STEEL CASTINGS HANDBOOK

SUPPLEMENT 6

REPAIR WELDING AND FABRICATION WELDING OF CARBON AND LOW ALLOY STEEL CASTINGS

STEEL FOUNDERS'
SOCIETY OF AMERICA

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REPAIR WELDING AND FABRICATION WELDING OF CARBON AND LOW ALLOY STEEL CASTINGS

By: John F. Wallace*

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PREFACE

This publication is an update of the 1969 Steel Foundry Research Foundation Report, "Recommended Practice for Repair Welding and Fabrication Welding of Steel Castings". The purpose of this publication is to provide a comprehensive source of detailed welding information that will assist engineers, welders, and weld operators in the repair and fabrication welding of steel castings.

To assure a complete set of references for welding steel castings welding engineers are recommended to gather in a three ring binder this publication along with the latest edition of the following publications:

1. Filler Metal Comparison Charts, AWS A5.0-78
   American Welding Society, 2501 N.W. 7th Street,
   Miami, FL 33125

2. Welding Terms and Definitions, AWS A3.0-76
   American Welding Society, 2501 N.W. 7th Street,
   Miami, FL 33125

3. Suggested Arc-Welding Procedures for Steels Meeting
   Standard Specifications, ISSN 0043-2326
   Welding Research Council, 345 E. 47th Street,
   New York, NY 10017

4. ASTM Specification A 488, Qualification of Procedures
   and Personnel for the Welding of Steel Castings,
   American Society for Testing and Materials, 1916 Race
   Street, Philadelphia, PA 19103

5. A Review of Welding Cast Steels and Its Effects on
   Fatigue and Toughness Properties, December, 1979.
   Steel Founders' Society of America, Cast Metals
   Federation Building, 20611 Center Ridge Rd., Rocky
   River, Ohio 44116

The report for this publication "Repair Welding and Fabrication Welding of Steel Castings" has been prepared by Professor J. F. Wallace upon request by the Carbon and Low Alloy Technical Research Committee of the Steel Founders' Society of America.

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SECTION I: WELDING PROCESSES

Description of Welding Processes and Parameters

The primary welding methods used for repair and fabrication welding of steel castings are described below. These welding processes include: shielded metal-arc, flux-cored arc, gas metal-arc, gas tungsten-arc, submerged-arc, and electroslag welding.

Shielded Metal-Arc Welding, SMAW

Shielded metal-arc welding, commonly called stick welding, is a manual welding process. Flux-covered consumable electrodes are used with the SMAW process. Combustion and decomposition of the flux provides a gaseous shielding for the weld puddle, electrode tip, and surrounding area. The shielding prevents air from reacting with the molten weld metal, reducing oxide and nitride formation and hydrogen absorption. Impurities in the molten weld metal, such as oxides and salts, react with the flux and form a slag. Additional shielding is provided by the slag. The SMAW process is shown schematically in Figure I-1.

A variety of covered electrodes are used with the SMAW process. These electrodes are classified by tensile strength of the deposited weld metal, allowable welding positions, and depth of penetration. A detailed list of electrode classifications and commercially available electrodes complying with these classifications are contained in Section II of this report.

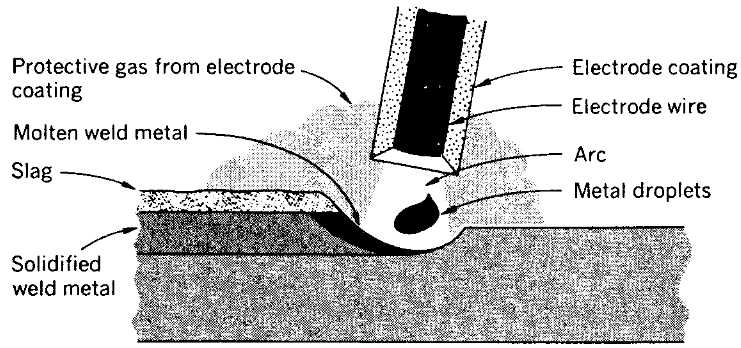
Either alternating current, AC, or direct current, DC, can be used with the SMAW process. DC current can be either straight or reverse polarity. The choice usually depends on availability of equipment and the type of electrode used. AC and DC equipment can be combined also. Some factors affecting the choice of the power supply include (1):

- Cable length. For AC welding the cable length is more critical than for DC welding because the voltage drop in long cables added to that at the arc can overload the power source or prevent its developing sufficient voltage for a proper arc.

- Current type. DC surpasses AC when low current values are used with small-diameter welding wires.

- Electrode type. All classes of covered electrodes are satisfactory for DC welding; only AC/DC-rated electrodes with coverings specifically formulated for alternating current should be used with AC welding.

- Arc starting. When small-diameter electrodes are used the arc is more difficult to start with AC than with DC current. When the arc is struck at a low current setting, the electrodes may stick or "freeze", unless designed specifically for AC operation.



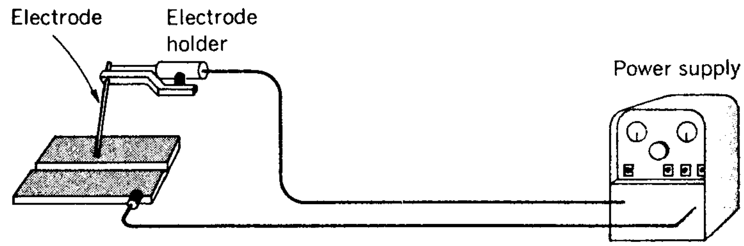
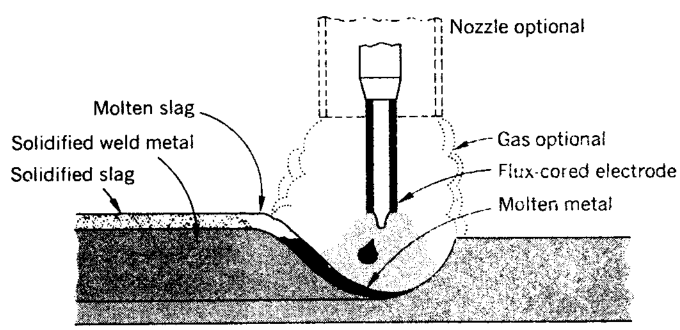


Figure I-1 Shielded Metal-Arc Welding, SMAW (1)



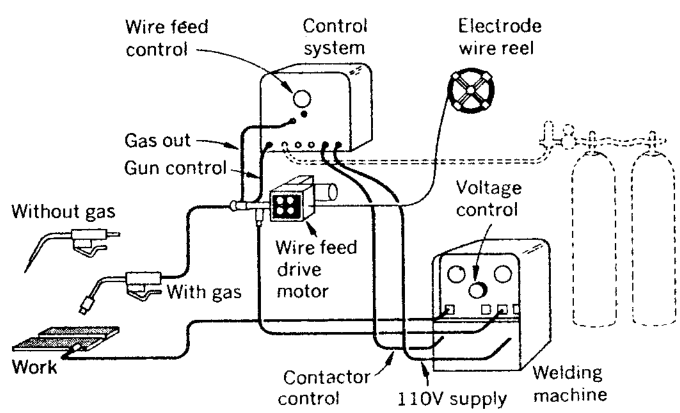


Figure I-2 Flux-Cored Arc Welding, FCAW (1)

- Thickness to be welded. Because of the steady, easily started arc, DC current is preferable for welding sheetmetal.
- Arc length. Maintaining a short arc, when the arc must be crowded into a molten puddle, is easier with DC than with AC.
- Arc blow. AC current is well-suited for welding thick sections using large-diameter electrodes and maximum current levels because arc blow is rarely a problem with AC current.
- Weld spatter. Somewhat more weld spatter is produced with AC welding, partly because of the pulsating nature of the current.
- Weld position. DC current is somewhat easier to use for out-of-position welding on thicker sections, because lower currents can be used.

The SMAW process is very versatile. The equipment is simple, portable, and less expensive than equipment used for other processes. All that is needed is an adequate power supply, a simple electrode holder, and cables. Furthermore, SMAW welding can be performed in any position. The SMAW process is suitable for repair welding because of its versatility, wide selection of available electrodes, and simplicity.

Several limitations of the SMAW process should be recognized. The deposition rate and deposition efficiency, which is defined as the ratio of the weight of deposited weld metal to the net weight of filler metal used (excluding stub), are low compared to other welding processes. Welding must be stopped after each stick is used and the remaining stub is wasted. Slag must be removed after each pass. The SMAW process cannot be automated since the flux covering would be damaged from coiling the electrode and automatic feeding. An adaptation of the SMAW process has been developed which permits automatic use. This process, flux-cored arc welding, is discussed below.

Flux-Cored Arc Welding, FCAW

The FCAW process overcomes major limitations of the SMAW process. Besides being suitable for automatic welding, FCAW provides higher deposition rates, less time lost from changing electrodes, and less wasted material. The FCAW process is shown schematically in Figure I-2.

In flux-cored arc welding a tubular electrode with a flux core replaces the covered stick electrodes used in SMAW. This allows coiling and mechanical feeding of the electrodes. Higher deposition rates are possible compared to those of the SMAW process since less electrode heating occurs which damages the flux covering of stick electrodes and limits the maximum current used in the SMAW process.

Two general processes are utilized: self-shielding, which is identical in principle to the SMAW process, and auxiliary gas shielding. In the latter process an auxiliary shielding gas, in addition to the flux gases and the slag provide shielding to the molten weld metal.

A DC reverse polarity hook-up is normally used with either constant current or constant voltage control. Arc voltage, current, travel speed, and electrical stickout* are the principal operating variables to be controlled. Arc voltage variations will have the following effects (1):

- Excessive arc voltage results in heavy splatter and a porous weld.
- Increasing the arc voltage flattens and widens the weld bead.
- Decreasing the voltage may cause a convex bead with a rope-like appearance.
- Extremely low voltage causes the electrode to "stub" on the workpiece. The electrode dives through the molten weld puddle and strikes the unmelted base metal at the bottom of the puddle.
- With higher current, higher voltage can be used without causing porosity. Using the highest voltage possible (without causing porosity) will result in a weld-bead shape which is satisfactory for most applications.

With all other variables held constant, current variations will have the following effects (1):

- Excessive current produces convex weld beads, which results in wasted weld material and poor appearance.
- Melting rate, deposition rate, and penetration are increased by increasing the current.
- Large-droplet transfer occurs when the current is too low and causes difficulty in maintaining a uniform weld bead.
- Increasing the current increases the maximum voltage that can be used without causing porosity.

With all other variables held constant, travel-speed variations will have the following effects (1):

- An excessive travel speed results in a convex weld bead with uneven edges and shallow penetration.
- Too slow a travel speed results in slag interference, slag inclusions, and a rough uneven weld bead.

---

*The length of the electrode extending between the point of electrical contact within the gun and the work.

With all other variables held constant, electrical stickout will have the following effects (1):

- Increasing the stickout decreases the welding current; decreasing stickout increases the current.
- When stickout is increased the actual arc voltage is lowered. A lower arc voltage increases weld-bead convexity and reduces the likelihood of porosity.
- When stickout is excessive, spatter and irregular arc action will result.
- Short stickout produces greater weld penetration than long stickout.
- When stickout is too short, spatter will build up on the nozzle and the contact tube.

Besides the advantages of the FCAW process already discussed, the self-shielding and auxiliary gas methods each have particular advantages. While both methods are suitable for out-of-position welding the self-shielding method is less penetrating than the auxiliary gas method. The self-shielding method is therefore suitable for poor joint fit-up. The auxiliary gas shielding method can be used for a wider range of thicknesses and produces better joint penetration.

Gas Metal-Arc Welding, GMAW

The GMAW process, also known as Metal-Inert Gas Welding, MIG, can be used as an automatic, or a semi-automatic welding process. The GMAW process uses a continuously-fed bare consumable electrode wire. Shielding is supplied by gas. The shielding gas is either helium, argon, carbon dioxide, or mixtures of these gases. The GMAW process is shown schematically in Figure I-3. The power source used with GMAW is basically direct current, constant voltage, and usually reverse polarity.

The GMAW process is capable of producing top quality welds. It is suitable for welding in all positions. Since flux is not used, slag removal is not required and slag entrapment in the weld is not of concern.

Electrodes are produced from high purity material. The electrode composition depends on the composition of the metal being repaired or fabricated, shielding gas, metal transfer technique, and welding position. Composite wires are available for welding alloy steels.

Generally, carbon dioxide shielding gas is used for welding steels. Good welding speed and penetration are attained with carbon dioxide. Carbon dioxide is also less expensive than the other gases

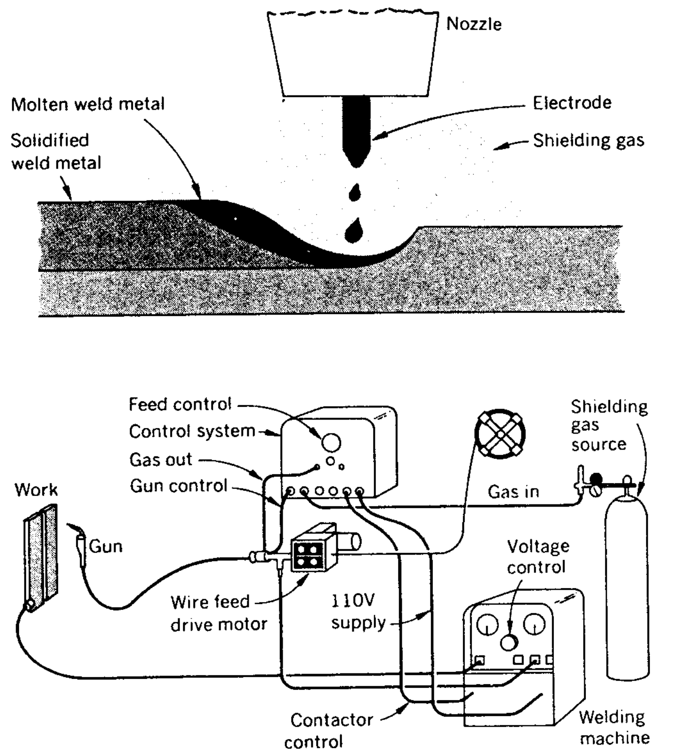


Figure I-3 Gas Metal-Arc Welding, GMAW (1)

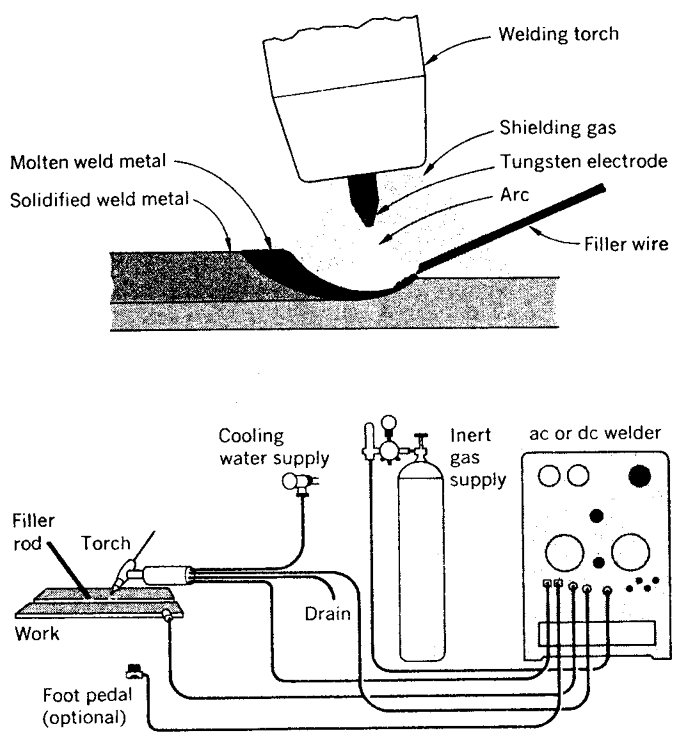


Figure I-4 Gas Tungsten-Arc Welding, GTAW (1) which could be used. Mixtures of carbon dioxide with argon, and sometimes helium are also common for welding steels. Argon, being relatively heavy, is used for downhand welding and horizontal fillet welds. Helium is used for thick sections.

Metal transfer is accomplished by either a short circuit or spray transfer technique. The short circuit method is a low heat input technique, which is suitable for welding thin sections. However, the metal transfer occurs by globular drops which fall downward regardless of the welding position. This limitation can be overcome by combining the short circuit and spray transfer techniques. Spray transfer is a high heat input technique which produces maximum penetration and higher deposition rates. Spray transfer is particularly suited for thicker sections. Unlike short circuit transfer, the weld metal is propelled from the electrode to the work piece; hence, spray transfer is suitable for out-of-position welding. With spray transfer, weld splatter is minimized, high deposition efficiency is attainable, and weld control is enhanced. The combination of the short circuit and spray transfer techniques lowers the heat input--thus, improving the GMAW process for welding thin sections. Sections with a thickness of about 3/8 in. are considered thin sections. Sections measuring two in. and heavier are thick sections.

Gas Tungsten-Arc Welding, GTAW

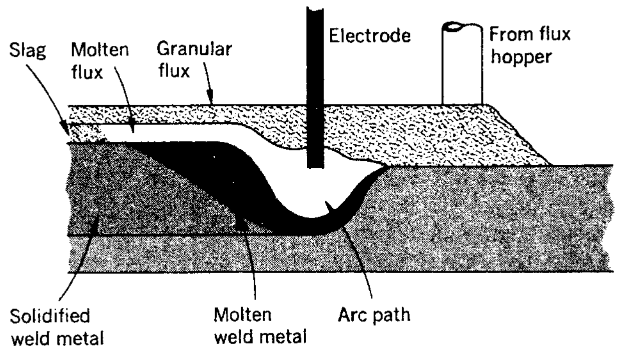
The GTAW process, also know as Tungsten-Inert Gas, TIG, can be used as an automatic or as a semi-automatic welding process. A non-consumable tungsten electrode is used to produce the arc and generate heat at the welding surface. Shielding is commonly provided by argon gas. Helium is also used at times. A filler metal may or may not be used, but it is usually for joining thick sections. The GTAW process is similar to the GMAW process, except that the work piece is joined by coalescence of the base metal, unless filler metal is added. The GTAW process is shown schematically in Figure I-4.

The end profile of the tungsten electrode determines the current density at the welding surface. Profiles range from pointed to a bulbous mass which has a greater diameter than the electrode. DC straight polarity is normally used, but pulsed current power supplies are also available.

Features of the GTAW process include: top quality welds, no weld splatter, no slag removal, all position welding. The GTAW process is suitable for welding a wide range of metal thicknesses. However the GTAW process is slow, and the shielding gas is expensive. Because of these limitations, the GTAW process may not be advantageous over other welding processes for welding steel castings.

Submerged-Arc Welding, SAW

The SAW process is used more frequently as a fully-automatic process, although it is adaptable for semi-automatic welding. The SAW process utilizes a bare, continuously fed, consumable electrode wire. A granular fusable flux shields the weld metal and the electrode. Either DC or AC current is used with the SAW process. This process is shown schematically in Figure I-5.



