocouples for local PWHT of pipe 1/2 inch or less wall thickness in horizontal piping runs.

Nominal Pipe Size, Inches (1)	Minimum Heating Band Width, Inches (2)	Minimum Number of Control Thermo-couples (3)	Minimum Number of Monitoring Thermo-couples (4)
3/4 - 1	4	1	1
1-½ - 3	6	1	1
4 - 6	8	1	1
12	10	2	1
18	11	2	2
24	12	2	2
26	14	2	2
30	14	2	2

(1) This table covers extra strong (<1/2 inch) and thinner pipe schedules.

(2) Two inches of ceramic fiber insulation (one or rwo layers) should be used to cover the resistance heating band and adjacent pipe for a minimum of nine inches on each side of the band.

(3) Locate the control thermocouples on the center of the weld with the first at 12 o'clock and the second (where required) at 6 o'clock.

(4) Locate the monitoring thermocouples 90 degrees from the control thermocouples.

See Figures 100-60 and 100-61 for the location of thermocouples and the placement of heating bands and insulation for pipe welds.

- Recording thermocouples should also be used for monitoring temperatures away from the control thermocouples. For pipe 12 inches and less, use a minimum of one monitoring thermocouple. For pipe larger than 12 inches, use

Fig. 100-60 Heating Band and Insulation for Pipe Welds

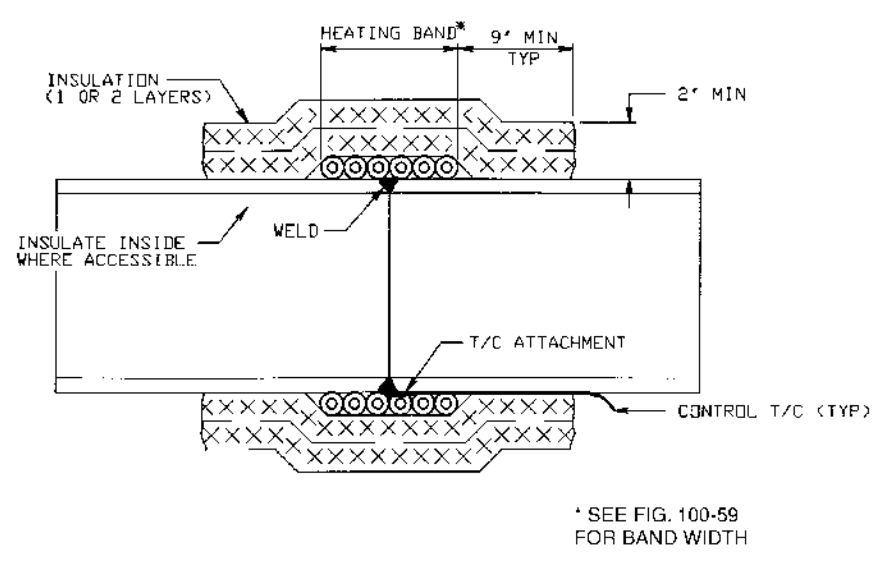
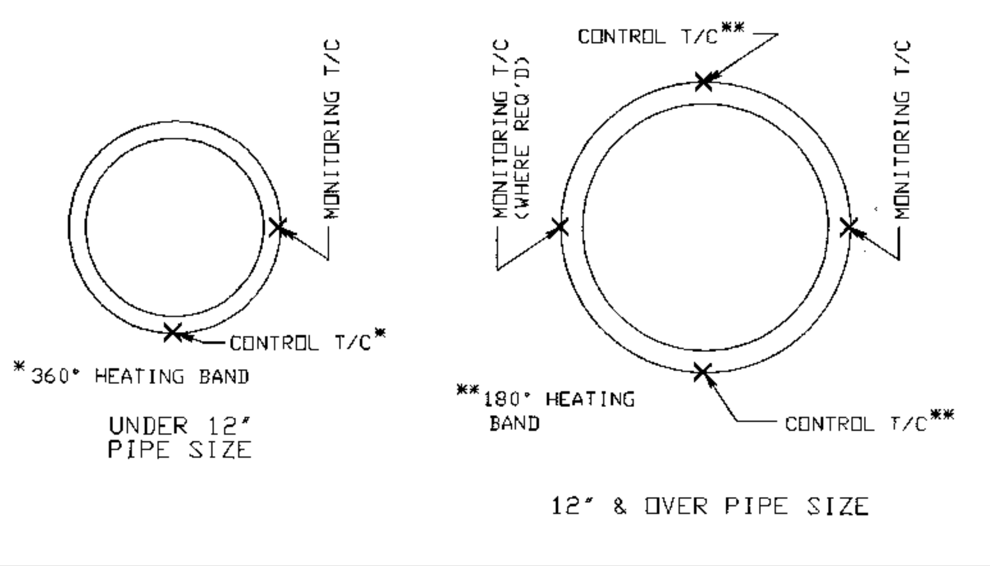


Fig. 100-61 Control and Monitoring Thermocouple (T/C) Location (Heating Band and Insulation not Shown) for Pipe Welds



a minimum of two monitoring thermocouples. Thermocouples should be located 90 degrees from the control thermocouples on the center of the weld and again should not be insulated from the resistance heaters.

- Use nichrome resistance-heating pads with ceramic beads. Install resistance heaters so they are centered on the weld and in good contact with the surface. For pipe to flange welds, the flange should be covered with resistance heaters to compensate for the thicker material.

- Two inches of ceramic fiber insulation should cover the resistance heater and adjacent pipe for a minimum of nine inches on each side of the heaters. Either one two-inch layer or two one-inch layers of insulation can be used but two one-inch layers generally produce lower heat losses. For open piping, where the inside is accessible, the same thickness and length of insulation (including heater width and nine inches on each side) should be used on the inside of the pipe. For flange to pipe welds, the flanges should be fully covered with insulation on the outside and insulated on the inside opposite the flange and pipe heaters and for nine inches beyond.
- Postweld heat treat all FCC main fractionator overhead piping at 1150 to 1250° F for one hour per inch but not less than one hour. The slightly higher temperature assists in further reducing residual stresses and is effective with the wider heater band and better insulation. PWHT recommendations for other materials are given in Appendix A.

Hardness Measurements and Requirements

Hardness measurements are commonly used to determine the effectiveness of PWHT on steel parts and equipment. For this reason, ANSI/ASME B31 and Company specifications require that hardness measurements be made on a representative portion of the welds on the actual structure. These requirements apply to measurements taken on weld metal, not HAZs or other areas.