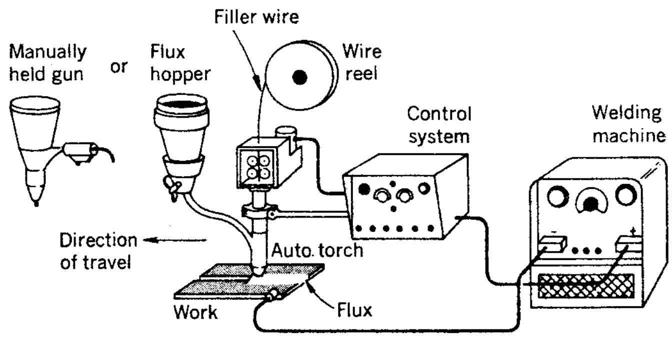
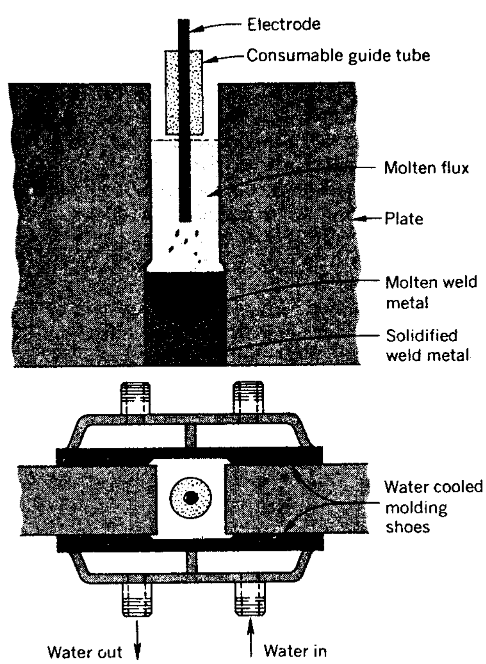


Figure I-5 Submerged-Arc Welding, SAW (1)



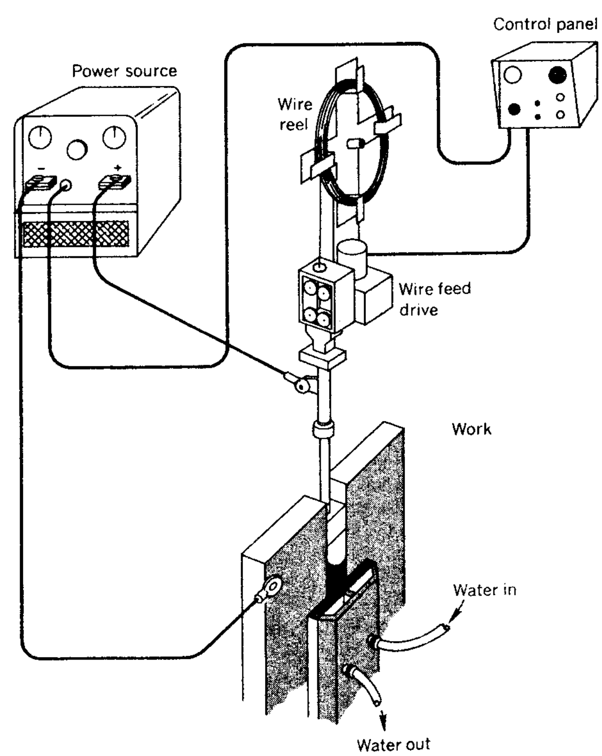


Figure I-6 Electroslag Welding, ESW (1)

The SAW process is most suitable for production welding of unalloyed low carbon steels containing less than 0.3% C, 0.05% P, and 0.05% S (1). Medium carbon steels and low alloy steels can be welded by this process, although preheat, postheat, and special electrodes are often required.

High welding currents can be used. This is possible with the bare electrode wire of the SAW process, since excessive resistance heating of the flux, which causes the flux to break down, is not a problem. High welding current produces high heat input, and therefore permits high welding speeds and deposition rates. Other advantages are: less filler metal is consumed, since shallow V-groove weld end preps can be used, wires for welding unalloyed low carbon steel are inexpensive, the insulating effect of the flux results in deeper penetration and heat distortion is minimized.

Limitations of the SAW process are largely those common to other flux-type welding processes. In particular, the SAW process is limited to flat position welding of groove welds, and flat and horizontal fillet welds with thicknesses of 3/16 in. (1) or greater, to prevent burn-through.

Electroslag Welding, ESW

The ESW process has some characteristics of submerged-arc welding; it is used for welding in the vertical position. One method utilizes bare electrode wires which are fed continuously into a molten slag pool contained between water-cooled dams. The ESW process begins with an arc to melt the flux and create a pool of molten slag. The arc is then extinguished and a molten pool of weld metal and base metal is maintained by the heat generated from the resistance of the flux to the passage of current from the electrode to the base metal. The metal solidifies as the water-cooled dams are moved upward. The ESW process is shown schematically in Figure I-6.

The ESW process has not been widely used in casting repair up to this time. It is widely used for cast weld assemblies with heavy sections (2, 3), and is well adapted to joining thick sections over 2 in. (2). Some features of the ESW process are (1) the extremely high deposition rates which can be attained, the thickness which can be welded in one pass, the minimal requirements for joint preparation and fit-up, little or no distortion, and low flux comsumption.

Selection of the Welding Process

Many factors must be considered when selecting a welding process for a particular application. The type of welding to be performed, types of steel to be welded, the size and quality of the weld, are but a few factors which must be evaluated.

The type of welding which will be performed--i.e., repair welding or fabrication welding is one practical consideration. Manual or semi-automatic welding processes are most adaptable for repair welding, except for very large repair welds when automatic welding processes could be feasible. Fabrication welding may allow application of high speed automatic processes. The amount of welding to be performed is another factor to consider. Sophisticated, complex, and expensive equipment may not be justified for a small operation or if welding is limited to repairs. Location can be a factor. If welding must be performed in areas that are difficult to keep clean and free from drafts, weld quality could be impaired when welding with shielding gas. If the gas is blown away, it will not be effective in preventing contamination of the weld metal. The necessity for high production rates may be an overriding factor. High deposition rates can be attained with automatic equipment. Figures I-7 through I-10 show approximate deposition rates for the various welding processes. Economics have already been mentioned, but capital costs and operating costs will also become a factor when comparing the alternatives.

The most significant factor in selecting a welding process is weld quality. The quality of the weld should at least meet, if not exceed, the requirements in effect for the base material. All of the welding processes discussed previously will produce welds of good quality and acceptability; this depends largely on welder performance and on the soundness of the welding procedures. However, some processes inherently result in better quality welds by the nature of the process--e.g., GTAW. The mechanical properties and nondestructive tests of the weld will ultimately be the judge of weld quality and acceptability. The effect of welding processes on fatigue and toughness is discussed in Reference 2.

The types of steel being welded must be considered since availability of some electrodes may be limited. Electrode selection and availability are discussed in detail in Section II of this publication.

The features of the various welding methods discussed previously in this section must be considered with the advantages and limitations of each when deciding on the best process. Each situation has to be considered based on the various circumstances and availability of welding equipment. The following individual comparison of the various welding processes highlights their differences.

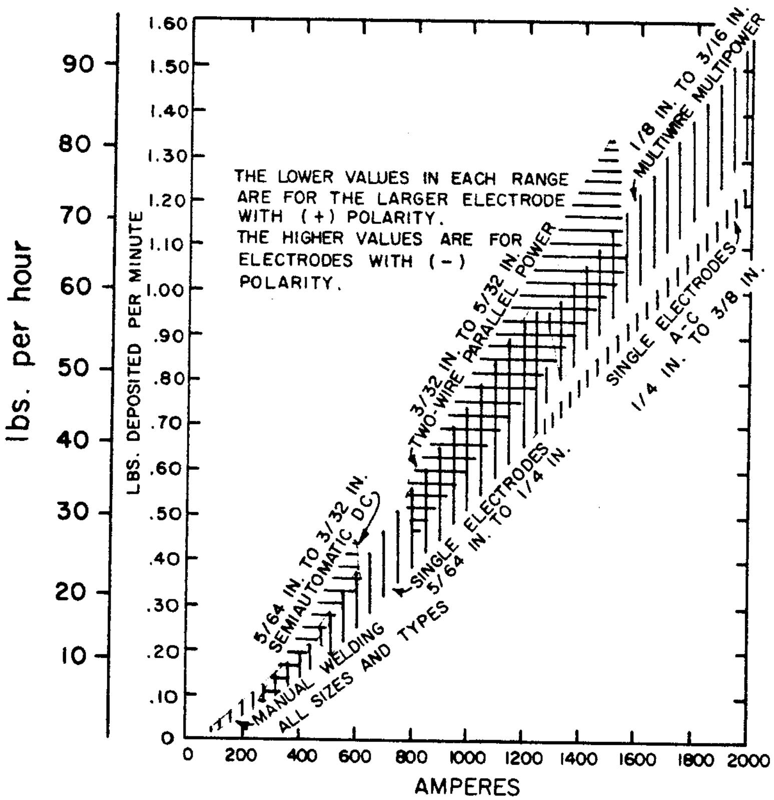


Figure I-7 Approximate deposition rate of shielded metal-arc and submerged-arc processes on mild steel (4).

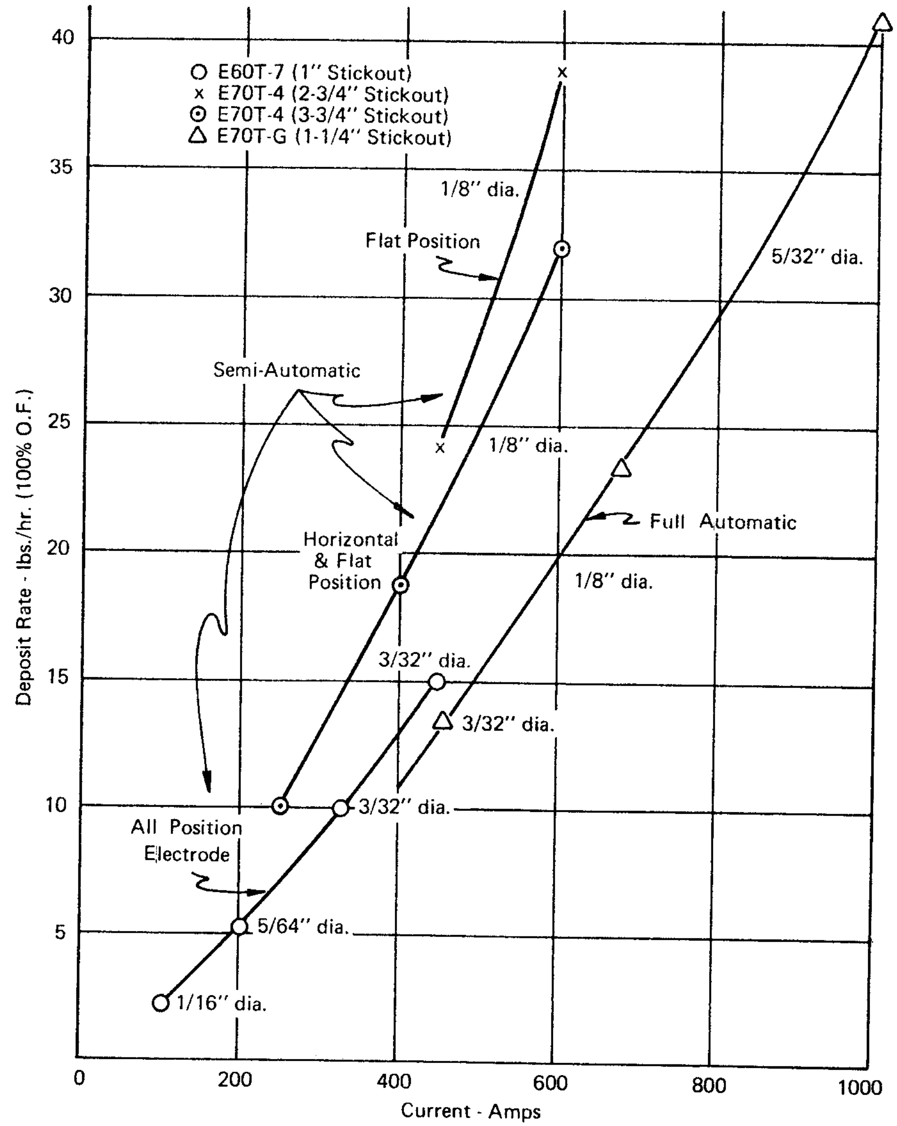


Figure I-8 Approximate deposition rate of flux-cored arc welding processes for self-shielded electrodes (5).

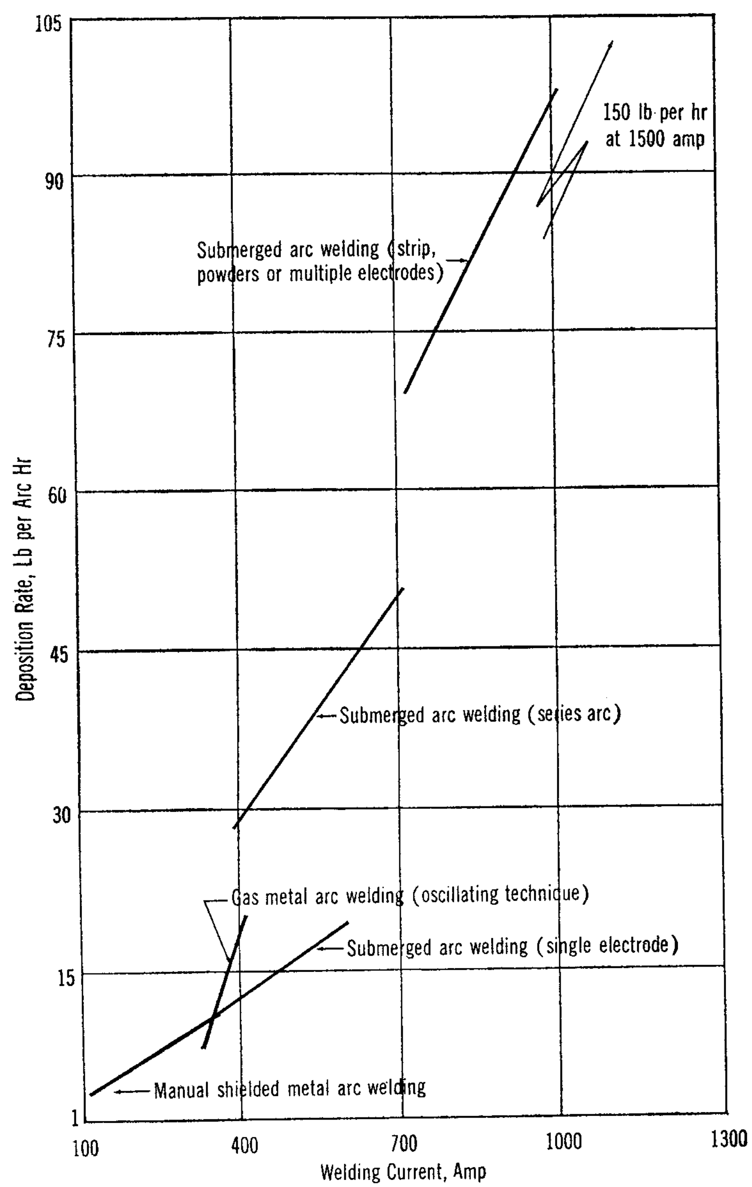


Figure I-9 Approximate deposition rate of Gas Metal-Arc Welding (6).

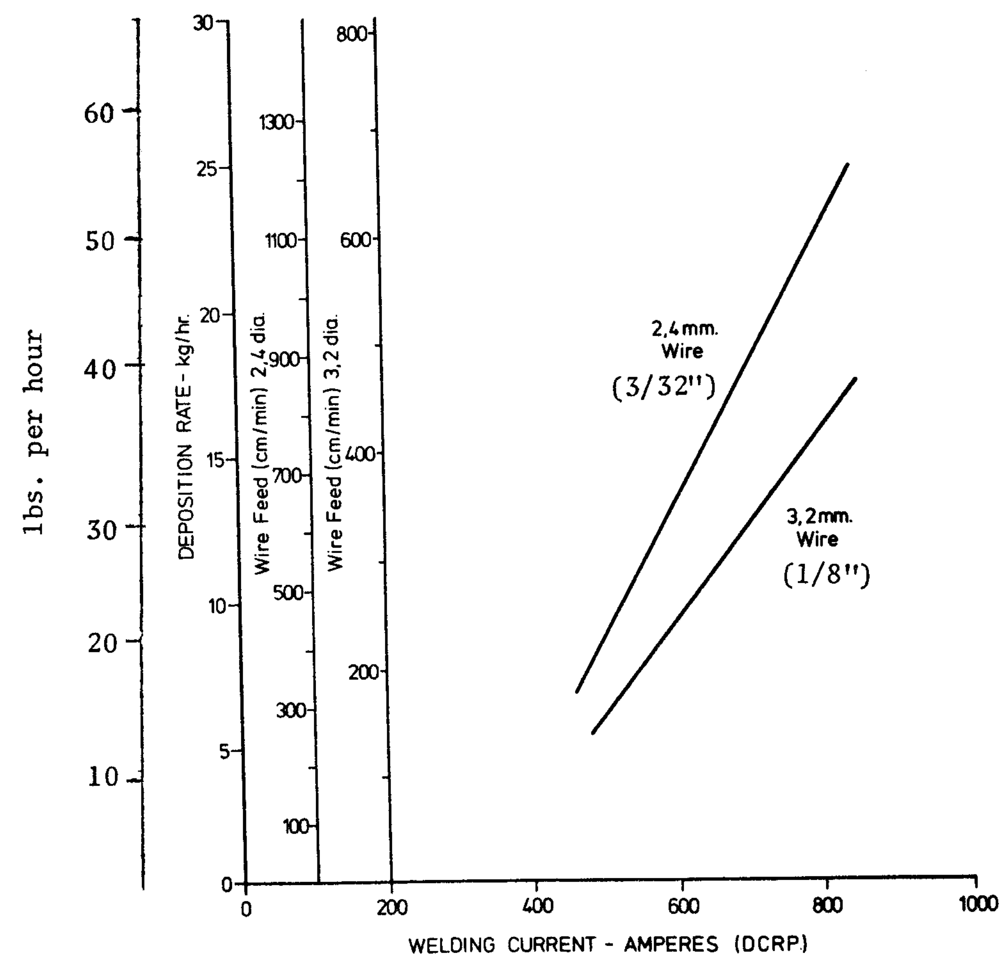


Figure I-10 Approximate deposition rate of Electroslag Welding for a single electrode (7).

a. The shielded metal arc welding, SMAW, is the most versatile and still a widely used process for repair and fabrication welding. Electrodes are available for a large range of steel alloys, welding positions and shielding atmospheres. The low hydrogen type of coating is employed widely for carbon and low alloy steel castings because of the reduced problems with cold cracking without preheating. However, the SMAW process has numerous disadvantages including: low deposition rates; low deposition efficiency of the electrode metal in the weld deposit (about 70%); high electrode stub losses; high losses in welding time to replace electrodes; and fairly difficult slag removal (8). The manual arc welding SMAW process also does not generally produce as high a weld quality as the semi-automatic processes. It is also more difficult to operate than processes that feed the electrode into the weld puddle and welding fume collection is more difficult (8).

b. The semi-automatic flux-cored arc welding FCAW, and CO_2 shielded, gas metal arc welding, GMAW, processes have significantly higher deposition rates, higher efficiency of electrode usage and welder time. These processes generally make higher quality welds and are easier to control and operate than the SMAW process (8, 9). For these reasons, many steel foundries are replacing the SMAW process with FCAW and GMAW processes for repair and fabrication welding (8-11). Advantages of these processes also include easier slag removal for the FCAW process and little slag problems with the GMAW process compared to the SMAW process. The shielding gas for carbon and low alloy steels should be CO_2 to minimize costs (10, 11). The FCAW process can be used together with CO_2 gas shielding if the quality of the weld requires this (1). However, electrode types are more limited as will be shown by the lists in Section II; in addition the semi-automatic equipment cannot be moved to difficult to reach locations with the ease of the manual SMAW process (1, 8, 10). While the modern equipment available for the FCAW and GMAW process is relatively trouble free, it does require more maintenance than manual equipment. Other limitations of the FCAW and GMAW processes are that they are not readily adaptable to: welding overhead except with special weld preparation, and to welding small castings or sections under 1/4 in. thickness (10). The GMAW process is susceptible to difficulties from drafts or air movement (1, 9).

c. The gas tungsten arc welding, GTAW, produces a high quality weld with an automatic or semi-automatic process. While it is adaptable to a wide variety of metals and thicknesses, the rate is slow compared to the FCAW and GMAW processes and the argon or helium shielding gas is expensive. For these reasons, it is not widely used for carbon and low alloy cast steel repair or fabrication welding.

d. Submerged arc welding, SAW, can be adapted to semi-automatic welding for steel casting repair with some advantages in selected applications (12). The automatic process is directly applicable to many types of fabrication welds (3). The deposition rates are high and under many conditions significantly higher than the FCAW and GMAW processes. Welder fatigue is reduced by the shielding effect of the flux, thus allowing higher heat inputs. The welds are of high quality and relatively free from spatter, reducing postweld finishing. The unfused flux can be recovered and different fluxes can be used to control the composition of the weld deposit. The process is limited to the flat or horizontal positions with flux retainers because of the loose granular flux. Steel thicknesses should be 3/16 in. or greater to prevent burn-through from the high heat (1, 12).

e. The electroslag welding, ESW, is primarily useful for cast weld assemblies of heavy sections because of the very high deposition rates. Because of this high deposition rate and minimal joint preparation, the process could have limited applicability to very large weld repairs in carbon and low alloy steel (1, 3). The process is limited to use in the vertical position.

SECTION II: ELECTRODES AND FLUX

American Welding Society Classification

Specifications for welding electrodes and flux are published by the American Welding Society, AWS. The AWS specifications are issued according to welding process and type of metal, e.g., flux-cored arc welding of mild and low alloy steels. Each specification identifies the classification system used for the type of electrode covered, and flux, if applicable. For example, covered electrodes for shielded metal-arc welding, SMAW, are designated by the letter prefix "E" followed by a set of four or five numbers. From left to right, the first two (or three) digits indicate the approximate minimum tensile strength of the as-deposited weld metal in thousands of pounds per square inch. The next-to-last digit indicates the welding position in which the electrodes can be used: "1" indicates an electrode that can be used for flat, horizontal, vertical, and overhead welding; "2" indicates an electrode that can be used for welds in the flat position and for horizontal fillet welds. The last digit indicates the current to be used and the type of covering on the electrode. In addition, a letter suffix used for low alloy steel covered electrodes designates the chemical composition of the deposited weld metal. Details of the electrode classification system for electrodes used with the other types of welding processes are described in the appropriate AWS specifications. It should be emphasized that AWS will qualify an electrode under one classification only, even though some electrodes can fulfill the requirements for more than one classification. For example, some E6013 electrodes can meet the requirements for E6012 electrodes.

The following paragraphs on various electrode classifications reference tables with pertinent information on mechanical properties and compositions as obtained from deposited weld metal without any significant admixture of base metal. In cases of welds where such mixing does occur, the mechanical properties and chemical analyses will probably be affected. The mechanical properties of welds are also influenced by the section size of the weld to some extent. The data shown for the various types of deposited electrodes in Tables II-1 through II-7 were obtained by welding a specified plate thickness according to the procedure contained in each reference (13-19) for the different types of electrodes. The thickness is 3/4 in. for the weld of mild steel covered arc welding electrodes (13), mild steel gas metal-arc welding electrodes (16), and mild steel flux-cored arc welding electrodes (17). This weld thickness decreases to 1/2 in. for low alloy steel covered arc-welding electrodes (14), and increases to one inch for carbon and low alloy submerged arc welding electrodes (15, 18). The thickness for electroslag welding consumables (19), is one inch for V-groove welds and two inches for square-groove welds.

Mild Steel Covered Arc-Welding Electrodes (13)

This specification contains requirements for covered mild steel electrodes for shielded metal-arc welding of carbon and low alloy steels (Tables II-1A through II-1D). The electrodes are classified on the basis of the mechanical properties of the as-welded deposited weld metal, type of covering, welding position of the electrode, and type of current.

Low Alloy Steel Covered Arc-Welding Electrodes (14)

This specification contains requirements for covered low alloy steel electrodes for shielded metal-arc welding of carbon and low alloy steels (Tables II-2A through II-2D). Electrodes are classified on the basis of the mechanical properties of the deposited weld metal, type of covering, welding position of the electrode, type of current and the chemcial composition of the deposited weld metal.

Bare C- Steel Electrodes and Fluxes for SAW (15)

This specification contains requirements for carbon steel electrodes and fluxes for submerged arc-welding of carbon and low alloy steels (Tables II-3A, -3B). Electrodes are classified on the basis of their as-manufactured chemical composition. Fluxes are classified on the basis of the mechanical properties of a weld deposit made by using the flux being tested in combination with a particular electrode.

Mild Steel Electrodes for GMAW (16)

This specification contains requirements for mild steel, solid electrodes for gas metal-arc welding of mild and low alloy steel (Tables II-4A through II-4C). Electrodes are classified on the basis of their as-manufactured chemical composition, and the as-welded mechanical properties of deposited weld metal.

Mild Steel Electrodes for FCAW (17)

This specification contains requirements for mild steel composite electrodes for flux-cored arc welding of mild and low alloy steels (Tables II-5A through II-5C). Electrodes are classified on the basis of whether or not carbon dioxide is required as a separate shielding gas, the type of current, their useability for either single or multiple pass applications, and the chemical composition and as-welded mechanical properties of deposited weld metal.

Bare Low Alloy Steel Electrodes and Fluxes for SAW (18)

This specification contains requirements for bare solid and composite electrodes and fluxes producing low alloy steel weld metal for submerged arc welding of carbon and low alloy steels (Tables II-6A through II-6D). Electrodes are classified on the basis of their as-manufactured composition. Fluxes are classified on the basis of the mechanical properties and the chemical composition of a weld deposit made by using the flux in combination with a particular electrode.

Consumables for ESW of
Carbon- and High Strength Low Alloy Steels (19)

This specification contains requirements for solid and metal cored electrodes and fluxes for the electroslag welding of carbon and high strength low alloy steels (Tables II-7A through II-7D). Solid electrodes are classified on the basis of their chemical composition. Metal cored electrodes are classified on the basis of chemical analysis of undiluted weld metal. Flux is classified on the basis of the mechanical properties of the weld deposit made with a particular electrode.

Selection

The selection of electrodes for the metal-arc welding of steel castings is not always simple. One reason for this is that electrode deposits are usually lower in carbon than the castings being welded. The weld metal, which is a mixture of the electrode metal and the fused base metal (manual metal-arc welds contain more electrode metal than base metal), is consequently also lower in carbon than the castings. In order to compensate for the lower carbon, alloying elements are frequently added. Most wrought steel welds are either left as deposited or are simply stress relieved, and the electrode compositions are designed to give adequate strength in these conditions. This simplifies the problem of selection when the castings are merely stress relieved after welding.

When the weld is intended to remain in the as-welded or stress relieved condition, the selection of an electrode should be based on the mechanical properties of the as-deposited weld metal. Generally, the mechanical properties of the weld are selected to match the base metal mechanical properties. However, some cases do occur where a specific chemical analysis range of the weld is a requirement. If possible, welding should be performed with a low carbon content electrode that produces a weld yielding the required mechanical properties since the lower carbon content improves weld-ability. The hardenability, the brittleness of the weldment and susceptibility to cracking increase with carbon content.

When castings are to be fully heat treated after welding, however, such treatment may make the weld metal weaker than in the as-deposited or stress-relieved condition. To insure that welds in castings will have strengths equal to the base metal, weld deposits should be of such a composition that they will have those strengths after heat treatment. Where such properties are listed, the choice of electrodes is obvious--use those whose heat-treated deposits match the heat-treated castings in properties, giving preference to the low-hydrogen types. Of course, it is not always necessary that welds match the strengths of the castings. Here, the lowering of weld strength by heat treatment is not important, unless it affects some other step in the processing of the casting, or the composite structure, such as machining.

Special Composition Electrodes

An electrode of increased carbon content should be used when the casting is heat treated after welding. Carbon is the most potent element for raising the strength of the weld metal. Thus, in order to produce good matching of mechanical properties after heat treatment, the carbon content should be increased to more closely match the base metal. However, the carbon content of the electrode will still be less than the base metal. When a repair or fabrication weld with close to homogeneous properties in the base metal and weld is required, the available shielded metal-arc welding electrodes that deposit heat treatable weld metal are listed in Table II-8 (20). This list of electrodes does not include many others available from various manufacturers. Other compositions of weld metal for high strength steels are also reported (20, 21) for use in the SMAW, GMAW, GTAW and SAW process. These electrodes are similar to those reported in Table II-8 and are not recognized classifications in current AWS-ASTM specifications but are available from various welding electrode suppliers. In general, these electrodes fall into the low carbon, medium carbon and matching carbon grades with the strength obtained from additional alloying elements added to the lower carbon weld deposits. Specific recommendations of the class of electrode for welding a high strength Mn-Ni-Cr-Mo steel for high strength levels are contained in Reference 22. The post weld heat treatment depends on the strength level and changes from tempering or stress relieving, to water quenching and tempering as the strength level increases (22).

Some welding is conducted with dissimilar filler metal on the heat treatable steels that are difficult to weld without cracking or where re-treatment of the casting after welding is not feasible.

This welding on low alloy steel castings is conducted with austenitic stainless steel welding electrodes of the types listed in Table II-9 (20) using the SMAW or GMAW processes. The types of electrodes used most widely for this welding are the 25Cr-12Ni (ER 309) and 25Cr-20Ni (ER 310). Austenitic stainless steel welds minimize cracking in the base metal and HAZ. The welding is conducted with little or no preheat. The deposited weld metal is tough, although lower in strength than the base metal. The shielded metal arc electrodes employed utilize a mineral coating to provide low hydrogen conditions. A hardened zone is produced in the base metal but this can be mitigated by multipass welding or a postweld tempering treatment (20). The use of austenitic weld deposits has been reduced recently by establishing low hydrogen conditions with low alloy electrodes, thereby minimizing cracking. These welds are then responsive to heat treatment.

The problem of dilution of the weld metal composition with the base metal exists in several instances. These include when: austenitic stainless steel weld deposits are used; carbon and high alloy steels are joined; and, to some extent, in welding higher carbon steels with the lower carbon electrodes described previously. Normally the weld beads are of a uniform composition and structure with only slight mixing at the weld edges because the lower alloy base metal is stirred into the weld melt by electromagnetic action (20). However, high speed welding or excessive melting of the base metal can produce more heterogeneity. The gas-shielded metal-arc and the submerged-arc processes produce deeper penetration of deposited weld metal compared to manual welding with shielded electrodes. Thus, more dilution of the weld metal and base metal occurs. Dilution may cause some problems with the use of austenitic stainless steel electrodes.

Drying Electrodes

The weld coatings and fluxes employed should be kept dry. This is usually accomplished by not opening the sealed containers until just before use and then storing the electrodes or submerged arc fluxes near the stress relieving furnaces or other ovens. Redrying the electrodes, should these become damp during storage, should follow specific guidelines which depend on the type of coatings (23). The moisture in low hydrogen coatings should be maintained below 0.3% to avoid underbead cracking. One practice followed is to return all opened but unused low hydrogen electrodes to a redrying oven held at 250-300°F (121-149°C) after each shift. These are dried for eight hours before reuse. If the low hydrogen coatings have picked up moisture by longer time exposure to humid atmospheres, the coatings are restored to low moisture contents by redrying at temperatures such as 550°F (288°C) for one hour in a well ventilated oven. The redrying temperature varies with the brand of electrode and the manufacturers recommendations should be followed. Cellulos-type coatings however normally require moisture contents of from 2 to 5% for proper operation. Accordingly, drying practices that lower the moisture below these levels are not recommended. These types of electrode coatings are held in 100-120°F (38-49°C) ovens after opening and limited exposure; they are held in ovens at 275°F (135°C) if the desired moisture content of the coating is exceeded (23).

Process Considerations

In addition to the factors relating to mechanical properties and chemical composition discussed above, the following additional items must be considered when selecting an electrode (24).

- Welding Position. Electrodes are designed to be used in specific positions. The third (or fourth) digit of the electrode classification indicates the welding position that can be used. Match the electrode to the welding position to be encountered.

- Welding Current. Some electrodes are designed to operate best with direct current (DC); other alternating (AC). Some will operate on either. Last digit indicates welding current useability. Select the electrodes to match the type of power source to be used.

- Joint Design and Fitup. Welding electrodes are designed with a digging, medium, or soft arc for deep, medium or light penetration. The last digit of the classification also indicates this factor. Deep penetrating electrodes with a digging arc should be used when edges are not beveled or fitup is tight. At the other extreme, light penetrating electrodes with a soft arc are required when welding on thin material or when root openings are too wide.

- Thickness and Shape of Base Metal. Weldments may include thick sections of complex shapes. The electrode selected should have maximum ductility to avoid weld cracking. Select the low-hydrogen types.

- Production Efficiency and Job Conditions. Some electrodes are designed for high deposition rates. The electrode selection should take this into consideration.

Once the proper electrode classification has been chosen, Reference 25, an American Welding Society publication listing filler metal comparisons will aid in the selection of commercially available electrodes and is highly recommended. These filler metal comparison charts list the manufacturers and brand names of the following types of electrodes: (1) covered mild steel electrodes, (2) covered low alloy steel electrodes, (3) bare carbon steel electrodes and fluxes for submerged-arc welding, (4) bare mild steel electrodes for gas metal-arc welding, (5) mild steel flux-cored arc welding electrodes, and (6) low alloy steel electrodes and fluxes for submerged-arc welding. Many of the classes of electrodes for electroslag welding are the same as those for submerged-arc welding and gas metal-arc welding. The comparison charts for these processes can be used to select electrodes for electroslag welding. Reference 25 also contains a description of the AWS classification system, an index of AWS classification designations, index of brand names, and names and addresses of electrode suppliers. Also included in Reference 25 are comparison charts for electrodes for stainless steel, aluminum, magnesium, copper, nickel, titanium, zirconium, cast irons, brazing filler metals and surface welding electrodes that are not applicable to this report.

Table II-1 Mild Steel Covered Arc Welding Electrodes - AWS A5.1-69 (13)

II-1A: AWS A5.1-69-Electrode Classification

AWS Classification	Type of Covering	Capable of Producing Satisfactory Welds in Positions Shown[a]	Type of Current[b]
E60 SERIES-MINIMUM TENSILE STRENGTH OF DEPOSITED METAL IN AS-WELDED CONDITION 60,000 PSI (OR HIGHER-SEE TABLE II-1C)			
E6010	High cellulose sodium	F, V, OH, H	dc, reverse polarity
E6011	High cellulose potassium	F, V, OH, H	ac or dc, reverse polarity
E6012	High titania sodium	F, V, OH, H	ac or dc, straight polarity
E6013	High titania potassium	F, V, OH, H	ac or dc, either polarity
E6020	High iron oxide	H-Fillets	ac or dc, straight polarity
		F	ac or dc, either polarity
E6027	Iron powder, iron oxide	H-Fillets	ac or dc, straight polarity
		F	ac or dc, either polarity
E70 SERIES-MINIMUM TENSILE STRENGTH OF DEPOSITED METAL IN AS-WELDED CONDITION 70,000 PSI (OR HIGHER-SEE TABLE II-1C)			
E7014	Iron powder, titania	F, V, OH, H	ac or dc, either polarity
E7015	Low hydrogen sodium	F, V, OH, H	dc, reverse polarity
E7016	Low hydrogen potassium	F, V, OH, H	ac or dc, reverse polarity
E7018	Iron powder, low hydrogen	F, V, OH, H	ac or dc, reverse polarity
E7024	Iron powder, titania	H-Fillets, F	ac or dc, either polarity
E7028	Iron powder, low hydrogen	H-Fillets, F	ac or dc, reverse polarity

[a] The abbreviations F, V, OH, H, and H-Fillets indicate welding positions (Figs. 1 and 2) of AWS A5.1-69 as follows:

F = Flat
H = Horizontal
H-Fillets = Horizontal Fillets
V = Vertical
OH = Overhead
} For electrodes 3/16 in. and under, except 5/22 in. and under for classifications E7014, E7015, E7016, and E7018.

[b] Reverse polarity means electrode is positive; straight polarity means electrode is negative.

II-1B: AWS A5.1-69-CHEMICAL REQUIREMENTS

AWS Classification	Chemical Composition, max, percent[a]					
	Manganese	Silicon	Nickel	Chromium	Molybdenum	Vanadium
E7014, E7015 E7016, E7018 E7024, E7028	1.25*	0.90	0.30*	0.20*	0.30*	0.08*
E6010, E6011 E6012, E6013 E6020, E6027	No chemical requirements					

* The sum total of all elements with the asterisk shall not exceed 1.50 per cent.

a For obtaining the chemical composition, dc, straight polarity only, may be used where dc, both polarities, is specified.

Table II-1C: AWS A5.1-69 Tensile Strength, Yield Point, and Elongation Requirements for All-Weld-Metal Tension Test in the As-Welded Condition[a]

AWS Classification	Tensile Strength, min, psi	Yield Point min, psi	Elongation in 2 in., min, per cent
	E60 Series[b]		
E6010	62,000	50,000	22
E6011	62,000	50,000	22
E6012	67,000	55,000	17
E6013	67,000	55,000	17
E6020	62,000	50,000	25
E6027	62,000	50,000	25
	E70 Series[c]		
E7014	72,000	60,000	17
E7015			22
E7016			22
E7018			22
E7024			17
E7028			22

a See Table 8 of AWS A5.1-69 for sizes to be tested.

b For each increase of one percentage point in elongation over the minimum, the yield point or tensile strength, or both may decrease 1,000 psi to a minimum of 60,000 psi for the tensile strength and 48,000 psi for the yield point for all classifications of the 60-series except E6012 and E6013. For the E6012 and E6013 classifications the yield point and tensile strength may decrease to a minimum of 65,000 psi for the tensile strength and 53,000 psi for the yield point.

c For each increase of one percentage point in elongation over the minimum, the yield point or tensile strength, or both, may decrease 1,000 psi to a minimum of 70,000 psi for the tensile strength and 58,000 psi for the yield point.