Hardness is usually measured in the field with a portable Brinell hardness tester such as the Telebrineller (Teleweld Inc., 416 North Park Street, Streator, IL 61364). The Telebrineller is widely used because it is simple to operate, fairly accurate, and very portable. Other portable hardness measuring devices found to be acceptable are the Ernst (New Age Industries, 2300 Maryland Road, Willow Grove, Pennsylvania, 19090) and the Equotip (Alina Corporation, 175 Sunnyside Boulevard, Plainview, Long Island, New York, 11803). Both are portable but require a smooth surface. The Company limits for deposited weld metal hardness are:

Carbon steel	200 BHN Max.
Carbon-moly steel	215 BHN Max.
Chrome-moly steel	215 BHN Max.
12-Chrome steel	235 BHN Max.

Company hardness requirements are lower than those in ANSI/ASME B31.3, Table 331.3.1 (see Figure 100-54). This assures hardnesses lower than the threshold for sulfide stress cracking in wet sour services.

In addition to field hardness tests made on the actual structure to determine average hardness of deposited weld metal, hardness measurements are sometimes required to be made on test plates during procedure qualification tests. These tests are of **micro**hardness, rather than the average hardness given by a Brinell tester. The Vickers test gives a more accurate measure of hardness and is used for services such as sour service. The Vickers test uses a different scale than the Brinell test. See Section 518 for a discussion of hardness testing. These tests are performed on cross sections of the weld, and the hardness of both the weld and HAZ are checked at a specified location (e.g., a specified distance below the surface of the weld). Sour service requirements that have been used for recent pipeline applications specify a maximum Vickers hardness of 250 (VHN) using a 5 kilogram load. Tests are required in both the weld and HAZ at a distance of 2 mm below both the inside and outside surfaces of the material.

PWHT of Stainless Steel and Clad Plate

The austenitic chrome-nickel (300 series) stainless steels are heat treated to improve resistance to stress corrosion cracking by reducing residual stresses from welding or cold forming. To be effective, temperatures must be high enough to reduce stresses to less than about one-fourth of the yield strength. Heat treatment at 1100-1200°F is too low for adequate reduction of residual stresses, and carbide precipitation (sensitization) may occur. Sensitization can reduce resistance to intergranular corrosion, but low carbon or stabilized stainless steels will resist sensitization during short heat treatment periods. The recommended stress relief temperature for stainless steel is 1550-1650°F for all grades. Type 316L weld metal may be susceptible to sigma phase embrittlement when cooling from 1550°F, and for this reason it has been stress relieved at 1200-1250°F in the past. However, this temperature range does not relieve the residual stresses sufficiently to avoid stress corrosion cracking. If stress corrosion cracking conditions are present, then the slight loss of ductility from sigma phase embrittlement is the lesser problem and the normal 1550-1650°F stress relief should be used for Type 316L.

PWHT requirements for pressure vessels made of stainless steel clad plate are determined by the type and thickness of the backing plate. The heat treatment temperature range of 1100 to 1400°F for typical vessel steels degrades the resistance to intergranular corrosion of some grades of stainless steel. For this reason, the effects of welding and heat treatment must be considered in the selection of stainless steel clad equipment. The best solution is to use low carbon or stabilized grades of stainless steel for the cladding.

The purpose of postweld heat treating a clad vessel is to heat treat the backing material and not the cladding. The cladding will have higher residual stresses because of the large differences in thermal expansion coefficients between austenitic stainless steel and carbon steel. When clad plate is heated, the stainless steel cladding tries to expand more than the steel backing, but cannot, so it yields in compression. When clad plate cools to ambient, the cladding tries to shrink more than the steel backing, but again is restrained. As a result, the cladding ends up with residual tension stresses almost as high as in the as-welded condition.

PWHT of Nonferrous Alloys

Nonferrous alloys may be heat treated to reduce residual stresses from welding or cold forming in order to improve resistance to corrosion or stress corrosion cracking. Low temperature heat treatment is often called stress equalization. At these low temperatures there is not much softening and likewise not much decrease in residual stresses. To be really effective, heat treatment must be at temperatures approaching those used for annealing. Aluminum alloys are heat treated at about 650°F. Copper alloys are heat treated at 400 to 700°F. Nickel alloys are heat treated at 1000 to 1500°F.

152 Alternatives to PWHT

Several other methods are sometimes used to reduce stresses or improve weldment properties in lieu of conventional heat treatment. The most frequently used methods are high preheat temperature, temper bead welding, peening, and vibrational stress relief. They should not be used if reducing susceptibility to environmental cracking such as stress corrosion cracking and sulfide stress cracking is the reason for stress relieving. See Section 350, "Repair Welding - Special Techniques for Repair Welding Without PWHT" for additional information.

Limitations

While these alternative stress relief methods are of varying value, each must be understood in order to avoid jeopardizing the integrity of the weldment. Peening will reduce distortion, but will not lower residual stresses below the threshold for stress corrosion cracking, and will not temper the HAZ of hardenable materials. Peening can also reduce the impact toughness of a weld if not applied properly. Higher preheat temperatures reduce residual stresses, but are restricted to carbon and carbon-moly steels by the National Board Inspection Code and API 510. Although temper beads work to break up low toughness zones with bands of higher toughness material, this method provides none of the other benefits of thermal stress relief, such as reducing residual stresses and tempering HAZs to acceptable levels. Vibrational stress relief is not permitted by the codes in place of thermal stress relief for pressure vessels and pressure piping, and it does not reduce HAZ hardness to avoid stress corrosion cracking.

Higher Preheat Temperatures

Higher preheat temperatures help reduce residual stresses from welding. This technique is recognized by the National Board Inspection Code and API 510 as an alternate method of PWHT for repairs to carbon and carbon-moly steels. The weld area and material for a distance of four times the plate thickness (4 inches minimum) on each side of the joint is required to be preheated to 300°F minimum and maintained at that temperature during welding. The maximum interpass temperature is restricted to 450°F. Toughness characteristics of the as-welded condition should be determined to be adequate for the operating and test pressure temperatures.

Temper Bead Welding

Temper bead welding is a technique used to improve resistance to low temperature brittle fracture of weldments that are not practical to heat treat. It is also recognized by the National Board Inspection Code and API 510 as an acceptable substitute for PWHT of repairs to carbon, carbon-moly, and manganese-moly steels. The technique employs weld passes that are ground thin on the first layer and kept small for the filler layers, so that each layer heat treats and refines much of the weld microstructure underneath. It is based on testing that has shown that there is a narrow band in each weld HAZ that is heated to the optimum stress relief or normalizing temperature by the adjacent weld pass. With this technique, when many thin layers (passes) are used to make a weld, there is a larger proportion of zones with good mechanical properties. The final layer should be made with the last weld pass placed in the center. The final layer of weld beads across the top is ground off, leaving only tempered beads underneath.

Peening

Peening cannot be substituted for code-required heat treatments or where thermal stress relief is needed to soften hard welds and HAZs to avoid hydrogen embrittlement or sulfide stress cracking.

Peening can be effective in reducing transverse shrinkage stresses that cause distortion or cracking in welds of thick parts or vessels. Weld metal shrinkage occurs during solidification and cooling from welding temperatures. Peening is done by plastically deforming (cold working) the surface of the weld metal. Subsequent passes of weld metal relieve the cold work of the prior passes. Peening is generally used on carbon and low alloy steel weld metals, although it has been used on stainless steels and high nickel alloys. Peening is used for repair welding of thick castings and forgings, and for welding nozzles or patches in thick-walled vessels.

Medium to heavy duty pneumatic chipping guns with round-nose tools are used to plastically deform the weld metal. Surface indentations and some flaking of the weld surface will occur but are not objectionable because the surface is remelted by the next layer of weld metal. The first layer of a weld should not be peened because of the risk of cracking the thin section of weld metal. The final layer should not be peened because of the poor properties of the cold worked layer. Peening should be done after the weld metal has cooled to the preheat or interpass temperature.

One method of determining if a weld is being adequately peened is to make pairs of punch marks across the weld joint and spaced along the length. After each layer of weld metal, peening should be done until the punch mark spacing has returned to its original dimension as measured by pointed dividers. After several layers of weld metal have been deposited and peened, the spacing should have decreased less than 1/32 inch. When the weld becomes more than one inch thick, the effect of shrinkage and peening has less effect on the punch-mark spacing. If the prior peening has been able to maintain punch-mark spacing, then the same degree of peening should be done for the balance of the weld. An alternate method of controlling peening is to peen until the weld ripples are smoothed out and then stop. This will generally provide adequate peening and will prevent excessive peening.

Vibrational Stress Relief

Vibrational stress relief is a method where a motor-driven, low-frequency vibrator matches the resonant frequency of the workpiece to obtain stress relaxation or redistribution of peak stress. The workpiece must be isolated and free to move on rubber mounts. The most successful application of the process has been in reducing distortion of complex weldments during machining. Other benefits are undocumented and more controversial.

153 Other Heat Treatments

Annealing

Annealing is a heat treatment used to achieve maximum softening and to reduce residual stresses to the lowest level. The term applies to all metals, including iron alloys such as steel and cast iron. For steel, the material is heated to about 50°F above the upper critical temperature followed by very slow cooling. This temperature is about 1600°F for 0.2% carbon mild steel, but varies for other carbon contents and alloying elements. The time at temperature is usually one hour per inch of thickness.

For **austenitic stainless steels** and **nonferrous alloys** that do not undergo transformation, annealing implies heating to above the recrystallization temperature where grain refinement of any cold worked material occurs. The time at temperature is usually 15 to 30 minutes. If the annealing temperature is too high, grain growth can occur, and this can cause a reduction in ductility and toughness. However, some stainless steels and nickel alloys are deliberately heated into the grain coarsening range to improve high temperature creep strength.

In the case of austenitic stainless steel, nickel alloys, and some other nonferrous alloys, a **high temperature solution anneal** is performed to put secondary phases such as carbides into solution. This gives these alloys their best resistance to intergranular corrosion and resistance to stress corrosion cracking (providing the cooling rate is fast enough to avoid reprecipitation).

The annealing temperature for aluminum alloys is about 800°F. Copper alloys are annealed in the 800-1500°F range, austenitic stainless steels from 1850 to 2050°F, and nickel alloys from 1300 to 1900°F. Figure 100-56 gives recommended specific temperatures for each heat treatment.

Normalizing

Normalizing is a heat treatment applicable only to ferritic steels such as carbon and low alloy steels. Normalizing refines the structure of both the weld metal and the HAZ. It removes all traces of the cast structure of the weld and tends to equalize the properties of the weld metal and base metal.

Electroslag weldments in ferritic steels are frequently normalized to increase toughness because the very coarse as-cast structure of the weld metal and coarse grains in the HAZ result in very low toughness.

Normalizing is similar to annealing, but in normalizing the steel is heated to about 100°F above the upper critical temperature and then air cooled. While the slow cooling in the annealing treatment produces a coarse pearlite structure in carbon steel and a spheroidized structure in chrome-moly steels, the faster cooling in normalizing produces a fine pearlite or bainite structure. Normalized steel is tougher and stronger than annealed steel, but both treatments reduce residual stress from welding or cold work and remove hardened HAZs.

Annealing and normalizing, while commonly performed on wrought materials such as flat plate, straight lengths of pipe, or forgings, are seldom performed on completed welded vessels or structures. This is due to the metal's low strength at these high temperatures, which makes supporting the structure difficult. These two procedures also require careful handling of the hot structure, and careful cooling to prevent distortion caused by the differences in cooling rate between a thick part of the work and a thinner one nearby. Another problem with annealing and normalizing is the decarburization and scaling that occur when steel is held for long periods at these high temperatures.

Tempering

In addition to normalizing, electroslag welds are frequently **tempered** for further improvement in toughness. Tempering, although similar to PWHT, has a different purpose. The purpose of tempering is to improve toughness or ductility of the metal. When used after welding, it is applied to both the weld and the base metal.

The principal reason for normalizing steel is to improve low temperature toughness. The improvement results from grain refinement during recrystallization and the inherently greater toughness of the fine structure produced. Parts are often tempered after normalizing to improve ductility and further improve toughness, but not always. For example, some of the low alloy medium strength tank and structural steels (about 50,000 psi yield strength) are supplied as normalized and are neither tempered before welding nor postweld heat treated afterwards.

Quenching

Quenching is a hardening heat treatment used for most ferritic steels. The term quench anneal is sometimes used for non-hardening alloys such as austenitic chromium-nickel stainless steel, high chromium ferritic stainless steel and nickel alloys to indicate the need for rapid cooling from the solution annealing temperature.

In quenching a hardenable steel, the work is heated to above the transformation temperature and then rapidly cooled to ambient temperature. The cooling, or quenching, is accomplished by immersion in water or oil, or by means of a water spray or high velocity air jets. When cooled rapidly, steel with sufficient carbon and alloying elements does not have time to transform to the soft structures produced during the slower cooling of annealing or normalizing. Instead, strong, hard (brittle) martensite and bainite are formed.