Table II-1D: AWS A5.1-69 Impact Property Requirements

AWS Classifications	Minimum V-Notch Impact Requirement[a]
E6010, E6011 E6027, E7015 E7016, E7018	20 ft-lb at -20°F
E7028	20 ft-lb at 0°F
E6012, E6013 E6020, E7014 E7024	Not required

[a] The extreme lowest value obtained together with the extreme highest value shall be disregarded for this test. Two of the three remaining values shall be greater than the specified 20 ft-lb energy level; one of the three may be lower but shall not be less than 15 ft-lb. The computed average value of the three remaining values shall be equal to or greater than the 20 ft-lb energy level.

Table II-2: Low-Alloy Steel Covered Electrodes - AWS A5.5-69 (14)

II-2A: AWS A5.5-69 Electrode Classification

AWS Classification	Type of Covering	Capable of Producing Satisfactory Welds in Positions Shown[a]	Type of Current[c]
E70 Series-Minimum Tensile Strength of Deposited Metal, 70,000 psi			
E7010-X[b]	High cellulose sodium	F,V,OH,H	dc, reverse polarity
E7011-X	High cellulose potassium	F,V,OH,H	ac or dc, reverse polarity
E7015-X	Low hydrogen sodium	F,V,OH,H	dc, reverse polarity
E7016-X	Low hydrogen potassium	F,V,OH,H	ac or dc, reverse polarity
E7018-X	Iron powder, low hydrogen	F,V,OH,H	ac or dc, reverse polarity
E7020-X	High iron oxide	H-Fillets	ac or dc, straight polarity
		F	ac or dc, either polarity
E7027-X	Iron Powder, iron oxide	H-Fillets	ac or dc, straight polarity
		F	ac or dc, either polarity
E80 Series-Minimum Tensile Strength of Deposited Metal, 80,000 psi			
E8010-X[b]	High cellulose sodium	F,V,OH,H	dc, reverse polarity
E8011-X	High cellulose potassium	F,V,OH,H	ac or dc, reverse polarity
E8013-X	High titania potassium	F,V,OH,H	ac or dc, either polarity
E8015-X	Low hydrogen sodium	F,V,OH,H	dc, reverse polarity
E8016-X	Low hydrogen potassium	F,V,OH,H	ac or dc, reverse polarity
E8018-X	Iron powder, low hydrogen	F,V,OH,H	ac or dc, reverse polarity
E90 Series-Minimum Tensile Strength of Deposited Metal, 90,000 psi			
E9010-X[b]	High cellulose sodium	F,V,OH,H	dc, reverse polarity
E9011-X	High cellulose potassium	F,V,OH,H	ac or dc, reverse polarity
E9013-X	High titania potassium	F,V,OH,H	ac or dc, either polarity
E9015-X	Low hydrogen sodium	F,V,OH,H	dc, reverse polarity
E9016-X	Low hydrogen potassium	F,V,OH,H	ac or dc, reverse polarity
E9018-X	Iron powder, low hydrogen	F,V,OH,H	ac or dc, reverse polarity
E100 Series-Minimum Tensile Strength of Deposited Metal, 100,000 psi			
E10010-X[b]	High cellulose sodium	F,V,OH,H	dc, reverse polarity
E10011-X	High cellulose potassium	F,V,OH,H	ac or dc, reverse polarity
E10013-X	High titania potassium	F,V,OH,H	ac or dc, either polarity
E10015-X	Low hydrogen sodium	F,V,OH,H	dc, reverse polarity
E10016-X	Low hydrogen potassium	F,V,OH,H	ac or dc, reverse polarity
E10018-X	Iron powder, low hydrogen	F,V,OH,H	ac or dc, reverse polarity
E110 Series-Minimum Tensile Strength of Deposited Metal, 110,000 psi			
E11015-X[b]	Low hydrogen sodium	F,V,OH,H	dc, reverse polarity
E11016-X	Low hydrogen potassium	F,V,OH,H	ac or dc, reverse polarity
E11018-X	Iron powder, low hydrogen	F,V,OH,H	ac or dc, reverse polarity
E120 Series-Minimum Tensile Strength of Deposited Metal, 120,000 psi			
E12015-X[b]	Low hydrogen sodium	F,V,OH,H	dc, reverse polarity
E12016-X	Low hydrogen potassium	F,V,OH,H	ac or dc, reverse polarity
E12018-X	Iron powder, low hydrogen	F,V,OH,H	ac or dc, reverse polarity

a The abbreviations F,V,OH,H, and H-Fillets indicate welding positions (Figures 1 and 2 of AWS A5.5-69) as follows:

F = Flat
H = Horizontal
H-Fillets = Horizontal Fillets
V=Vertical, OH=Overhead } For electrodes 3/16 in. and under, except 5/32 in. and under, for Classifications Exx15-X, EXX16-X, and EXX18-X.

b The letter suffix "-X" as used in this table stands for the suffixes A1, B1, B2, etc. (see Table 2 of AWS A5.5-69) and designates the chemical composition of the deposited weld metal.

c Reverse polarity means electrode is positive, straight polarity means electrode is negative.

Table II-2B: AWS A5.5-69 Chemical Requirements

AWS Classification[a]	Chemical Composition-%[d]								
	Carbon	Manganese	Phosphorus	Sulfur	Silicon	Nickel	Chromium	Molybdenum	Vanadium
Carbon-Molybdenum Steel Electrodes									
E7010-A1	0.12	0.60	0.03	0.04	0.40	--	--	0.40 to 0.65	--
E7011-A1	0.12	0.60	0.03	0.04	0.40	--	--	0.40 to 0.65	--
E7015-A1	0.12	0.90	0.03	0.04	0.60	--	--	0.40 to 0.65	--
E7016-A1	0.12	0.90	0.03	0.04	0.60	--	--	0.40 to 0.65	--
E7018-A1	0.12	0.90	0.03	0.04	0.80	--	--	0.40 to 0.65	--
E7020-A1	0.12	0.60	0.03	0.04	0.40	--	--	0.40 to 0.65	--
E7027-A1	0.12	1.00	0.03	0.04	0.40	--	--	0.40 to 0.65	--
Chromium-Molybdenum Steel Electrodes									
E8016-B1	0.12	0.90	0.03	0.04	0.60	--	0.40 to 0.65	0.40 to 0.65	--
E8018-B1	0.12	0.90	0.03	0.04	0.80	--	0.40 to 0.65	0.40 to 0.65	--
E8015-B2L	0.05	0.90	0.03	0.04	1.00	--	1.00 to 1.50	0.40 to 0.65	--
E8016-B2	0.12	0.90	0.03	0.04	0.60	--	1.00 to 1.50	0.40 to 0.65	--
E8018-B2	0.12	0.90	0.03	0.04	0.80	--	1.00 to 1.50	0.40 to 0.65	--
E8018-B2L	0.05	0.90	0.03	0.04	0.80	--	1.00 to 1.50	0.40 to 0.65	--
E9015-B3L	0.05	0.90	0.03	0.04	1.00	--	2.00 to 2.50	0.90 to 1.20	--
E9015-B3	0.12	0.90	0.03	0.04	0.60	--	2.00 to 2.50	0.90 to 1.20	--
E9016-B3	0.12	0.90	0.03	0.04	0.60	--	2.00 to 2.50	0.90 to 1.20	--
E9018-B3	0.12	0.90	0.03	0.04	0.80	--	2.00 to 2.50	0.90 to 1.20	--
E9018-B3L	0.05	0.90	0.03	0.04	0.80	--	2.00 to 2.50	0.90 to 1.20	--
E8015-B4L	0.05	0.90	0.03	0.04	1.00	--	1.75 to 2.25	0.40 to 0.65	--
E8016-B5	0.07 to 0.15	0.40 to 0.70	0.03	0.04	0.30 to 0.60	--	0.40 to 0.60	1.00 to 1.25	0.05
Nickel Steel Electrodes									
E8016-C1	0.12	1.20	0.03	0.04	0.60	2.00 to 2.75	--	--	--
E8018-C1	0.12	1.20	0.03	0.04	0.80	2.00 to 2.75	--	--	--
E8016-C2	0.12	1.20	0.03	0.04	0.60	3.00 to 3.75	--	--	--
E8018-C2	0.12	1.20	0.03	0.04	0.80	3.00 to 3.75	--	--	--
E8016-C3[b]	0.12	0.40 to 1.25	0.030	0.030	0.80	0.80 to 1.10	0.15	0.35	0.05
E8018-C3[b]	0.12	0.40 to 1.25	0.030	0.030	0.80	0.80 to 1.10	0.15	0.35	0.05
Manganese-Molybdenum Steel Electrodes									
E9015-D1	0.12	1.25 to 1.75	0.03	0.04	0.60	--	--	0.25 to 0.45	--
E9018-D1	0.12	1.25 to 1.75	0.03	0.04	0.80	--	--	0.25 to 0.45	--
E10015-D2	0.15	1.65 to 2.00	0.03	0.04	0.60	--	--	0.25 to 0.45	--
E10016-D2	0.15	1.65 to 2.00	0.03	0.04	0.60	--	--	0.25 to 0.45	--
E10018-D2	0.15	1.65 to 2.00	0.03	0.04	0.80	--	--	0.25 to 0.45	--
All Other Low-Alloy Steel Electrodes[e]									
EXX10-G	--	1.00 min[c]	--	--	0.80 min[c]	0.50 min[c]	0.30 min[c]	0.20 min[c]	0.10 min[c]
EXX11-G	--	1.00 min[c]	--	--	0.80 min[c]	0.50 min[c]	0.30 min[c]	0.20 min[c]	0.10 min[c]
EXX13-G	--	1.00 min[c]	--	--	0.80 min[c]	0.50 min[c]	0.30 min[c]	0.20 min[c]	0.10 min[c]
EXX15-G	--	1.00 min[c]	--	--	0.80 min[c]	0.50 min[c]	0.30 min[c]	0.20 min[c]	0.10 min[c]
EXX16-G	--	1.00 min[c]	--	--	0.80 min[c]	0.50 min[c]	0.30 min[c]	0.20 min[c]	0.10 min[c]
EXX18-G	--	1.00 min[c]	--	--	0.80 min[c]	0.50 min[c]	0.30 min[c]	0.20 min[c]	0.10 min[c]
E7020-G	--	1.00 min[c]	--	--	0.80 min[c]	0.50 min[c]	0.30 min[c]	0.20 min[c]	0.10 min[c]
E9018-M[b]	0.10	0.60 to 1.25	0.030	0.030	0.80	1.40 to 1.80	0.15	0.35	0.05
E10018-M[b]	0.10	0.75 to 1.70	0.030	0.030	0.60	1.40 to 2.10	0.35	0.25 to 0.50	0.05
E11018-M[b]	0.10	1.30 to 1.80	0.030	0.030	0.60	1.25 to 2.50	0.40	0.25 to 0.50	0.05
E12018-M[b]	0.10	1.30 to 2.25	0.030	0.030	0.60	1.75 to 2.50	0.30 to 1.50	0.30 to 0.55	0.05

NOTE-Single values shown are maximum percentages, except where otherwise specified.

a The suffixes A1, B3, C2, etc. designate the chemical composition of the electrode classification.

b These classifications are intended to conform to classifications covered by the military specifications for similar compositions. See Note under A1.5.1.3 in Appendix A1.

c In order to meet the alloy requirements of the G group, the weld deposit need have the minimum, as specified in the table, of only one of the elements listed.

d For determining the chemical composition, dc, straight polarity only, may be used where dc, both polarities, is specified.

e The letters "XX" used in the classification designations in this table stand for the various strength levels (70, 80, 90, 100, 110, and 120) of electrodes.

II-2C: AWS A5.5-69 Tensile Strength, Yield Strength, and Elongation Requirements for All-Weld-Metal Tension Test[a,b]

AWS Classification[c]	Tensile Strength, min, psi	Yield Strength at 0.2 per cent offset,[d] psi	Elongation in 2 in., min, per cent
E7010-X			22
E7011-X			22
E7015-X			25
E7016-X	70,000	57,000[e]	25
E7018-X			25
E7020-X			25
E7027-X			25
E8010-X			19
E8011-X			19
E8013-X	80,000	67,000	16
E8015-X			19
E8016-X			19
E8018-X			19
E8016-C3	80,000	68,000 to 80,000	24
E8018-C3			
E9010-X			17
E9011-X			17
E9013-X	90,000	77,000	14
E9015-X			17
E9016-X			17
E9018-X			17
E9018-M	90,000	78,000 to 90,000	24
E10010-X			16
E10011-X			16
E10013-X	100,000	87,000	13
E10015-X			16
E10016-X			16
E10018-X			16
E10018-M	100,000	88,000 to 100,000	20
E11015-X			
E11016-X	110,000	97,000	15
E11018-X			
E11018-M	110,000	98,000 to 110,000	20
E12015-X			
E12016-X	120,000	107,000	14
E12018-X			
E12018-M	120,000	108,000 to 120,000	18

a For the E7010-G, E8010-G, E8018-C3, E9018-M, E10018-M, E11018-M and E12018-M electrode classifications the values shown are for specimens which are tested in the as-welded condition. Specimens which are tested for all other electrodes are in the stress-relieved condition (See Table 11 of AWS A5.5-69).

b See Table 9 for sizes to be tested. Also, see Table A2 in Appendix A2 for Metric Equivalents.

c The letter suffix "-X" as used in this table stands for all the suffixes (A1, B1, B2, etc.) except the M and C3 suffixes (see Table 2).

d Single values shown are minimums.

e For the as-welded condition the required yield strength is 60,000 psi.

II-2D: AWS A5.5-69 Impact Property Requirements[a]

AWS Classification	Minimum V-Notch Impact Requirement[b]
E8016-C3 E8018-C3	20 ft-lb at -40°F[c]
E9015-D1 E9018-D1 E10015-D2 E10016-D2 E10018-D2	20 ft-lb at -60°F[d]
E9018-M E10018-M E11018-M E12018-M	20 ft-lb at -60°F[c]
E8016-C1 E8018-C1	20 ft-lb at -75°F[d]
E8016-C2 E8018-C2	20 ft-lb at -100°F[d]
All other classifications	not required

a See Table A2 in Appendix A2 for Metric Equivalents.
b The extreme lowest value obtained together with the extreme highest value shall be disregarded for this test. Two of the three remaining values shall be greater than the specified 20 ft-lb energy level; one of the three may be lower but shall not be less than 15 ft-lb. The computed average value of the three remaining values shall be equal to or greater than the 20 ft-lb energy level.
c As-welded impact properties.
d Stress relieved impact properties.

Table II-3 Bare Carbon Steel Electrodes & Fluxes For Submerged Arc Welding - AWS A5.17-76[15]

II-3A: AWS A5.17-76 Chemical Composition Requirements for Electrodes

AWS Classification	Chemical Composition, Percent (See Notes 1-6.) C	Mn	Si	S	P	Cu	Total Other Elements
Low manganese classes							
EL8	0.10	0.30 to 0.55	0.05				
EL8K	0.10	0.30 to 0.55	0.10 to 0.20				
EL12	0.07 to 0.15	0.35 to 0.60	0.05				
Medium manganese classes							
EM5K[a,b]	0.06	0.90 to 1.40	0.40 to 0.70	0.035	0.03	0.30	0.50
EM12	0.07 to 0.15	0.85 to 1.25	0.05				
EM12K	0.07 to 0.15	0.85 to 1.25	0.15 to 0.35				
EM13K[c]	0.07 to 0.19	0.90 to 1.40	0.45 to 0.70				
EM15K	0.12 to 0.20	0.85 to 1.25	0.15 to 0.35				
High manganese class							
EH14	0.10 to 0.18	1.75 to 2.25	0.05				

Notes:

1. Analysis shall be made for the elements for which specific values are shown in this table. If however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine that the total of these other elements is not present in excess of the limits specified for "Total other elements" in the last column of the table.
2. Single values shown are maximum.
3. The copper limit includes any copper coating which may be applied to the electrode (see 1.6 Finish and Temper and 3. Chemical Analysis).
4. The suffix letter "N", when added to classification designations in this table, stands for nuclear grade. Grade "N" restricts sulfur content to 0.013 percent max, phosphorus content to 0.010 percent max, copper content to 0.08 percent max and vanadium content to 0.05 percent max. Grade N electrodes shall not be coppercoated or coated with a copper-containing material.
5. Analysis shall be made for the elements for which specific values are shown in this table. In addition to the elements listed, other elements intentionally added in a classification shall be reported. The total of both these other elements, and other elements not intentionally added (as per Note 1), shall not exceed 0.50 percent except as noted in Note b.
6. AISI check tolerances pertaining to carbon steel wire and rod are applicable.

a The chemical composition requirements for EM5K classification are similar to the chemical composition requirements for E70S-2 classification in AWS A5.18-69, Specification for Mild Steel Electrodes for Gas Metal Arc Welding.

b This electrode contains 0.05 to 0.15 percent titanium, 0.02 to 0.12 percent zirconium, and 0.05 to 0.15 percent aluminum, which is exclusive of the "Total other elements" requirement.

c The chemical composition requirements for the EM13K classification are similar to the chemical composition requirements for E70S-3 classification in AWS A5.18-69, Specification for Mild Steel Electrodes for Gas Metal Arc Welding.

II-3B: AWS A5.17-76 Mechanical Property Requirements (see comments in text)

AWS Flux classification	Tensile strength psi (MPa)	Yield strength, at 0.2 percent offset, min psi (MPa)	Elongation, min percent in 2 in. (51 mm)	Charpy V-notch impact strength, min[b] Digit Indicating
F6Z-EXXX	62,000			
F60-EXXX[c]	(430)			
F62-EXXX[c]	to	50,000		
F64-EXXX[c]	80,000	(345)	22[d]	Z-No impact requirement
F66-EXXX[c]	(550)			0-20 ft-lb at - 0°F (27 J at -18°C)
F7Z-EXXX	72,000			2-20 ft-lb at -20°F (27 J at -29°C)
F70-EXXX[c]	(500)	60,000		4-20 ft-lb at -40°F (27 J at -40°C)
F72-EXXX[c]	to	(415)	22[e]	6-20 ft-lb at -60°F (27 J at -51°C)
F74-EXXX[c]	95,000			
F76-EXXX[c]	(655)			

a The letters "EXXX" as used in this table stand for the electrode designations EL8, EL8K, etc. (see Table 1).

b The lowest value obtained, together with the highest value obtained, shall be disregarded for the test. Two of the three remaining values shall be greater than the specified 20 ft-lb (27 J) energy level; one of the three may be lower but shall not be less than 15 ft-lb (20 J). The computed average value of the three values shall be equal to or greater than the 20 ft-lb (27 J) energy level.

c Note that if a specific flux-electrode combination meets the requirements of a given F6X-xxxx classification, this classification also meets the requirements of all lower numbered classifications in the F6X-xxxx series. For instance, a flux-electrode combination meeting requirements of the F64-xxxx classification also meets the requirements of the F62-xxxx, F60-xxxx, and F6Z-xxxx classifications. This applies to the F7X-xxxx series also.

d For each increase of one percentage point in elongation over the minimum, the yield strength or tensile strength, or both, may decrease 1000 psi (7 MPa) to a minimum of 60,000 psi (415 MPa) for the tensile strength, and 48,000 psi (330 MPa) for the yield strength.

e For each increase of one percentage point elongation over the minimum, the yield strength or tensile strength, or both, may decrease 1000 psi (7 MPa) to a minimum of 70,000 psi (485 MPa) for the tensile strength and 58,000 psi (400 MPa) for the yield strength.