Quenched steels are almost always tempered after quenching to reduce strength and improve toughness and ductility. Tempering also reduces locked up residual stress. The temperatures used for PWHT must be lower than the temperatures used for tempering or additional softening of the base metal will occur and tensile strength will be decreased.

High strength low alloy (HSLA) structural steels with about 100,000 psi yield strength are supplied in the quenched and tempered condition. These steels can be left as-welded or may be given a PWHT. Postweld heat treating temperatures are usually below 1150°F in order not to soften the steel to less than its specified strength. HSLA steels require carefully chosen heat treatment temperatures depending on their specific composition. Some of the HSLA steels contain over 0.05% vanadium and/or 0.002% boron, which can cause embrittlement in the coarse grain region of the HAZ when heated into the 1000-1200°F temperature range during PWHT. This embrittlement causes cracking and is termed **reheat cracking**. As a result, it is generally recommended that welds in these steels **not** be postweld heat treated.

Some ferrous and nonferrous alloys can be hardened by a heat treatment called **age hardening** or **precipitation hardening**. Aging these alloys at PWHT temperatures after solution annealing causes hardening. The hardenable aluminum alloys are hardened by aging between room temperature and about 350°F. This is rarely done to aluminum weldments. Nickel alloys like K-monel and precipitation hardening stainless steels like 17-4 PH and A-286 are susceptible to cracking during welding if in the hardened condition. To avoid cracking, these alloys are first given an over-aging anneal to soften them and then after welding they are hardened by solution annealing and aging.

160 Heat Treatment Procedures

PWHT can be performed by placing the work in a furnace, either in the shop or in the field, or it can be applied locally to a single weld or to a small portion of the work.

161 Shop Furnace Heat Treatment

PWHT is best performed in a shop furnace, which can be gas, oil, or electrically heated. In general, furnace heat treatment costs will be lower, schedules shorter, and temperature control better than with local heat treating methods. A large complex pipe spool can be heat treated in a shop furnace for about the same cost as local heat treatment of a single weld in the field.

However, shop furnaces do not automatically produce good heat treatments. Care must be exercised to assure good temperature measurement and control, along with proper positioning and support of the work.

Positioning the Work

It is important to locate the work in the furnace to avoid both cold and hot areas. Since in most furnaces the door, back, and floor tend to be cooler and the sides and the top hotter, the work should be located away from all six sides. Locate the work away from burner ports as much as possible. Check for malfunctioning burners or flame impingement, which should be corrected immediately.

It is also important to be sure there is adequate, uniform support of the work and freedom for thermal expansion and contraction.

Temperature Monitoring

It is important to monitor and control the temperature of the work being heat treated. Uniformity of the temperature within the furnace depends on the furnace heating rate, whether the furnace is well designed for even heating, and whether it has been properly maintained so that there are no clogged burner nozzles, misaligned burners, etc. Thermocouples on the work are used to monitor temperature.

The various thermocouple types have different maximum temperatures, as shown below. Be sure the maximum temperature of the thermocouple is high enough to use at the planned temperature.

Thermocouple Type	Maximum Temperature
Iron-Constantan	1200°F
Chromel-Constantan	1500°F
Chromel-Alumel	2000°F
Platinum Rhodium	2500°F

Thermocouples must be positioned **on the work** to detect and prevent localized overheating or cold spots. Thermocouples must be placed at critical locations for monitoring to assure even heating and to prevent high thermal stresses, distortion, overheating or insufficient tempering of hard welds.

A serious mistake that is frequently made, especially in furnace heat treating at commercial heat treaters, is to rely completely on the **furnace** thermocouples to monitor heat treating temperature. Furnace thermocouples only measure the temperature of the furnace atmosphere at the actual location of the thermocouples. These thermocouples are useful for furnace control, but they cannot substitute for thermocouples on the work being heat treated. Parts of the work being heat treated may be several hundred degrees hotter or cooler than these furnace control points.

There are no set guidelines covering the number of thermocouples needed, except that as a minimum at least one plus a spare is required. Determining the need for additional thermocouples is a matter of experience and judgment, and this must be evaluated for each job. For accurate results, thermocouples should be securely attached to the work by direct spot or resistance welding, peening, bolting, or welded thermocouple pads. Thermocouples in long probes that are placed on or near the workpiece in the furnace are often not much better than furnace thermocouples for monitoring temperature.

Heating and Cooling Rate

The rate of heating and cooling of the workpiece is very important. Too rapid heating or cooling causes thin sections of metal to heat or cool more rapidly than thick sections. This non-uniform heating and cooling can cause distortion, residual stresses and, if sufficiently severe, cracking. A good rule to follow is to maintain temperature differences within the structure being heat treated to 250°F or less.

If the temperature spread during heating approaches this amount, the furnace firing rate should be cut back and the work allowed to “soak” until the temperatures even out. Application of the rule limiting the temperature spread to 250°F will automatically provide a suitable heating rate. However, if temperatures are only being measured by furnace thermocouples exposed to hot furnace gases rather than by thermocouples directly on the work, the heating rate should be limited to about 400°F per hour. Even tighter control on temperature spread may be necessary when heat treating equipment with complex shapes, such as heat exchanger bundles with thick tube sheets.

Uniformity of temperature during cooling is just as important as it is during heating, and the temperature spread should be limited to about 250°F during cooling from the heat treating temperature to about 800°F. It is not advisable to remove the work from the furnace until the temperature has dropped to about 800°F. If it is desired to speed up the cooling cycle, **consult with a Materials Specialist**, as there are problems that may be involved in doing this.

It is advisable to look in the furnace occasionally after the metal has reached a red heat (around 1150°F) to check visually for any dark or bright spots, which are an indication of uneven temperature.

Complex Shapes

Complex shapes like heat exchanger tube bundles require slow heating rates to achieve uniform temperatures and avoid distortion. For this type of work, convection furnaces that depend on the circulation of hot gases for heating are better than furnaces that depend on radiation from hot brickwork. Thermocouples should be placed near the center of the tube bundle (to tell when that area is up to temperature) and on the tubes closest to the burners or radiant walls (to avoid overheating).

Temperature Ranges

Temperature ranges must often be held within narrow limits if the heat treatment is to be successful. While the temperature range for carbon steel is broad, there are much narrower limits for other alloys. For example, Type 304 stainless steel is usually stress relieved at 1550 to 1650°F. If the minimum temperature is not reached, inadequate stress relief results and the metal may fail in service from stress corrosion cracking. 5 Cr-1/2 Mo steel is stress relieved at 1325 to 1400°F. If this minimum temperature is not reached and held for two hours minimum, the weld may remain too hard and brittle. If the weld is heated much above the upper limit of 1400°F, undesirable hardening of the entire fabrication may occur during cooling.