Table II-4 Mild Steel Electrodes For Gas Metal-Arc Welding, GMAW - AWS A5.18-69[16]

II-4A: AWS A5.18-69 Chemical Composition Requirements (Solid Wire)

AWS Classification	Carbon	Manganese	Silicon	Phosphorus	Sulfur	Nickel[a]	Chromium[a]	Molybdenum[a]	Vanadium[a]	Titanium	Zirconium	Aluminum
	Chemical Composition, percent											
Group A-Mild Steel Electrodes												
E70S-1	0.07 to 0.19		0.30 to 0.50									
E70S-2	0.06		0.40 to 0.70							0.05 to 0.15	0.02 to 0.12	0.05 to 0.15
E70S-3	0.06 to 0.15	0.90 to 1.40	0.45 to 0.70	0.025	0.035							
E70S-4	0.07 to 0.15		0.65 to 0.85									
E70S-5	0.07 to 0.19		0.30 to 0.60									0.50 to 0.90
E70S-6	0.07 to 0.15	1.40 to 1.85	0.80 to 1.15									
E70S-G	no chemical requirements[b]											
Group B-Low Alloy Steel Electrodes[c]												
E70S-1B	0.07 to 0.12	1.60 to 2.10	0.50 to 0.80	0.025	0.035	0.15		0.40 to 0.60				
E70S-GB	no chemical requirements											
Group C-Emissive Electrode												
E70U-1	0.07 to 0.15	0.80 to 1.40	0.15 to 0.35	0.025	0.035							

NOTE: Single values shown are maximums.

a For Groups A and C these elements may be present but are not intentionally added.

b For this classification there are no chemical requirements for the elements listed with the exception that there shall be no intentional addition of Ni, Cr, Mo, or V.

c See Paragraph A1.3.4 in the Appendix of AWS A5.18-69 for the explanation of why low-alloy steel electrodes are included in this specification.

II-4B: AWS A5.18-69 Mechanical Property Requirements[a]

AWS Classification	Shielding Gas[b]	Current and Polarity[c]	Tensile Strength min., psi	Yield Strength at 0.2% Offset, min.	Elongation in 2 in. min. %
Group A-Mild Steel Electrodes					
E70S-1	AO	dc, reverse polarity	72,000[e,f]	60,000[e,f]	22[e,f]
E70S-2	AO & CO_2[d]	dc, reverse polarity	72,000[e,f]	60,000[e,f]	22[e,f]
E70S-3	AO & CO_2[d]	dc, reverse polarity	72,000[e,f]	60,000[e,f]	22[e,f]
E70S-4	CO_2	dc, reverse polarity	72,000[e,f]	60,000[e,f]	22[e,f]
E70S-5	CO_2	dc, reverse polarity	72,000[e,f]	60,000[e,f]	22[e,f]
E70S-6	CO_2	dc, reverse polarity	72,000[e,f]	60,000[e,f]	22[e,f]
E70S-G	not spec.	not spec.	72,000[e,f]	60,000[e,f]	22[e,f]
Group B-Low Steel Electrodes					
E70S-1B	CO_2	dc, reverse polarity	72,000[e,f]	60,000[e,f]	17[e,f]
E70S-GB	not spec.	not spec.	72,000[e,f]	60,000[e,f]	22[e,f]
Group C-Emissive Electrode					
E70U-1	AO & A[d]	dc. straight polarity	72,000[e]	60,000[e]	22[e]

a As welded mechanical properties.

b Shielding gases are designated as follows:

AO = argon, plus 1 to 5 percent oxygen
CO_2 = carbon dioxide
A = argon

c Reverse polarity means electrode is positive; straight polarity means electrode is negative.

d Where two gases are listed as interchangeable (that is, AO and CO_2 and AO and A) for classification of a specific electrode, the classification tests may be conducted using either gas.

e Mechanical properties as determined from an all-weld-metal tension test specimen.

f For each increase of one percentage point in elongation over the minimum, the yield strength or tensile strength, or both, may decrease 1,000 psi to a minimum of 70,000 psi for the tensile strength and 58,000 psi for the yield strength.

II-4C: AWS A5.18-69 Impact Property Requirements

AWS Classification	Minimum V-notch Impact Requirement[a]
E70S-2 E70S-6 E70S-1B E70U-1	20 ft-lb at -20°F
E70S-3	20 ft-lb at 0°F
E70S-1, E70S-4, E70S-5, E70S-G, E70S-GB	not required

a The extreme lowest value obtained, together with the extreme highest value obtained, shall be disregarded for this test. Two of the three remaining values shall be greater than the specified 20 ft-lb energy level; one of the three may be lower but shall not be less than 15 ft-lb. The computed average value of the three values shall be equal to or greater than the 20 ft-lb energy level.

Table II-5 Mild Steel Flux-Cored Arc Welding Electrodes - AWS A5.20-69 (17)

II-5A: AWS A5.20-69 Chemical Composition Requirements[b] (Solid Wire)

AWS Classification	Chemical Composition, per cent											
	Carbon	Manganese	Silicon	Phosphorus	Sulfur	Nickel	Chromium	Molybdenum	Vanadium	Titanium	Zirconium	Aluminum
E60T-7		1.50	0.90			0.50	0.20[a]	0.30[a]	0.08[a]			1.8
E60T-8		1.50	0.90			0.50	0.20[a]	0.30[a]	0.08[a]			1.0
E70T-1		1.75	0.90			0.30[a]	0.20[a]	0.30[a]	0.08[a]			
E70T-2, E70T-3	no chemical requirements											
E70T-4		1.50	0.90			0.50	0.20[a]	0.30[a]	0.08[a]			1.8
E70T-5		1.50	0.90			0.30[a]	0.20[a]	0.30[a]	0.08[a]			
E70T-6		1.50	0.90			0.80	0.20[a]	0.30[a]	0.08[a]			
E70T-G	no chemical requirements											

NOTE - Single values shown are maximums

a These elements may be present but are not intentionally added.

b Chemical composition requirements for electrodes are based on the analysis of deposited weld metal.

II-5B: AWS A5.20-69 Mechanical Property Requirements[a]

AWS Classification	Shielding Gas[b]	Current and Polarity[c]	Tensile Strength min.,f psi	Yield Strength at 0.2% offset, min., f psi	Elongation in 2 in., min.f %
E60T-7	None	dc, straight polarity	67,000	55,000	22
E60T-8	None	dc, reverse polarity	62,000	50,000	22
E70T-1	CO_2	dc, reverse polarity	72,000	60,000	22
E70T-2	CO_2	dc, reverse polarity	72,000	Not Required	
E70T-3	None	dc, reverse polarity	72,000	Not Required	
E70T-4	None	dc, reverse polarity	72,000	60,000	22
E70T-5[g]	CO_2 / None	dc, reverse polarity	72,000	60,000	22
E70T-6	None	dc, reverse polarity	72,000	60,000	22
E70T-G	not spec.	not spec.	72,000[d] / 72,000[e]	Not Required / 60,000[e]	22[e]

a As welded mechanical properties.

b Shielding gases are designated as follows:
CO_2 = carbon dioxide
None = no separate shielding gas

c Reverse polarity means electrode is positive; straight polarity means electrode is negative.

d Requirement for single pass only electrodes.

e Requirement for multiple pass electrodes.

f For each increase of one percentage point in elongation over the minimum, the minimum required yield strength or the tensile strength, or both, may decrease 1000 psi, for a maximum reduction of 2000 psi in either the required minimum yield strength or the tensile strength, or both.

g Where CO_2 and None are indicated as the shielding gases for a given classification, chemical analysis pads and test assemblies shall be prepared using both CO_2 and no separate shielding gas.

II-5C: AWS A5.20-69 Impact Property Requirements

AWS Classification	Minimum V-notch Impact Requirement[a]
E70T-5	20 ft-lb at -20°F
E60T-8 E70T-1 E70T-6	20 ft-lb at 0°F
E60T-7 E70T-2 E70T-3 E70T-4 E70T-G	not required

a The extreme lowest value obtained, together with the extreme highest value obtained, shall be disregarded for this test. Two of the three remaining values shall be greater than the specified 20 ft-lb energy level; one of the three may be lower but shall not be less than 15 ft-lb. The computed average value of the three values shall be equal to or greater than the 20 ft-lb energy level.

Table II-6 Low Alloy Steel Bare Electrodes and Fluxes for Submerged Arc Welding - AWS A5.23-77[18]

II-6A: AWS A5.23-77 Chemical Requirements for Solid Electrodes

AWS Classification	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu	Al	Ti	Zr
						Chemical Composition, % (see Notes 1-5)							
						Carbon steel[1]							
EL12	0.07/0.15	0.35/0.60	0.030	0.035	0.05	--	--	--	--	0.30	--	--	--
EM12K	0.07/0.15	0.85/1.25	0.030	0.035	0.15/0.35	--	--	--	--	0.30	--	--	--
						Carbon-molybdenum steel							
EA1	0.07/0.15	0.70/1.00	0.025	0.035	0.05	--	--	0.45/0.65	--	0.30	--	--	--
EA2	0.07/0.15	1.00/1.30	0.025	0.035	0.05	--	--	0.45/0.65	--	0.30	--	--	--
EA3	0.10/0.18	1.70/2.40	0.025	0.035	0.05	--	--	0.45/0.65	--	0.30	--	--	--
						Chromium-molybdenum steel							
EB1	0.10	0.40/0.70	0.025	0.030	0.05/0.30	--	0.40/0.75	0.45/0.65	--	0.30	--	--	--
EB2	0.09/0.14	0.40/0.70	0.025	0.030	0.05/0.30	--	1.00/1.75	0.45/0.65	--	0.30	--	--	--
EB2H	0.28/0.33	0.45/0.65	0.015	0.015	0.55/0.75	--	1.00/1.50	0.40/0.65	0.20/0.30	0.30	--	--	--
EB3	0.09/0.14	0.45/0.70	0.025	0.030	0.05/0.30	--	2.25/3.00	0.90/1.10	--	0.30	--	--	--
EB5	0.18/0.23	0.40/0.70	0.025	0.025	0.40/0.60	--	0.45/0.65	0.90/1.10	--	0.30	--	--	--
EB6	0.10	0.40/0.65	0.025	0.025	0.25/0.50	--	4.50/6.00	0.45/0.65	--	0.30	--	--	--
EB6H	0.25/0.40	0.75/1.00	0.025	0.030	0.25/0.50	--	4.80/6.00	0.45/0.65	--	0.30	--	--	--
						Nickel steel							
ENi1	0.10	0.75/1.25	0.010	0.010	0.15/0.25	0.85/1.15	0.15	0.30	--	0.30	--	--	--
ENi2	0.10	0.75/1.25	0.010	0.010	0.15/0.25	2.10/2.90	--	--	--	0.30	--	--	--
ENi3	0.10	1.00/1.50	0.010	0.010	0.15/0.25	3.10/3.80	--	--	--	0.30	--	--	--
						Manganese-molybdenum steel							
ED1	0.07/0.15	1.60/2.10	0.025	0.035	0.05/0.30	--	--	0.45/0.65	--	0.30	--	--	--
ED2	0.07/0.15	2.00/2.50	0.025	0.035	0.05/0.30	--	--	0.45/0.65	--	0.30	--	--	--
						All other low-alloy steel[2]							
EF1	0.07/0.15	0.90/1.70	0.020	0.020	0.20/0.35	0.95/1.60	--	0.25/0.55	--	0.30	--	--	--
EF2	0.10/0.17	1.70/2.40	0.020	0.020	0.10	0.40/0.75	--	0.40/0.65	--	0.30	--	--	--
EF3	0.10/0.17	1.70/2.40	0.020	0.020	0.10	0.70/1.10	--	0.45/0.65	--	0.30	--	--	--
EF4	0.18/0.23	0.70/0.90	0.025	0.035	0.20/0.35	0.40/0.70	0.40/0.60	0.15/0.25	--	0.30	--	--	--
EF5	0.11/0.17	1.70/2.20	0.010	0.010	0.15	2.30/2.80	0.25/0.50	0.45/0.65	--	0.50	--	--	--
EM1	0.10	0.90/1.50	0.010	0.010	0.20/0.55	1.40/2.10	0.15	0.15/0.35	0.05	0.25	0.10	0.10	0.10
EM2	0.10	1.25/1.80	0.010	0.010	0.20/0.60	1.40/2.10	0.30	0.25/0.55	0.05	0.25	0.10	0.10	0.10
EM3	0.10	1.40/1.80	0.010	0.010	0.20/0.60	1.90/2.60	0.55	0.25/0.65	0.04	0.25	0.10	0.10	0.10
EM4	0.10	1.40/1.80	0.010	0.010	0.20/0.60	2.00/2.80	0.60	0.30/0.65	0.03	0.25	0.10	0.10	0.10
EM5	0.10	0.80/1.60	0.020	0.020	0.20/0.60	0.90/1.20	0.30	0.20/0.55	0.05	0.40/1.00	0.10	0.10	0.10
EW	0.12	0.35/0.65	0.030	0.040	0.20/0.35	0.40/0.80	0.50/0.80	--	--	0.30/0.80	--	--	--
EG						No specific chemical requirements							

Notes:

1. Single values shown are maximums.
2. The addition of the letter "N" as a suffix to the classification indicates that the electrode is intended for nuclear applications and changes the limits on the sulfur, phosphorus, vanadium, and copper as follows:

   S = 0.013% max
   P = 0.010% max
   V = 0.05% max
   Cu = 0.08% max

   Grade "N" electrodes shall not be copper coated or coated with material containing copper. Neither the "EF5," the "EM5," nor the "EW" electrodes may be designated as a nuclear grade.
3. A copper or other coating, if present, shall not be removed prior to determining chemical composition.
4. The AISI check tolerances pertaining to alloy steel wire and rods are applicable.
5. Analysis shall be made for the elements for which specific values are shown in this table. In addition to the elements listed, other elements intentionally added in a classification shall be reported. The total of these "other" elements shall not exceed 0.50 percent.

[1]The chemical composition requirements for EL12 and EM12K are identical to the chemical composition requirements for the same electrode classifications in AWS A5.17-69, Specification for Bare Mild Steel Electrodes and Fluxes for Submerged Arc Welding.

[2]Classifications with the "EM" prefix are intended to conform to classifications covered by military specifications for similar compositions.

II-6B: AWS A5.23-77 Chemical Requirements for Deposited Weld Metal With Solid and Composite Electrodes

AWS deposited weld metal classification	C	Mn	P	S	Si	Ni	Cr	Mo	V, Ti, Zr[1]	Cu[2]
	Chemical composition, % (see Notes 1-4)									
	Carbon-molybdenum steel weld metal									
A1	0.12	1.00	0.030	0.040	0.80	--	--	0.40/0.65	--	0.30
A2	0.12	1.40	0.030	0.040	0.80	--	--	0.40/0.65	--	0.30
A3	0.15	1.60	0.030	0.040	0.80	--	--	0.40/0.65	--	0.30
	Chromium-molybdenum steel weld metal									
B1	0.12	1.60	0.030	0.040	0.80	--	0.40/0.65	0.40/0.65	--	0.30
B2	0.15	1.60	0.030	0.040	0.80	--	1.00/1.50	0.40/0.65	--	0.30
B2H	0.25	1.60	0.030	0.040	0.80	--	1.00/1.50	0.40/0.65	0.30V	0.30
B3	0.15	1.60	0.030	0.040	0.80	--	2.00/2.50	0.90/1.20	--	0.30
B4	0.12	1.60	0.030	0.040	0.80	--	1.75/2.25	0.40/0.65	--	0.30
B5	0.18	1.60	0.030	0.040	0.80	--	0.40/0.65	0.90/1.20	0.05	0.30
B6	0.12	1.60	0.030	0.040	0.80	--	4.50/6.00	0.40/0.65	--	0.30
B6H	0.25	1.60	0.030	0.040	0.80	--	4.50/6.00	0.40/0.65	--	0.30
	Nickel-steel weld metal									
Ni1	0.12	1.60	0.030	0.030	0.80	0.80/1.10	0.15	0.35	0.05	0.30
Ni2	0.12	1.60	0.030	0.030	0.80	2.00/2.90	--	--	--	0.30
Ni3	0.12	1.60	0.030	0.030	0.80	3.00/3.75	--	--	--	0.30
	Manganese-molybdenum steel weld metal									
D1	0.12	1.25/1.75	0.030	0.040	0.80	--	--	0.40/0.65	--	0.30
D2	0.12	1.65/2.00	0.030	0.040	0.80	--	--	0.40/0.65	--	0.30
	All other low-alloy steel weld metal[3]									
F1	0.12	0.70/1.50	0.030	0.040	0.80	0.90/1.70	0.15	0.55	0.03	0.30
F2	0.17	1.50/2.25	0.030	0.040	0.80	0.40/0.70	--	0.40/0.65	--	0.30
F3	0.17	1.50/2.25	0.030	0.040	0.80	0.70/1.00	--	0.40/0.65	--	0.30
F4	0.17	1.60	0.030	0.040	0.80	0.70	0.60	0.25	0.03	0.30
F5	0.17	1.20/1.80	0.030	0.030	0.80	2.50	0.65	0.30/0.80	--	0.50
M1	0.10	0.60/1.60	0.030	0.040	0.80	1.25/2.00	0.15	0.35	0.03	0.25
M2	0.10	0.90/1.80	0.030	0.040	0.80	1.40/2.10	0.35	0.25/0.55	0.03	0.25
M3	0.10	0.90/1.80	0.030	0.030	0.80	1.80/2.60	0.65	0.30/0.80	0.03	0.25
M4	0.10	1.30/2.25	0.030	0.030	0.80	2.00/2.80	0.80	0.30/0.80	0.03	0.25
M5	0.12	0.80/1.25	0.030	0.030	0.80	0.80/1.25	0.30	0.15/0.60	0.05V	0.40/1.10
W	0.12	0.50/1.30	0.030	0.040	0.35/0.80	0.40/0.80	0.45/0.70	--	--	0.30/0.75
G	No specific alloy requirements									

Notes:

1. Single values shown are maximums.
2. The addition of the letter"N" as a suffix indicates that the weld metal is intended for nuclear applications and changes the limits on the sulfur, phosphorus, vanadium, and copper as follows:

   S = 0.015% max
   P = 0.012% max
   V = 0.05% max
   Cu = 0.08% max

   Neither the "F5", "W", nor "M5" classifications may be designated as a nuclear grade.
3. The AISI tolerances not applicable.
4. In addition to the elements listed, other elements intentionally added in a classification shall be reported. The total of these elements shall not exceed 0.50 percent.

[1]Single values shown applicable to V, Ti, and Zr are maximum percentages for the total of these elements. The V after value indicates limit for vanadium only.
[2]The copper limit includes any copper coating that may be applied to the electrode.
[3]Weld metal classifications with the "M" prefix are intended to conform to classifications covered by military specifications for similar compositions.

II-6C: AWS A5.23-77 Mechanical Property Requirements[1]

AWS Classification[2]	Tensile strength range		Yield strength[3] at 0.2%, offset, min		Elongation in 2 in. (51 mm) % min
	psi	MPa	psi	MPa	
F7X-EXX-X	70,000- 90,000	485-620	60,000	415	22
F8X-EXX-X	80,000-100,000	550-690	68,000	470	20
F9X-EXXX-X	90,000-110,000	620-760	78,000	540	17
F10X-EXXX-X	100,000-120,000	690-825	88,000	605	16
F11X-EXXX-X	110,000-130,000	760-895	98,000	675	15
F12X-EXXX-X	120,000-140,000	825-965	108,000	755	14

[1]For as-welded specimens, for each increase of one percentage point in elongation over the minimum, the yield strength or tensile strength, or both, may decrease 1,000 psi (7 MPa) each with a maximum reduction of 2,000 psi (14 MPa).

[2]The letter "X" used in this table in various places in the classification designations stands for, as appropriate, the weld metal toughness, electrode designation, and the chemical composition of the weld metal (see Fig. 1).

[3]When weld assemblies have been postweld heat treated as prescribed in Table 7 of AWS A5.23-77, the required yield strength shall be reduced as follows:

Classification	Amount of Reduction	
	psi	MPa
F7X-EXX-X	8,000	55
F8X-EXX-X	8,000	55
F9X-EXXX-X	5,000	34
F10X-EXXX-X	3,000	21
F11X-EXXX-X	3,000	21
F12X-EXXX-X	3,000	21

II-6D: AWS A5.23-77 Impact Property Requirements

Digit	Required Impact Strength	
Z	No impact requirement	
0	20 ft-lb at 0°F	(27 J at -18°C)
2	20 ft-lb at -20°F	(27 J at -29°C)
4	20 ft-lb at -40°F	(27 J at -40°C)
6	20 ft-lb at -60°F	(27 J at -51°C)
8	20 ft-lb at -80°F	(27 J at -62°C)
10	20 ft-lb at -100°F	(27 J at -73°C)
15	20 ft-lb at -150°F	(27 J at -101°C)

Note: In the classification designations listed in Table 5 the letter "X" substituting for the impact digit as indicated in Fig. 1 of AWS A5.23-77 shall be replaced by the manufacturer with one of the digits shown above determined by the impact test for the toughness capability of the weld metal made using the flux in combination with a specific electrode.

If a specific flux-electrode combination meets the requirements of a given impact designation, this combination also meets the requirement of all higher temperature designations in this table. For instance, a flux-electrode combination meeting the requirements of impact designation 4 also meets the requirements of designations 2, 0, and Z.

The lowest value obtained, together with the highest value obtained, shall be disregarded for the test. Two of the three remaining values shall be greater than the specified 20 ft-lb (27 J) energy level; one of the three may be lower but shall not be less than 15 ft-lb (20 J). The computed average value of the three values shall be equal to or greater than 20 ft-lb energy level.

Table II-7 Consumables Used for Electroslag Welding
of
Carbon and High Strength Low Alloy Steels - AWS A5.25-78 [19]

II-7A: AWS A5.25-78 Chemical Composition for Deposited Weld Metal From Metal Cored Electrodes, Percent

AWS Classification	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V
EWT1	0.13	2.00	0.03	0.03	0.60	--	--	--	--	--
EWT2	0.12	0.50 to 1.60	0.03	0.04	0.25 to 0.80	0.40 to 0.80	0.40 to 0.70	--	0.25 to 0.75	--
EWT3	0.12	1.00 to 2.00	0.02	0.03	0.15 to 0.50	1.50 to 2.50	0.20	0.40 to 0.65	--	0.05
EWT4	0.12	0.50 to 1.30	0.03	0.03	0.30 to 0.80	0.40 to 0.80	0.45 to 0.70	--	0.30 to 0.75	--
EWTG	No chemical requirements									

Notes:
1. Single values shown are maximum percentages
2. May be used with and without guide tubes. Guide tubes when used must conform to AISI Specifications for 1008 to 1020 Carbon Steel Tubing.
3. The sample for chemical composition for the metal cored electrode shall be taken from an undiluted ingot made in a water-cooled copper mold using the typical electroslag welding conditions shown in Fig. 4 of AWS A5.25-78.

II-7B: AWS A5.25-78 Chemical Composition for Solid Electrodes, Percent

AWS Classification[a]	C	Mn	P	S	Si	Ni	Cr	Mo	Cu[b]	Total Other Elems.
Medium manganese classes										
EM5K-EW[c,d]	0.06	0.90 to 1.40	0.03	0.035	0.40 to 0.70	--	--	--	0.30	0.50
EM12-EW	0.07 to 0.15	0.85 to 1.25	0.03	0.035	0.05	--	--	--	0.30	0.50
EM12K-EW	0.07 to 0.15	0.85 to 1.25	0.03	0.035	0.15 to 0.35	--	--	--	0.30	0.50
EM13K-EW[e]	0.07 to 0.19	0.90 to 1.40	0.03	0.035	0.45 to 0.70	--	--	--	0.30	0.50
EM15K-EW	0.12 to 0.20	0.85 to 1.15	0.03	0.035	0.15 to 0.35	--	--	--	0.30	0.50
High manganese classes										
EH14-EW	0.10 to 0.18	1.75 to 2.25	0.03	0.035	0.05	--	--	--	0.30	0.50
Special classes										
EWS-EW	0.07 to 0.12	0.35 to 0.65	0.03	0.040	0.22 to 0.37	0.40 to 0.75	0.50 to 0.80	--	0.25 to 0.55	0.50
EH10Mo-EW[f]	0.07 to 0.12	1.60 to 2.10	0.03	0.035	0.50 to 0.80	--	--	0.40 to 0.60	0.15	0.50
EH10K-EW	0.06 to 0.14	1.40 to 2.00	0.025	0.030	0.15 to 0.30	--	--	--	--	0.50
EH11K-EW[g]	0.07 to 0.15	1.40 to 1.85	0.025	0.035	0.80 to 1.15	--	--	--	--	--
ES-G-EW	No chemical requirements									

Notes:
1. Analysis shall be made for the elements for which specific values are shown in this table. If however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine that the total of these other elements is not present in excess of the limits specified for "Total Other Elements" in the last column of the table.
2. Single values shown are maximum percentages.

a May be used with and without guide tubes. Guide tubes when used must conform to AISI Specifications for 1008 and 1020 Carbon Steel Tubing.

b The copper limit includes any copper or other suitable coating which may be applied to the electrode (see Finish and Temper and Chemical Analysis).

c The chemical composition requirements for the EM5K-EW classification are similar to the chemical composition requirements for the E70S-2 classification for Mild Steel Electrodes for Gas Metal Arc Welding (AWS A5.18-69).

d This electrode contains 0.05 to 0.15 percent titanium, 0.02 to 0.12 percent zirconium, and 0.05 to 0.15 percent aluminum, which is exclusive of the "Total Other Elements" requirement.

e The chemical composition requirements for the EM13K-EW classification are similar to the chemical composition requirements for the E70S-3 classification for Mild Steel Electrodes for Gas Metal Arc Welding (AWS A5.18-69).

f The chemical composition requirements for the EH10Mo-EW classification are similar to the chemical composition requirements for the E70S-1B classification for Mild Steel Electrodes for Gas Metal Arc Welding (AWS A5.18-69).

g The chemical composition requirements for the EH11K-EW classification are similar to the chemical composition requirements for the E70S-6 classification for Mild Steel Electrodes for Gas Metal Arc Welding (AWS A5.18-69).

II-7C: AWS A5.25-78 As-Welded Mechanical Property Requirements for Flux-Electrode Classification

AWS flux[a] classification	Tensile strength MPa	Yield strength at 0.2% offset, min, MPa	Elongation in 50 mm, min, percent	Charpy V-notch impact strength, min[b]
	(When using ASTM A36 plate)[d]			
FES6Z-xxxx	420 to 550	250	24	Not required
FES60-xxxx				20 J at -18°C[c]
FES62-xxxx				20 J at -29°C[c]
	(When using ASTM structural steels, A242, A441, A572 Grade 50, or A588)[d]			
FES7Z-xxxx	490 to 650	350	22	Not Required
FES70-xxxx				20 J at -18°C[c]
FES72-xxxx				20 J at -29°C[c]

a The letters "xxxx" as used in this table stand for the electrode designation EM12K-EW, EM13K-EW, etc. (see Tables 1 & 2 of AWS A5.25-78).

b The lowest value obtained, together with the highest value obtained, shall be disregarded for this test. Two of the three remaining values shall be greater than the specified 20 J energy level; one of the three may be lower, but shall not be less than 14 J. The computed average value of the three values shall be equal to or greater than the 20 J energy level.

c Note that if a specific flux-electrode combination meets the requirements of a given FES6 X-xxxx classification, this classification also meets the requirements of all lower-numbered classifications in the FES 6X-xxxx series. For instance, a flux-electrode combination meeting the requirements of the FES 62-xxxx classification, also meets the requirements of FES 6Z-xxxx classification. This applies to the FES 7X-xxxx series also.

II-7D: AWS A5.25-78 As-welded Mechanical Property Requirements for Flux-Electrode Classification

AWS flux[a] classification	Tensile strength, psi	Yield strength at 0.2% offset, min, psi	Elongation in 2 in., min, percent	Charpy V-notch impact strength, min[b]
	(When using ASTM A36 plate)[d]			
FES6Z-xxxx	60,000 to 80,000	36,000	24	Not required
FES60-xxxx				15 ft-lb at 0°F[c]
FES62-xxxx				15 ft-lb at -20°F[c]
	(When using ASTM structural steels, A242, A441, A572 Grade 50, or A588.)[d]			
FES7Z-xxxx	70,000 to 95,000	50,000	22	Not required
FES70-xxxx				15 ft-lb at 0°F[c]
FES72-xxxx				15 ft-lb at -20°F[c]

a The letters "xxxx" as used in this table stand for the electrode designation EM12K-EW, EM13K-EW, etc. (See Tables 1 & 2 of AWS A5.25-78).

b The lowest value obtained, together with the highest value obtained, shall be disregarded for this test. Two of the three remaining values shall be greater than the specified 15 ft-lb energy level; one of the three may be lower, but shall not be less than 10 ft-lb. The computed average value of the three values shall be equal to or greater than the 15 ft-lb energy level.

c Note that if a specific flux-electrode combination meets the requirements of a given FES 6X-xxxx classification, this classification also meets the requirements of all lower-numbered classifications in the FES 7X-xxxx series. For instance, a flux-electrode combination meeting the requirements of the FES 62-xxxx classification, also meets the requirements of FES 6Z-xxxx classification. This applies to the FES 7X-xxxx series also.

d Restriction of plate materials for tensile/yield strengths listed is necessary due to inherent characteristics of the Electroslag Process.

Table II-8 Low-Alloy Steel Covered Electrodes
for
Heat Treatable Weld Deposits* (20)

	C	Mn	S	Si	Cr	Ni	Mo	V
Cr-Mo	0.10	0.55	0.02	0.45	0.50		1.10	
Cr-Ni-Mo	0.20	1.50	0.02	0.50	0.50	1.25	0.25	
4130	0.25	1.00	0.02	0.50	1.00		0.25	
4140	0.40	1.00	0.02	0.50	1.00		0.25	
4340	0.40	1.00	0.02	0.50	1.00	2.00	0.25	
MIL-13018	0.10- 0.15	0.80- 1.15	0.030 max	0.30- 0.60	0.90- 1.20	1.50- 2.00	0.45- 0.75	0.02 max

*Not recognized classifications in current AWS-ASTM specification.

Table II-9 High-Alloy Steel Welding Rods

and

Bare Electrodes (20)

CHEMICAL COMPOSITION REQUIREMENTS IN PERCENTS FOR THE ROD OR ELECTRODE, AWS A5.9 (ASTM A371)

Phosphorus and sulfur are each limited to 0.03 max percent. Single values shown are maximum percentages except where otherwise specified.

AWS-ASTM classification	C	Cr	Ni	Mo	Cb + Ta	Mn	Si
ER308	0.08	19.5-22.0[a]	9.0-11.0	--	--	1.0-2.5	0.25-0.60
ER308L	0.03	19.5-22.0[a]	9.0-11.0	--	--	1.0-2.5	0.25-0.60
ER309	0.12	23.0-25.0	12.0-14.0	--	--	1.0-2.5	0.25-0.60
ER310	0.08-0.15	25.0-28.0	20.0-22.5	--	--	1.0-2.5	0.25-0.60
ER312	0.08-0.15	28.0 32.0	8.0 10.5	--	--	1.0-2.5	0.25-0.60
ER316	0.08	18.0-20.0	11.0-14.0	2.0-3.0	--	1.0-2.5	0.25-0.60
ER316L	0.03	18.0-20.0	11.0-14.0	2.0-3.0	--	1.0-2.5	0.25-0.60
ER317	0.08	18.5-20.5	13.0-15.0	3.0-4.0	--	1.0-2.5	0.25-0.60
ER318	0.08	18.0-20.0	11.0-14.0	2.0-3.0	8xC min, 1.0 max	1.0-2.5	0.25-0.60
ER321[b]	0.08	18.5-20.5	9.0-10.5	0.5	--	1.0-2.5	0.25-0.60
ER330[d]	0.15-0.25	15.0-17.0	34.0 min	--	--	1.0-2.5	0.25-0.60
ER347	0.08	19.0-21.5[a]	9.0-11.0	--	10xC min, 1.0 max	1.0-2.5	0.25-0.60
ER348	0.08	19.0-21.5[a]	9.0-11.0	--	10xC min, 1.0 max	1.0-2.5	0.25-0.60

a Chromium, min = 1.9 x nickel, when so specified.
b Also titanium 9 x C min. to 1.0 max.
c Also titanium 0.10 to 0.30 and tungsten 1.25 to 1.75.
d Not a recognized classification in the AWS-ASTM specification.

SECTION III: THE WELDING OPERATION

Removal of Casting Defects

Material specifications for steel castings govern the extent of inspection for defects, and the types and extent of defects that can be repaired. Nondestructive testing requirements relate to the discontinuities that are considered defects. Discontinuities which are considered defects must be removed and the resultant cavity replaced with weld metal (26).

Defect removal is accomplished by mechanical metal removal methods including machining, chipping, and grinding. Rough machining when economically feasible eliminates many unnecessary welds and has much to recommend it as a procedure. Chipping and grinding are the more commonly used mechanical removal techniques with local machining in isolated areas. The mechanical metal removal methods can be performed without any preheat. Cavity size is usually kept at a minimum with chipping and, therefore, the volume of weld metal used to repair the cavity is usually minimized. However, chipping generally results in slower metal removal rates than achieved with grinding and the noise level is high (26). Grinding, particularly with the high speed grinders can be an efficient metal removal technique.

Defect removal with flame cutting as a gouging operation is faster than chipping, but the resultant cavities are larger than those produced by chipping and grinding. Preheat should be applied when using flame cutting, if the metal requires preheat when welding. Welding over flame gouged surfaces can be accomplished after removing adhering metal and slight grinding (26).

Air carbon-arc cutting, also referred to as the arcair process, is widely used in the casting industry for removing defects as well as eliminating excess metal from gates, risers, and pads. Arcair is the fastest of these gouging metal removal techniques and leaves the smallest cavity. The process is shown schematically in Figure III-1. An arc is established between a carbon-graphite electrode and the work piece. The high temperatures produced at the arc melts the base metal. A high velocity air jet aimed at the arc blows away the molten metal, leaving a cavity.

The equipment required for air carbon-arc gouging includes an electrode holder, electrodes, power source, and an air supply. The electrode holder, or cutting torch can be operated manually as well as in the semi-automatic, or the automatic mode. The electrodes consist of a mixture of carbon and graphite. Three types of electrodes are normally used: DC copper-coated electrodes, which

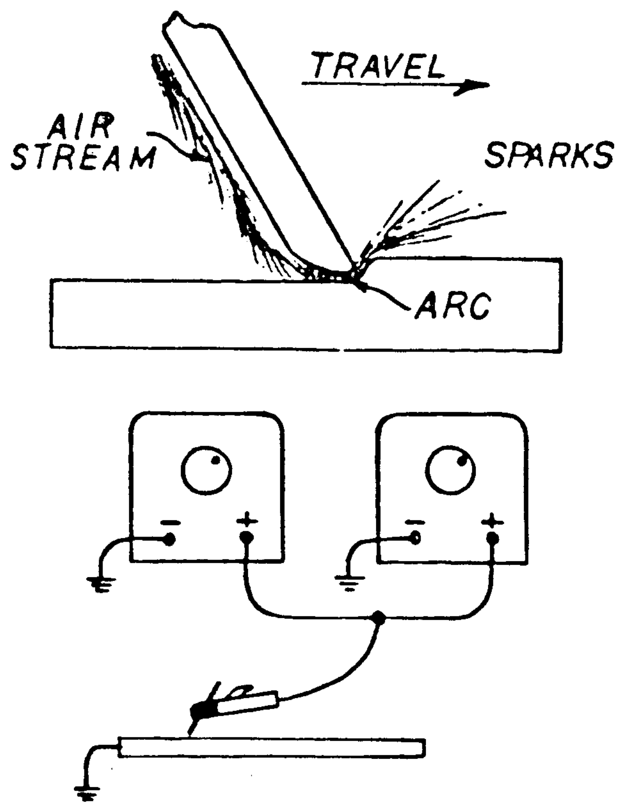


Figure III-1 Schematic illustration of air carbon-arc gouging. Two DC power supplies connected in parallel are shown. An AC power supply can be used also.

are the most commonly used electrodes; DC plain electrodes; and AC copper-coated electrodes, Electrodes are available in round sizes from 5/32 in. (4 mm) to 3/4 in. (19 mm) and flat half round shapes. Standard welding power units are used, Table III-1 lists power sources recommended for arc gouging. Table III-2 recommends current ranges for the various size electrodes. DC electrodes with direct current reverse polarity hook-up are recommended for arc gouging carbon and low alloy steels (27-29). Compressed air, at pressures ganging from 80 to 100 psi, is normally required for arcair gouging (27). Compressed nitrogen or inert gas may be used in emergencies. The air stream must be of sufficient velocity and volume to remove the melted metal and slag. Table III-3 contains recommended air pressures and consumption rates. It is important that the air pressure does not fall below the minimum specified for the torch. If this should happen, slag and carbon deposits could remain in the gouged cavity.

The arcair process induces hardening on the gouged surface and in the heat affected zone (HAZ), which can result in subsequent cold cracking. Hardening is induced by carburization of the surface of the gouged area and from rapid thermal cycling that occurs during the gouging operation. The higher hardness in the heat affected zone is attributed more to the cooling cycle of the arc gouging rather than from the presence of additional carbon (26, 30). Carbon pickup can occur from the electrode when the molten metal is allowed to dwell on the gouged surface. Carbon pickups from base metal levels of about 0.20 to 0.35% have been measured for reverse polarity; this is reduced significantly by straight polarity DC (31). Carbon pickup can be minimized by using an adequate supply of air to remove the molten metal from the gouged surface (32).

Experiments (33) evaluating the effect of operating variables on the heat affected zone, HAZ, hardness have been performed on grades of carbon-manganese cast steel ranging from 0.20%C to 0.45%C using the arcair process for removing metal. Carbon electrodes size, current, gouging techniques, and preheat were varied in the experiments. The hardness levels were measured after arcair gouging, and following subsequent welding of the gouged area.