Large Assemblies

When pressure vessels, pipe assemblies or structures are too long to fit inside an available furnace, they can be heat treated in sections. Usually the furnace door is replaced with temporary insulated panels or bricks stacked around the vessel or structure. ASME Section VIII (Boiler and Pressure Vessel Code) requires an overlap of five feet for vessel sections heat treated separately.

Heating for treatments such as annealing, normalizing, and quenching is almost always performed in a furnace because of the need to heat the entire weldment to a uniform high temperature.

162 Field Furnace Heat Treatment

Field Erected Furnaces

Heat treatment in a furnace is not limited to shop operations, because temporary furnaces can be built around the work in the field. Some field furnaces are simply a cylindrical box made of large diameter pipe insulation placed around a pipe weld.

The insulation box becomes a convection furnace by the addition of a tangential propane burner. Other field furnaces are more elaborate, consisting of metal boxes or frames lined with insulation and built around the structure. They are heated by fuel-fired burners or electric resistance panels. With field erected furnaces, more attention must be paid to temperature control and thermocouple placement than in shops because of inexperienced operators and lack of knowledge of the temperature gradients within the furnace.

Vessel As Furnace

In some cases an entire vessel is made into a furnace for its own field heat treatment. This is done by insulating the outside surfaces and heating from the inside with a large luminous flame, resistance heating panels, or by circulating hot gases through the vessel. Usually supplementary resistance heaters are used around nozzles and other areas of heat loss.

Fired Heater Tubes

Fired heater tubes that have been in service can be heat treated in place by firing the heater with the tubes empty or with controlled circulation of steam or inert gas. While the risk of spot underheating and/or overheating is great, the savings in time and labor over removal of tubes for shop heat treatment may also be great. For this type of heat treatment, many more temperature indicating points are needed than the number normally present for the operation of a fired process heater. There must be close coordination between the operation of the burners and the recording of temperature data, so that temperature swings can be anticipated and avoided. Although attractive, this method is not practical for new construction since access completely around the welds is restricted when the tube banks are in place, and nondestructive testing and repairs to welds are also more difficult due to restricted access.

Large Structures

Field heat treatment of large structures is a complex problem, and technical assistance should be obtained from experienced specialists for placement of thermocouples, design and operation of burners, and control of temperature to avoid collapse or buckling.

163 Local Heat Treatment

Local heat treatment consists of heating single welds or small portions of the work. Local heat treatment of welds in structures, piping, and parts of vessels is often required for repair, maintenance, or field assembly of weldments too large to be furnace heat treated or shipped in one piece. The precautions needed for furnace heat treatment are equally important in local heat treatment. Many different types and arrangements of heat sources have been successfully used for local field heat treatment.

Support of Work

Before heat treatment is started, the work must be adequately and evenly supported, and it must be free to expand and contract during the heating and cooling cycles. Material properties are significantly reduced at heat treating temperatures and may result in significant sagging or buckling if the structure is not adequately supported. For example, when heat treating one weld in a furnace tube that is connected to others by headers or U-bends, adjacent tubes must also be heated so the tubes can expand together. In heat treating shafts, it is common practice to hang them vertically in the furnace to provide freedom to expand and contract.

Temperature Control

Care should be exercised in the placement of thermocouples and insulation in relation to the source of heat. Thermocouples should be placed so they measure temperatures at the hottest and coolest locations. This allows proper control of maximum temperature gradients as well as sensitivity to the effects of convection currents inside the furnace and cooling from wind and rain outside the furnace. The weld zone to be given local heat treatment is usually so well insulated that temperature indicating crayons or contact pyrometers cannot be used to measure and monitor temperature. The usual method for monitoring temperature is to tack weld thermocouples to the required temperature measurement locations and then lead the wires out through the heaters and insulation. The type of thermocouple must match the recording instrument. To prevent false high readings, thermocouple ends should be protected from direct radiation by covering them with a lump of high temperature mortar or with a metal shield welded to the work.

In piping and other hollow or open-ended structures, such as heat exchanger tube bundles, the inside should be plugged off as close to the heated zone as possible without causing steep thermal gradients. In local PWHT of pressure vessels, the side opposite the heat source should be insulated. Insulation should be left in place until the work has cooled to about 800°F.

Code Requirements

In addition to engineering and metallurgical requirements, the codes impose rules for the local heat treatment of pressure vessels and piping. The heating and cooling rates specified by the ASME Pressure Vessel Code must be followed for vessels, and for both piping and vessels the part must be held in the correct temperature range for the required length of time. Maximum heating and cooling rates are not specified for piping in ANSI/ASME B31.3.

For heat treatment of a nozzle or branch connection, a circumferential band that is six wall thicknesses wider each way than the attaching weld must be heat treated. For a circumferential weld, the heated zone must be at least two wall thicknesses wider each way than the weld. In all cases, the weld and nearby surface should be insulated to avoid steep temperature gradients.

164 Local Heat Treatment Methods

Electric Resistance Heating

Resistance heating is probably the most widely used method of local heat treatment of vessels and piping, but it is not always the lowest cost method. This method generates heat by passing an electric current through a high resistance wire. NiChrome wire is used because of good oxidation resistance at high temperatures.

Resistance heaters may be as simple as an assembly of wires in tubular or flat insulators in the shape of ropes or mats, which are wrapped around the work and then covered with insulation. They can be hinged boxes that contain heating elements and insulation, and plug into programmed controllers and power supplies. Some resistance heaters are designed to use welding machines as the power supply. However, one supplier, Cooperheat, has taken advantage of recent developments in ceramics, refractories and electrical controls to produce a complete line of modular resistance heat treating equipment. There are several other reputable companies in this field, such as Western Stress, Exomet, Universal Stress Relief, Analytical Stress Relieving, and Reliant Heating and Controls.

In all cases, temperature information from thermocouples must be fed back to the controllers for the power supplies. The availability of electrical power is the only limit to the size of vessel that can be heat treated with resistance heating elements. In one case, a nuclear reactor weighing 800 tons was stress relieved in a single heating.

Flame Heating

Hand held torches are almost never used for final PWHT because of poor temperature control with the risk of overheating and associated hardening. Pipe rings holding multiple gas burners and an enclosure have been successfully used, but this is done infrequently because a different setup is needed for each size of pipe, and automatic controlling is difficult.

One successful operation of hand held torch annealing has been the solution annealing in place of high carbon cast stainless steel furnace tubes, headers, and tube supports, performed to avoid weld zone cracking when making repair welds. In this application, two or four oxyacetylene heating torches are used to heat the part into the 2000-2100°F temperature range for about one-half hour. Temperatures can be measured with an optical pyrometer, temperature-indicating crayons or thermocouples.

Exothermic Heating

Heat treating by means of the controlled combustion of solid exothermic materials was developed in the early 1950's. Exo-Anneal kits of preformed combustible material and insulation are manufactured by Exomet, Inc., Conneant, Ohio 44030. These can be tied around a pipe joint or structural member with soft wire, ignited, and left to accomplish the stress relief heat treatment. After heat treatment, just remove the burned kit and loose covering. Tests have shown that satisfactory heat treatment in the 1100°F to 1650°F temperature range can be applied to standard sizes and wall thicknesses of pipe without temperature measuring equipment. While the exothermic heat treatment kits are fairly expensive, no skilled labor is needed.

A disadvantage of Exo-Anneal is that each pipe size, schedule, weld configuration, and temperature range of heat treatment requires a different kit. In recent years, Exomet has reduced delivery lead time by establishing warehouses in major industrial areas, with stocks of kits for standard sizes of pipe and fittings of carbon steel and chrome-moly steel. A different product along the same lines, Flex-Anneal, may further reduce delivery time because it can be adapted to various sizes and shapes in the field.

Many construction companies use Exo-Anneal kits for much of their field heat treatment of piping. However, improvement in resistance heating equipment has significantly reduced the Company's use of these kits.

Induction Heating

Induction heating is similar to resistance heating in that electrical coils must be wrapped around the part. The coils carry alternating current and generate heat within the steel by means of eddy current and hysteresis losses as the magnetic field in the metal reverses rapidly. The coils used vary from asbestos-insulated electrical power cable or water-cooled copper tubing to lightweight bellows-type water-cooled tubing covered with a braided conductor and insulation.

Various commercial induction heating power supplies for the heat treatment of piping, beams, and vessels produce alternating current at 400 Hz and higher. Alternating current welding machines can be used as power supplies, but they are inefficient.

Although induction heating is fast and uniform and can be readily programmed, power supplies are large and expensive. For this reason induction heating has only been used extensively for treating heavy chrome-moly steam piping in power plants. Another drawback is that the coils must be large enough to completely encircle the area to be heat treated. This requires proportionately larger supporting power sources, which limits the size of parts that can be economically heat treated by this method.

Radiant Heating

Radiant heaters are usually used in shop or production line installations, but packages for field work are marketed. These include controls and power supplies for heat treating piping from instrument line sizes through aqueduct sizes. Several types of radiant heat sources are used for PWHT. Several manufacturers supply equipment using high intensity quartz lamps as the heat source (GE Heat-Tech and Sylvania Thermomatics). Others use a gas-heated metal screen (Van-Dorn) or ceramics (Selas and Cooperheat).

170 Cutting Of Metals

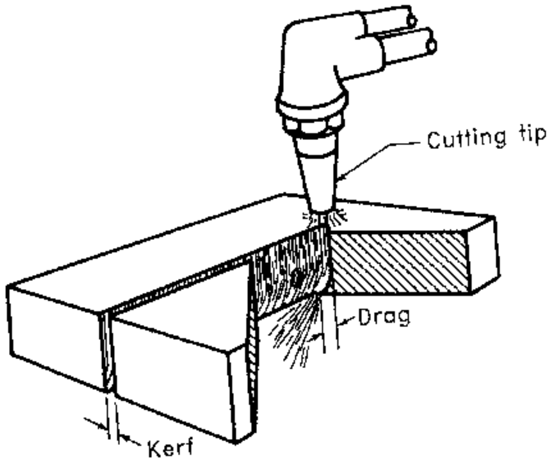
A number of thermal cutting processes are available that are divided broadly into **oxyfuel gas cutting** and **arc cutting**. Selection of the cutting process depends on the alloy to be cut, the availability of equipment, the amount of cutting to be done, and accessibility of the work.

More detailed information on metal cutting processes is given in the *AWS Welding Handbook*, Volume 2, Seventh Edition.

171 Oxyfuel Gas Cutting

Oxyfuel gas cutting uses a fuel gas combined with oxygen. On carbon steels and low alloy steels containing less than about 9% chromium, **acetylene** is the fuel gas most commonly used for cutting. Acetylene mixed with oxygen is used to preheat the base metal prior to cutting. A stream of pure oxygen is introduced to do the actual cutting by a high temperature exothermic reaction of the oxygen with iron. Metal oxides and molten metal are expelled from the cut by the kinetic energy of the oxygen stream. A view of oxyfuel gas cutting is shown in Figure 100-62, which also illustrates the terminology of kerf (cut width) and drag of the cut.

Fig. 100-62 Oxyfuel Gas Cutting *(Courtesy of the American Welding Society)*



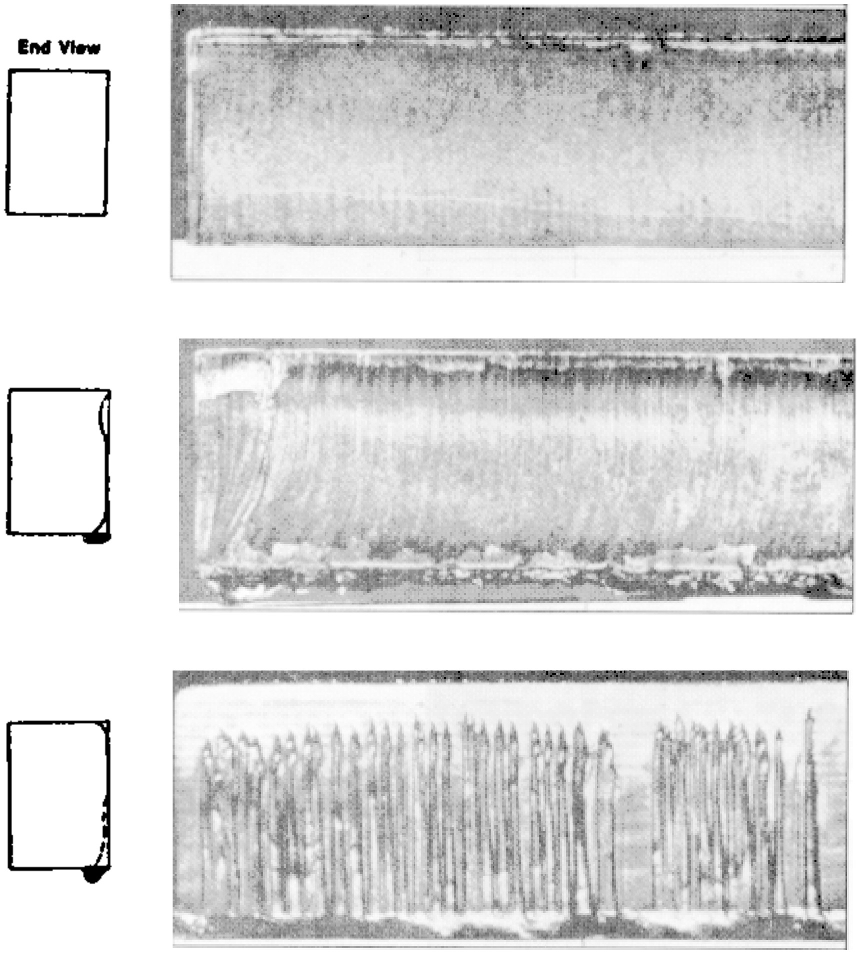
Propane or **natural gas** can be substituted for acetylene as the fuel gas. Propane is safer to use than acetylene. It is stored as a liquid and so requires less cylinder handling.