In summary, the results of these experiments indicate that subsequent welding appears to remove the HAZ left by the arcair process. However, it should be recognized that the hardened surface of the gouged area is remelted during subsequent welding. This remelted layer forms the fusion zone between the base metal and weld metal. The hardness levels of the HAZ after welding approach levels that can be expected from welding alone. Preheat did not appear to affect the HAZ hardness after welding was performed for the

Table III-1 Power Sources for Arc Gouging [27,28]

Type of current	Type of power source	Remarks
DC	Variable voltage motor-generator, rectifier, or resistor-grid equipment	Recommended for all electrode sizes
DC	Constant-voltage motor-generator or rectifier	Recommended only for electrodes above 1/4 in. diameter.
AC	Transformer	Should be used only with AC electrodes
AC-DC	Rectifier	DC supplied by three phase transformer rectifier is satisfactory. DC from single phase source not recommended. AC from AC-DC power source is satisfactory if AC electrodes are used.

Table III-2 Recommended current ranges for Arc Gouging, Amperes (27,28)

Type of electrode (and power)	Electrode size, in. 5/32	3/16	1/4	5/16	3/8	1/2
DC electrodes (DCRP)	90-150	150-200	200-400	250-450	350-600	600-1000
AC electrodes (AC)		150-200	200-300		300-500	400-600
AC electrodes (DCSP)		150-180	200-250		300-400	400-500

Table III-3 Air Consumption for Arc Gouging (27,28)

Maximum electrode size in.	Application	Pressure, psi	Consumption, cfm
1/4	Intermittent-duty, manual electrode holder	40	3
1/4	Intermittent-duty, manual electrode holder	80	9
3/8	General purpose	80	16
3/4	Heavy-duty	80	20
5/8	Semiautomatic mechanized electrode holder	80	25

casting sizes used in these experiments. However, preheat may be required to relieve the hardening effects of the arcair process for thick casting sections, particularly in the high carbon range, and for hardenable low alloy steel castings. The conclusions from these experiments are listed below (32).

1. The size of carbon electrode used at the optimum current has little effect on the hardness of the HAZ.

2. The gouging and application methods have a marked effect on the hardness values of the HAZ, and this appears to be associated with the amount of metal removed. In most instances the values were lower with the pad washing technique where relatively small amounts of metal are removed.

3. The depth of the HAZ after gouging varied from 0.004 to 0.032 in. The shallower depths were generally associated with the pad washing technique.

4. The hardness values obtained after gouging do not appear to have any detrimental effect on the surface of the gouge. There was no evidence of cracking or other defects.

5. Where subsequent machining is required, the HAZ may present some problems initially, although machining is usually carried out in the same areas as pad washing or shaping, where HAZ is shallowest.

6. Subsequent welding of a gouged surface removes the HAZ left by the arcair process without detriment to the fusion zone and weld deposit.

7. The HAZ after welding is less well defined and much lower in hardness. The hardness values approach those considered to be a generally acceptable level for welded applications.

8. Preheating prior to arcair gouging generally lowers the HAZ hardness, especially where a small electrode is used or where a pad washing technique is adopted.

9. Subsequent welding of the gouged surfaces using preheat appears to have little or no effect on the resultant hardness of the HAZ when compared with those obtained where no preheat was used. The values in each example are very similar.

10. Preheating appears to cause a slight rise in the hardness values obtained from the parent metal adjacent to the gouged and welded area.

11. The work carried out in this survey indicates that the arcair process can be used without detriment to subsequent welding or machining operations on carbon-manganese steels up to 0.40-0.45% carbon content. It also indicates that the use of preheat prior to arcair gouging is not always necessary. The decision whether or not to use preheat must be governed by a number of factors including the shape, size, and analysis of the casting. Of necessity, the samples used in this survey have been limited in size and it would be expected that on larger castings, especially in the higher carbon range, higher HAZ hardnesses would occur, so that preheat may be required (32).

The high hardness surface and heat affected zone of an air carbon-arc gouged surface left in the as-gouged condition are potential sources of cracking. This layer can cause cracks to initiate unless removed by welding over this surface or by grinding. Because of the influence of the arcair process on hardening, castings should be heat treated after arcair metal removal. Preheating prior to arc airing can be employed to reduce the extent of hardening.

A qualification and testing program may be implemented in order to obtain control of parameters that will minimize hardness levels and minimize pick-up of carbon on the gouged surface. Such a program may use the type of specimen shown in Figure III-2a that is gouged out by the operator using arcair. This area is heat treated as specified in the welding procedure and tested with a guided side bend specimens removed as shown in Figure III-2b (26).

Weld Preparation

Figures III-3 and -4 show suggested weld preparations for partial penetration and full penetration repair welds. Typical weld preparations for weld joint design are shown in Figures III-5 through III-10 (34). In general, the weld preparation should have gradual contours and sufficient taper and root radii to avoid stress concentrations and to allow adequate access to the root of the cavity or weld joint with the welding electrode. Sharp inside corners serve as points of stress concentration which may start cracks during welding. Deep, narrow grooves hinder electrode manipulation and make it difficult to achieve full penetration.

When discontinuities extend entirely through a casting, it is

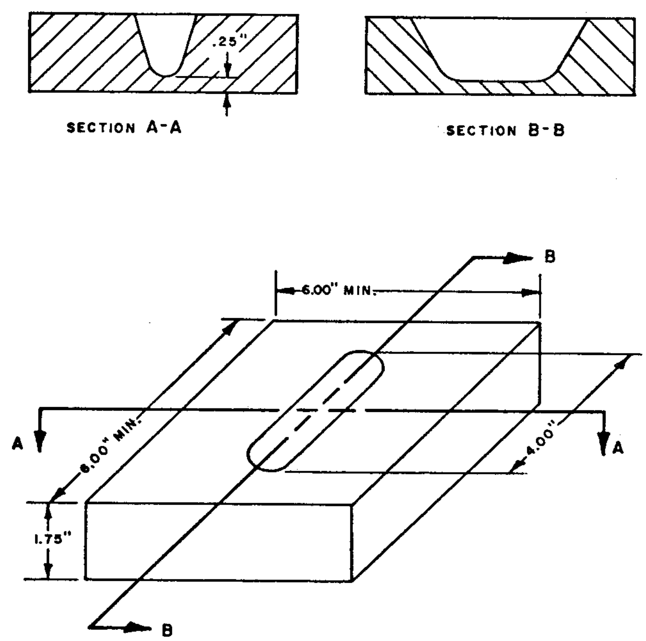


Figure III-2a Configuration for air carbon-arc cutting performance qualification specimen (26).

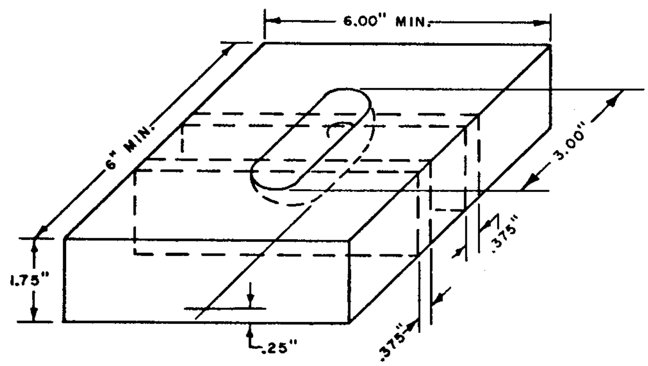


Figure III-2b Locations for removal of guided side bend samples after welding (26).

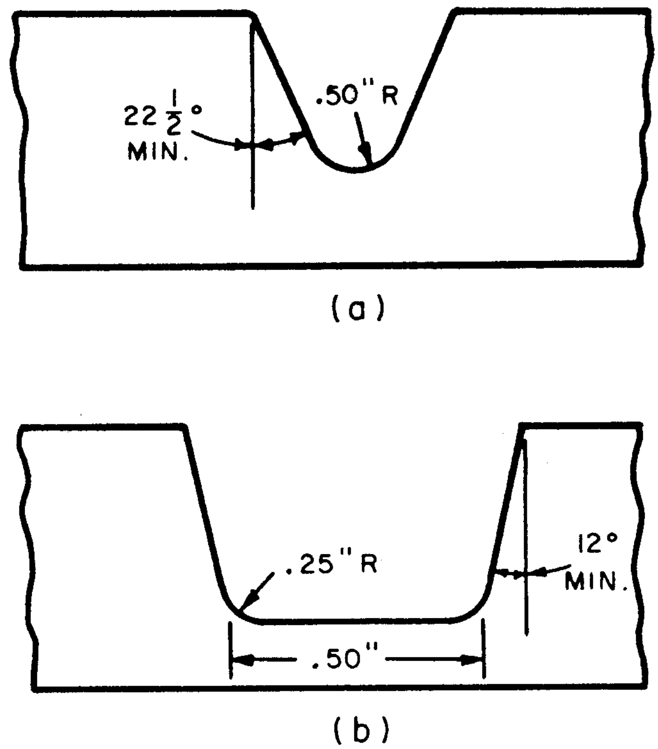


Figure III-3 Weld preparations for partial penetration welds: (a) for minimum root width, (b) for bottom of cavity greater than 1/2 in. (26).

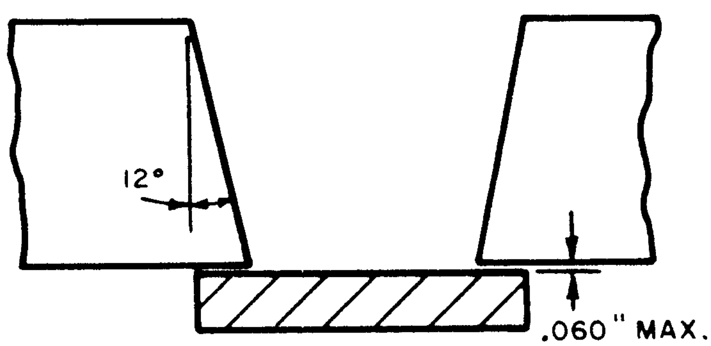


Figure III-4 Weld preparation for full penetration welds (26).

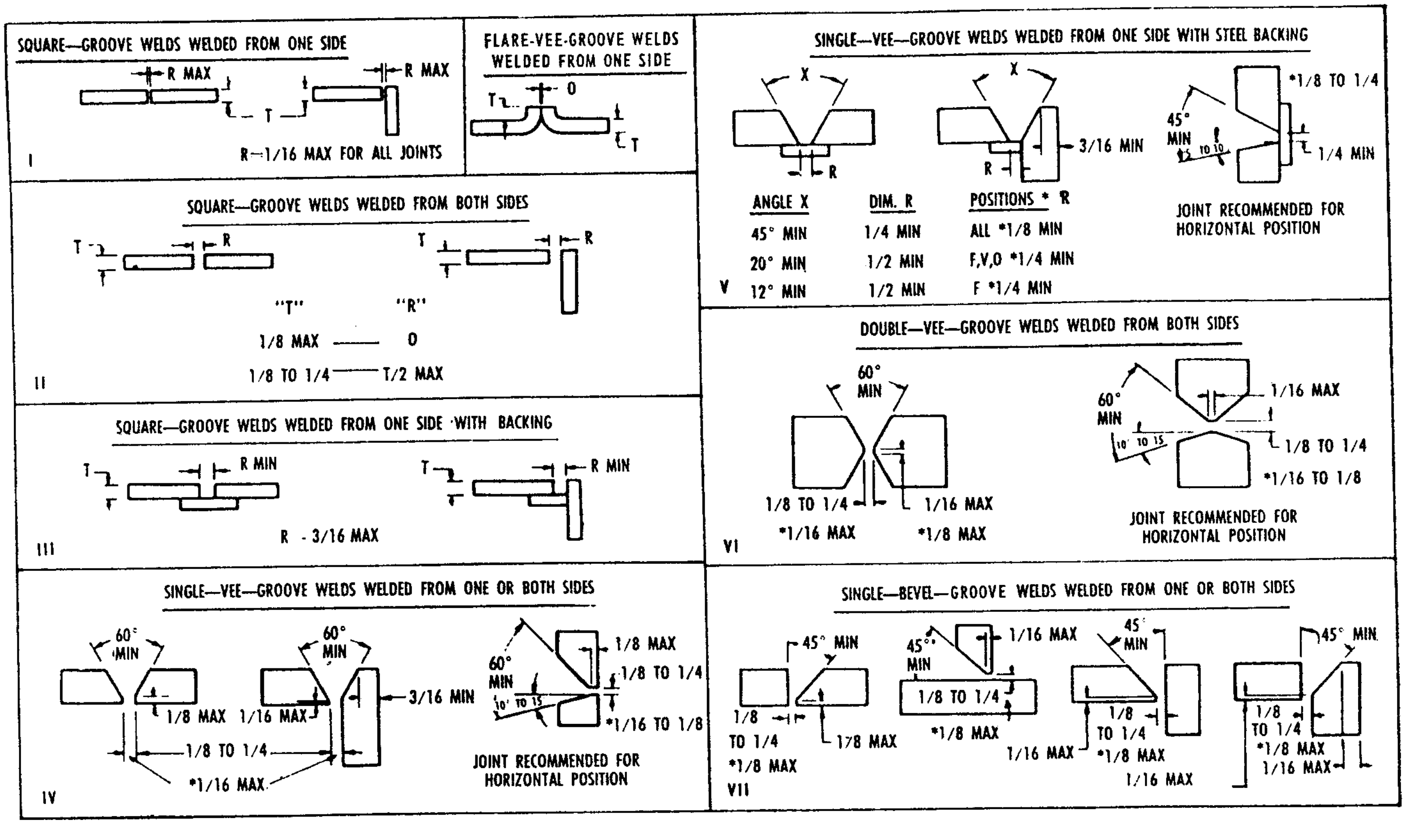


Figure III-5 Recommended proportions of grooves for shielded metal-arc, gas tungsten-arc, gas metal-arc, flux-cored arc and gas welding (except pressure gas welding). Note: Dimensions marked * are exceptions that apply specifically to designs for gas metal-arc welding (34).

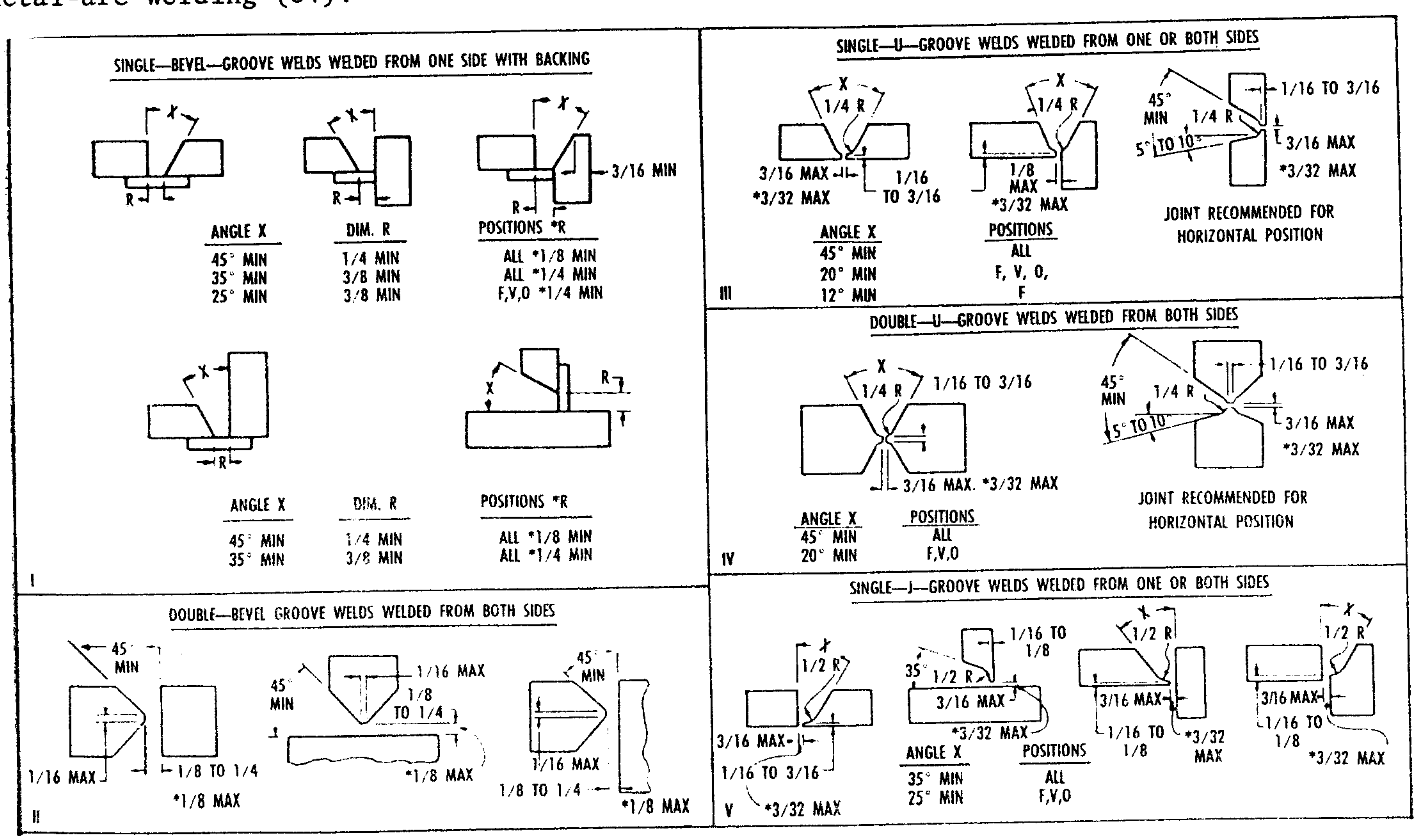


Figure III-6 Recommended proportions of grooves for shielded metal-arc, gas tungsten-arc, gas metal-arc, flux-cored arc and gas welding (except pressure gas welding). Note: Dimensions marked * are exceptions that apply specifically to designs for gas metal-arc welding (34).