Another acetylene substitute is **methylacetylene-propadiene stabilized (MPS)**, a proprietary acetylene. MPS is a mixture of several hydrocarbons, including propadiene, propane, butane, butadiene, and methylacetylene. MPS burns hotter than propane or natural gas and is easier to use than acetylene for cutting preheat because it has more even heat distribution in the flame. Like propane, MPS is a liquid and so requires less cylinder handling. Use of alternate fuel gases such as propane and MPS generally depends upon availability, safety requirements, and economics.

Oxidation-resistant steels, such as stainless steels and steels with chromium contents of over 9%, are more difficult to cut. When oxyfuel gas cutting of oxidation-resistant steels is attempted, high melting temperature refractory oxides are formed that prevent cutting. For these steels, cutting can be facilitated by introducing flux or iron powder into the oxygen stream. **Flux cutting** uses a flux to react chemically with the chromium oxides formed during cutting to produce compounds with melting points nearer to those of iron oxides. **Powder cutting** uses iron-rich powdered metal that accelerates the oxidation reaction and increases melting temperature and spalling action of the base material.

A troubleshooting guide for flame cutting is shown in Figure 100-63.

Fig. 100-63 Troubleshooting Guide to Oxyfuel Gas Cutting *(Courtesy of the American Welding Society)* (1 of 3)

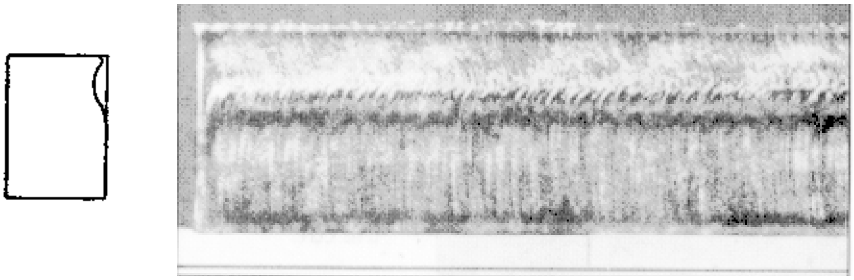


A good quality cut requires no conditioning: Underside is free of slag, cut surface is smooth and square with plate surfaces.

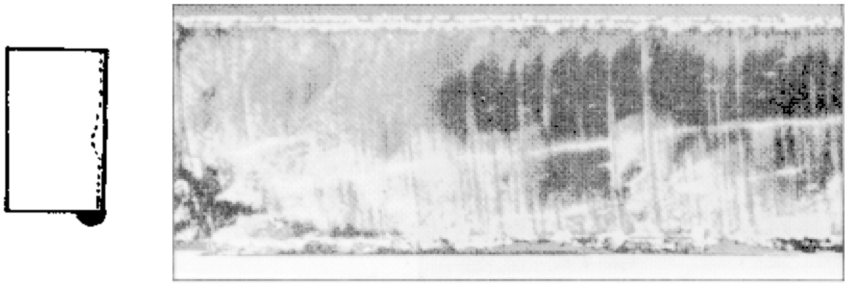
Cutting too fast: Slag and metal globules stick to the underside of the plate, and the trailing oxygen stream leaves drag lines on the kerf edge.

Cutting too slowly: Slag builds up on the underside of the plate, the top edge melts under excessive heat, and the wandering oxygen stream gouges the kerf face.

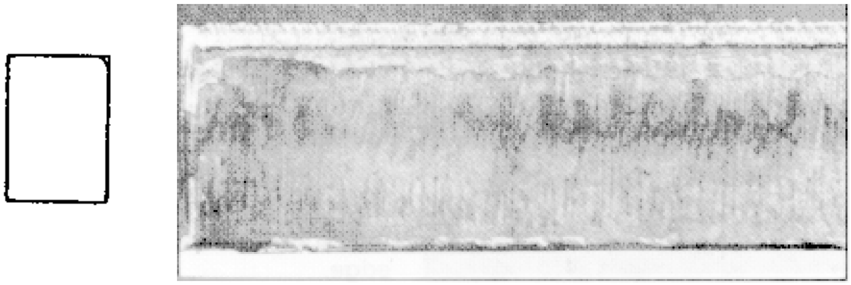
Fig. 100-63 Troubleshooting Guide to Oxyfuel Gas Cutting *(Courtesy of the American Welding Society)* (2 of 3)



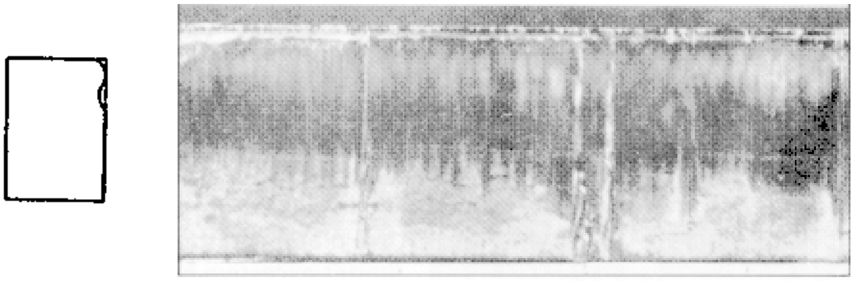
Cutting oxygen pressure too high: The oxygen stream removes too much metal from the top of the cut, and leaves a hard residue on the bottom. Some of the oxygen blows back, depositing metal beads on top of the plate.



Cutting oxygen pressure too low: Excessive slag makes cut parts stick together; the cut surface is irregular.

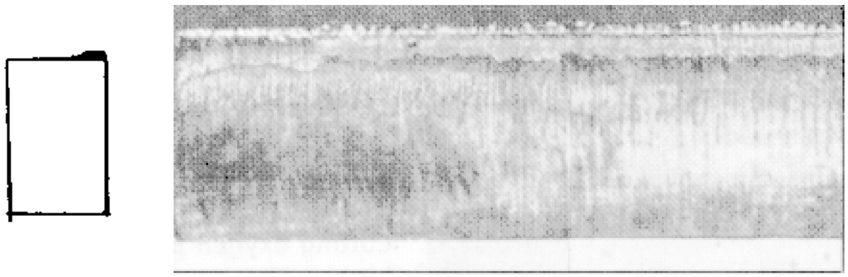


Preheat too high: The top edge of the plate melts, leaving a round edge.

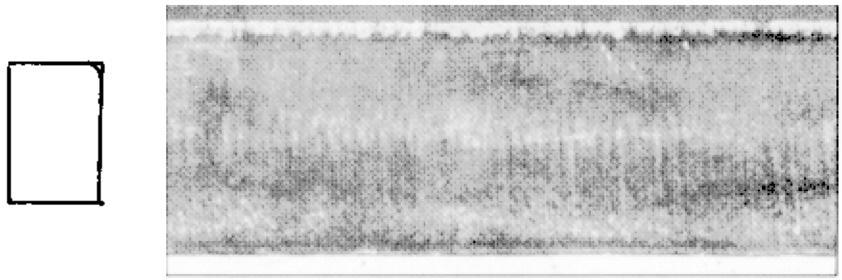


Insufficient preheat: Cutting slows, oxidation may be interrupted.

Fig. 100-63 Troubleshooting Guide to Oxyfuel Gas Cutting *(Courtesy of the American Welding Society)* (3 of 3)



Stand-off distance too high: The preheat flame wanders on the top of the plate, deposits hard-to-remove scale.



Tip too close: Preheat flame interferes with the cutting oxygen stream, causing the irregular surface at the top of the cut.

172 Arc Cutting

Arc cutting involves severing or removing metals by melting them with the heat of an arc generated between an electrode and the base material.

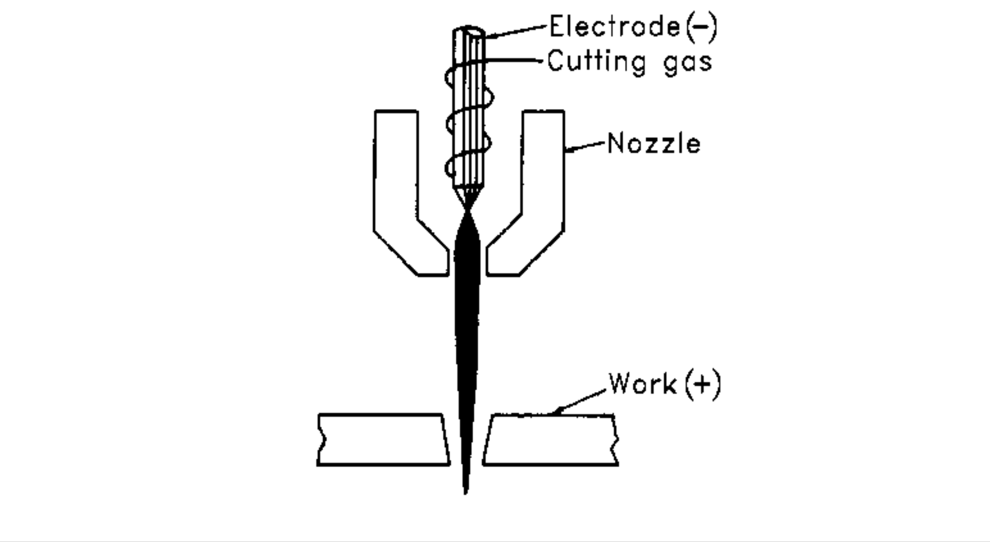
Air Carbon Arc Cutting

Air carbon arc cutting (also called air arc gouging) can produce reasonable quality cuts on ferrous or nonferrous materials. Melting is achieved with an arc between a consumable carbon-graphite electrode and the base material. The molten metal is blown away with a high velocity jet of compressed air. The air is directed so that it strikes the molten metal immediately behind the arc.

Plasma Arc Cutting

The plasma arc process is the highest quality cutting process for alloy steel and nonferrous alloys. (The alternative is to use powder cutting.) It generates a very high temperature, high velocity constricted arc between a non-consumable tungsten electrode (contained within a torch) and the base metal. The intense heat continuously melts the metal, which is removed by a high velocity stream of ionized gas. Plasma arc cutting produces a fast, clean cut with a much thinner HAZ and oxide layer than with other processes. Plasma arc cutting produces a slightly tapered cut because the kerf is on the top rather than on the bottom. The taper can be placed on one side of a cut in order to obtain one straight side if needed. Although plasma arc cutting is the most economical process on high alloys, it can also have an advantage on thinner carbon steel, where it allows cutting speeds that are much faster than for oxyfuel gas cutting with thicknesses up to about one inch. Figure 100-64 is a schematic of a conventional plasma arc cutting torch.

Fig. 100-64 Conventional Plasma Arc Cutting (Transferred Arc) *(Courtesy of the American Welding Society)*



173 Applications of the Cutting Processes

Oxyfuel gas cutting, plasma arc cutting and powder cutting are the processes most often used for cutting of plate and pipe materials.

Oxyfuel gas cutting is widely used on carbon and low alloy steels because of economy and simplicity.

Plasma arc cutting does an excellent job of producing smooth, clean cuts on all metals (both ferrous and nonferrous), but the cost of equipment is significantly greater than for oxyfuel gas cutting. On higher alloy steels plasma arc cutting has generally replaced powder cutting because of better cut quality and greatly reduced cleanup after cutting. Powder cutting generally requires removing by grinding about 1/8 inch of material contaminated by the iron powder after cutting.

Automatic air carbon arc cutting equipment can be used for smoothing rough plate surfaces for weld overlay, preparing U-shaped grooves in square butt joints, and preparing weld bevels on square cut edges.

174 Company Applications

Most of the thermal cutting done by the Company is by oxyfuel gas cutting or by air carbon arc cutting. Air carbon arc cutting generally results in rougher cuts, and grinding is usually required after cutting.

Plasma arc cutting equipment has become more widely used as people recognize the advantages of the process and as equipment becomes less costly.

The need for preheat before cutting depends upon material thickness and alloy content (see Figure 100-53 for recommended preheat for cutting).

180 References

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