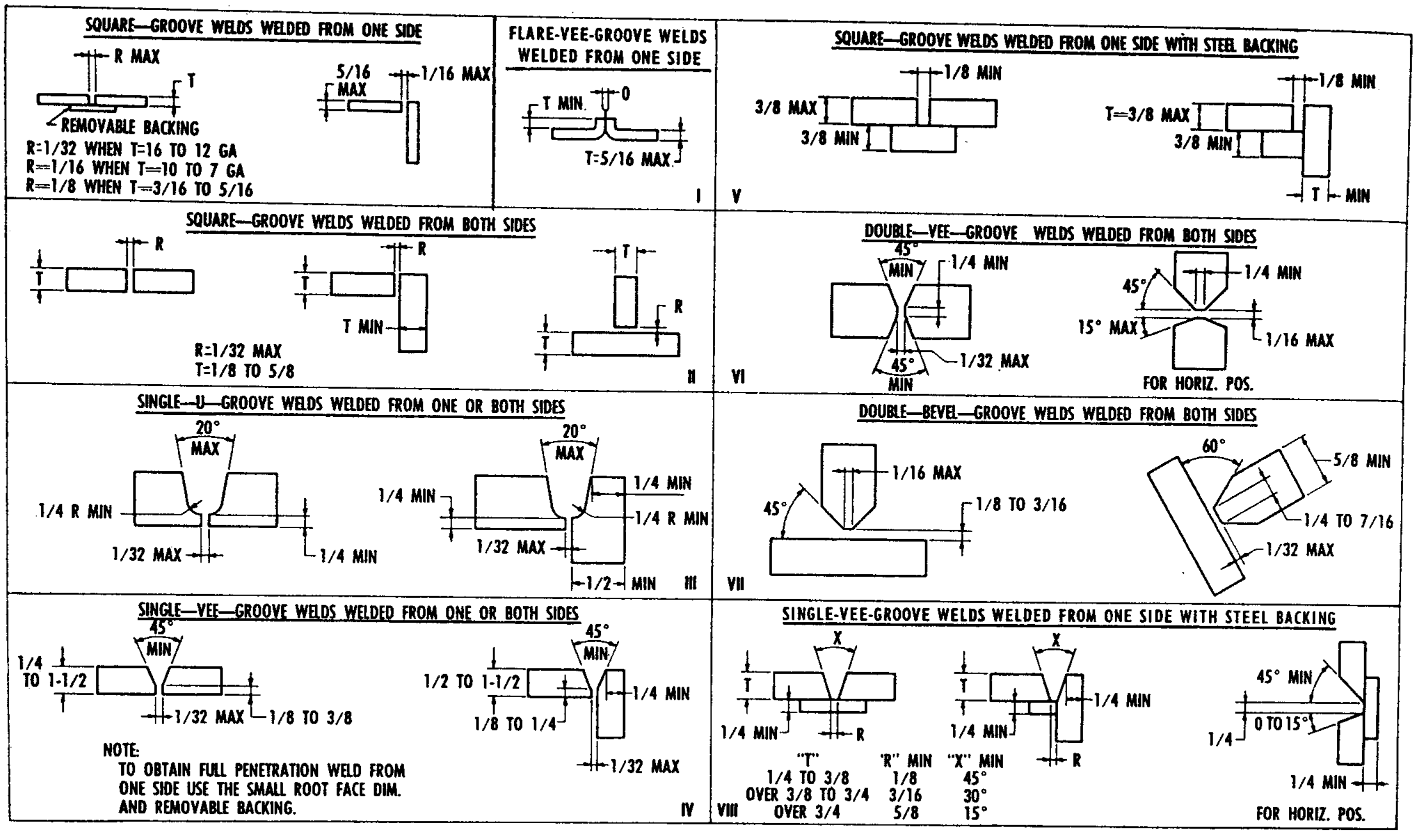


Figure III-7 Recommended proportions of grooves for submerged arc welding of steel (34).

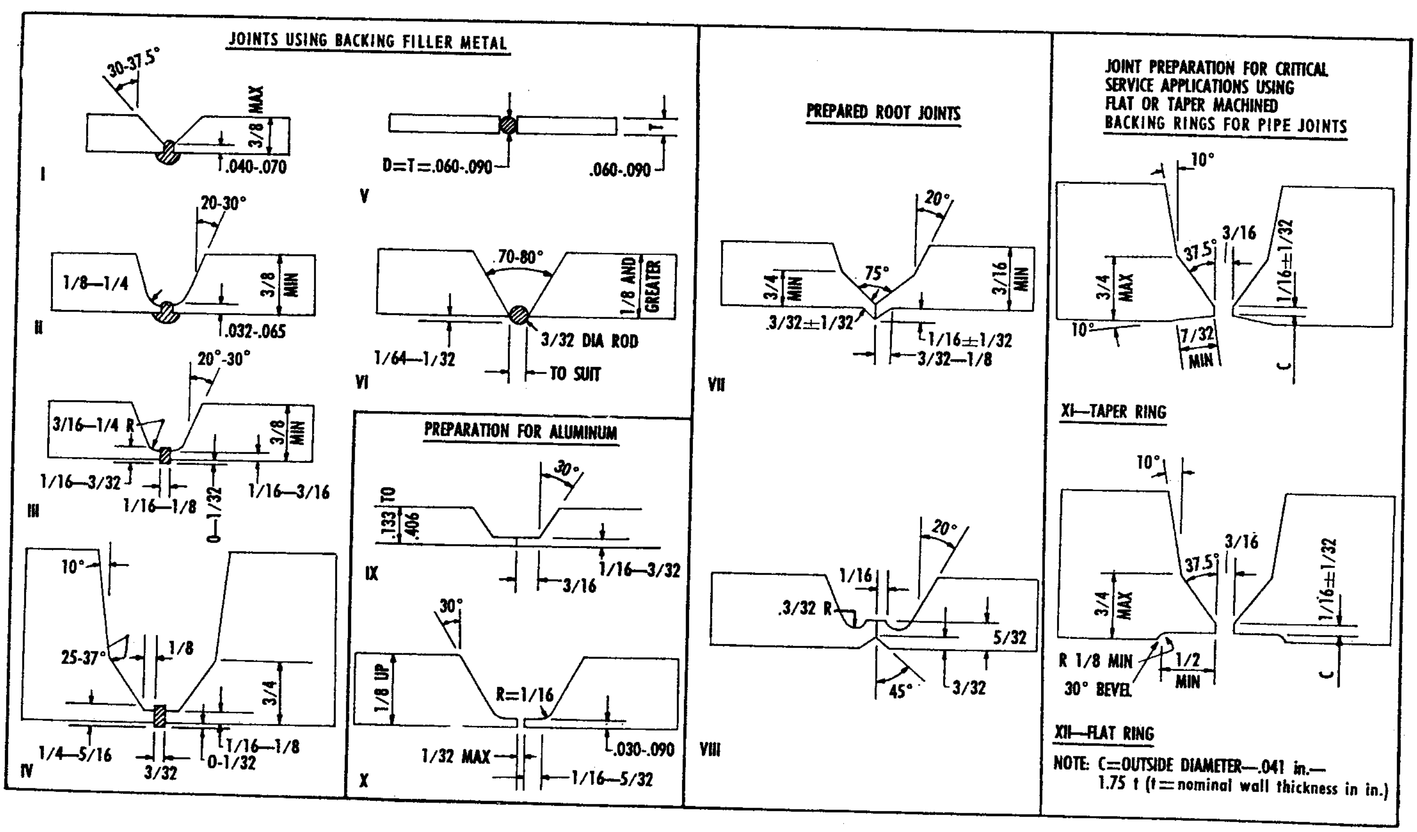


Figure III-8 Recommended proportions of grooves for metal-arc welding processes used to obtain controlled and complete penetration. Note: For steel except as noted (34).

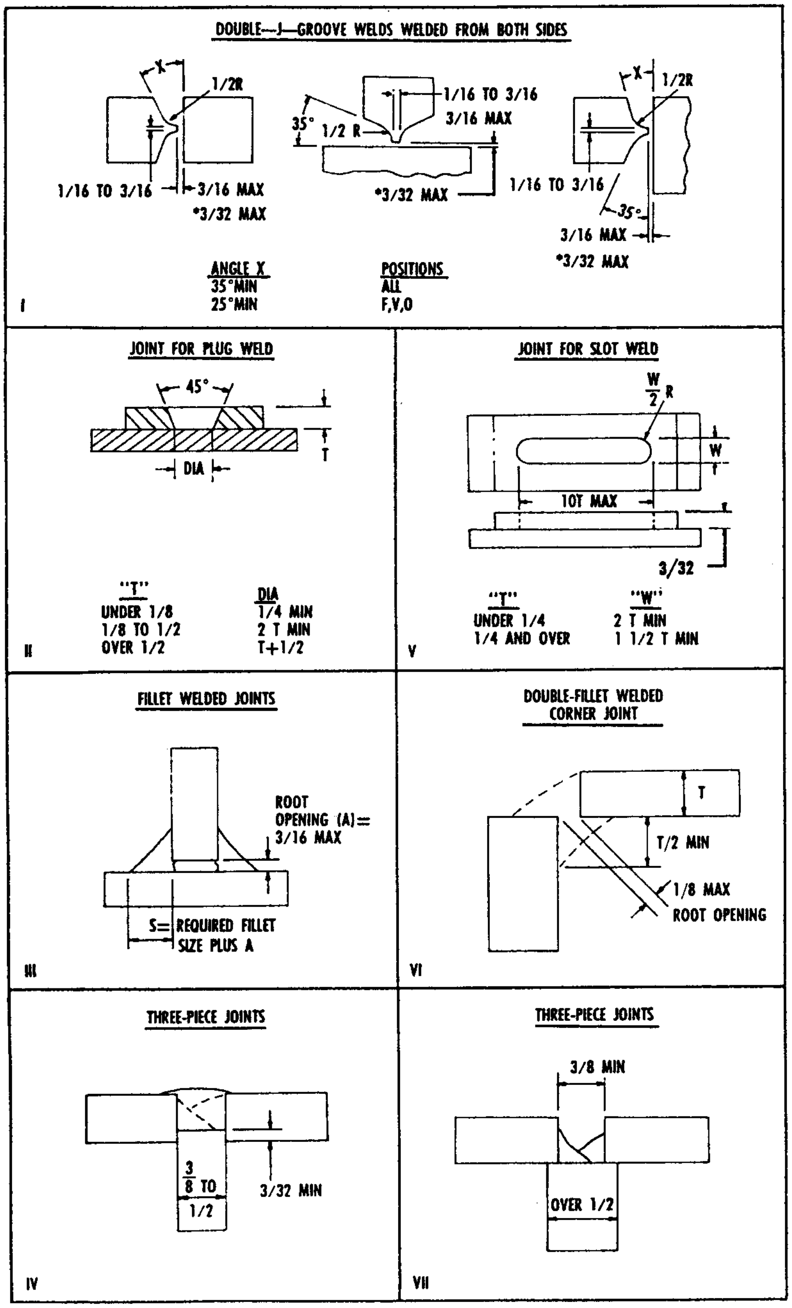


Figure III-9 Recommended proportions of grooves for shielded metal-arc, gas metal-arc, gas tungsten-arc, flux-cored arc and gas welding (except pressure gas welding). Note: Dimensions marked * are exceptions that apply specifically to gas metal-arc welding (34).

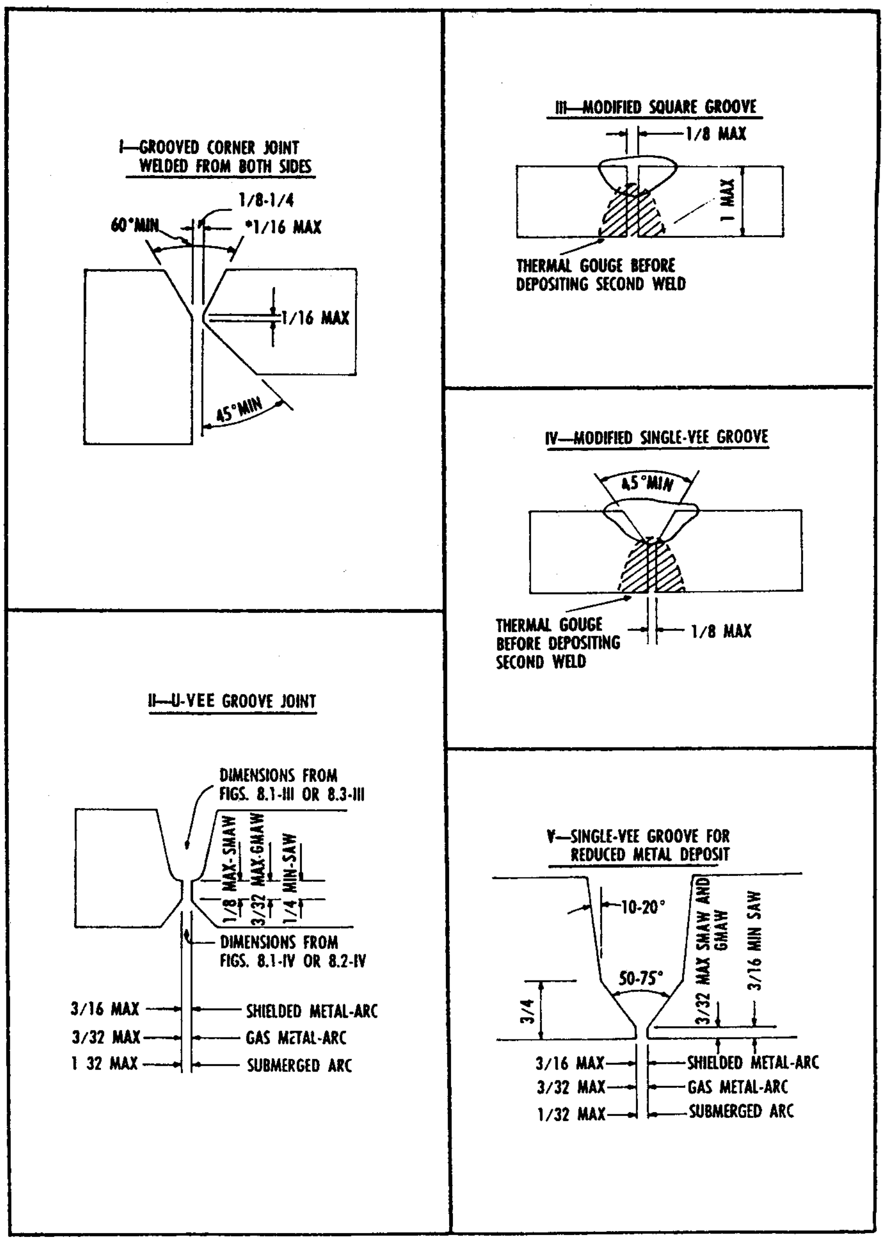


Figure III-10 Recommended proportions of mixed grooves for metal-arc welding processes (34).

best to turn it over and lay one or more sealing passes from the root side of the repair weld. If this cannot be done, a backing should be used wherever possible. Backings can be made from refractory materials available in the foundry, such as firebrick, silica brick, mullite brick, magnesite, or carbon plates. These should be thoroughly dried, because water vapor produced during welding may cause cold cracking at the joint. Metals, such as copper, plain-carbon steel, or stainless steel may also be used as backing material. Ordinarily, the backup material merely acts as a dam and is not bonded to the weld metal. Such is the case with refractories and copper. Backings forming integral parts of the castings should generally have the same composition. Where pick-up of backing metal is not wanted, it is possible to cover the backings with washes of refractory materials, but contamination should be avoided.

To prepare a casting properly for repair welding, the weld preparation must be inspected with a suitable nondestructive examination technique prior to welding. The inspection is intended to verify complete removal of defects, although this may be difficult because the method of removing the defect may smear the metal across a crack. Normally, a visual inspection followed by a liquid penetrant or magnetic particle inspection are performed. ASTM steel casting specifications contain requirements concerning the weld preparation inspection and the degree of inspection required prior to welding.

Sometimes two or more discontinuities may be located so close together that one is not detected during inspection. After the known defects are removed, the repair weld may penetrate through the sound metal between the defects to expose the undetected defect. When this occurs, welding should be stopped until the entire defective area can be removed (26).

Preheat

Arc welding involves the application of a high intensity short duration localized source of heat to the casting. This results in rapidly cooled weld metal and rapid heating and cooling of the surrounding base metal. These thermal effects can lead to cracking during welding (hot cracking) or after welding (cold cracking), a high hardness weld and heat affected zone with a correspondingly detrimental effect on mechanical properties, residual stresses, and distortion of the part being welded. Preheat minimizes these undesirable effects by reducing the thermal gradient between the molten weld metal and cooler base metal, and by lowering the cooling rate. In addition, preheat provides more time for hydrogen to diffuse from the weld zone, and it reduces the moisture content on the surface of the base metal, which is a source of hydrogen absorption into the weld. Hydrogen levels must be controlled when welding crack-sensitive metals in order to prevent hydrogen embrittlement.

Preheating can be accomplished by two general methods: furnace preheating, which involves heating the entire casting; and local preheating, which utilizes torches or induction heaters to heat a localized area surrounding the weld joint. The availability of furnaces, casting size, and ability to maintain preheat upon removal of the casting from the furnace are a few items that should be considered when deciding on the method of applying preheat. It should be stated, however, that furnace preheating is preferable since it minimizes localized stresses and provides more reliable insurance that the required preheat temperature is attained.

Reference 35 contains suggested minimum preheat temperatures for carbon steel and low alloy steel casting materials and is highly recommended to complement this report. Excerpts are presented in Table III-4 at the end of this section. Table III-4 lists the welding procedures for carbon and low alloy steels of AISI, SAE, and API grades and the cast carbon and low alloy steels complying with the following ASTM Specifications A27-77, A148-73, A216-75, A217-75, A352-76, A356-75, A486-74, A487-76, A389-74, and A643-75. A large number of wrought steels are also listed in the tables of Reference 25. An index of the types of steels for which the welding procedure is listed precedes the table of procedures. The steels discussed are limited to 0.5% maximum carbon and 5.0% maximum alloy of any given alloy except the stainless chromium and 8.5% nickel steel grades. It is possible that special steels may be cast that are not listed on one of the casting specifications. However, nearly all compositions are listed in the wrought grade lists and the welding procedure can be obtained from the wrought steel of that composition. The welding procedures are limited to thicknesses of a minimum of 0.25 to a maximum of 4 in., or the maximum thickness of the specification, if this is lower. The welding procedures for each grade include suggested preheat and interpass temperatures, postweld heat treatment, and peening where required. Preheat and interpass temperatures are listed for welding with low hydrogen and other types of electrodes. The preheat and interpass temperatures for the low hydrogen grades are normally lower because of the reduced cracking propensity. Postweld heat treatments are suggested in three categories: optional, desirable; or required. When post weld heat treatments are used, the weld metal should contain no more than 0.05% vanadium to avoid embrittlement.

The suggested preheat temperature depends on the properties of the casting and weld metal and on the size and shape of the casting. Some general rules exist for selecting the correct preheat temperature. In the first place, it should be as low as practically possible, because, with increasing temperature, it is more difficult to lay a weld bead without undercut, and protection for the welding operator becomes a problem. While the use of the minimum preheating temperature is desirable for the above reasons, a temperature of 50 to 100°F above the minimum will seldom do any harm. Other sources of welding procedures are available (36), but Reference 35 is the most complete.

The chemical composition of the casting is a major factor in selecting preheat. Steels low in carbon and alloy contents do not tend to quench harden excessively nor to form cold cracks. They require either no preheat, or much less preheat than needed for a high-carbon, high-alloy castings. This reasoning also applies to the deposited weld metal, particularly in multipass welds.

Thickness and shape of the casting also must be considered. Thicker castings have greater heat-absorbing capacities, and therefore, in effect, greater quenching powers. As a rule, the thicker the casting (provided it needs preheat at all), the higher the preheat should be. Simple shapes with fairly uniform cross sections will cool uniformly, and require a minimum of preheat. Complex castings consisting of alternating thin and thick sections will cool more rapidly in the thin sections, which may lead to severe internal stresses. In such a case, a higher preheat should be used than for a more uniform shape. Also, such castings should be protected from drafts during welding and should be cooled slowly.

Another factor influencing the selection of a preheating temperature is the size of the defect in relation to the thickness of the casting. A small weld cools more rapidly than a large one. Thus, tack welding on a crack-sensitive steel can be a dangerous procedure and casting failures have resulted from cracks started from a tack weld made without preheat.

In order to obtain correct preheating temperatures, furnaces with accurate controls can be used with thermocouples attached to the casting for measuring preheat temperatures. Temperature-sensitive crayons are normally used with local preheating methods. These crayons leave a mark that melts when the part reaches the required temperature.

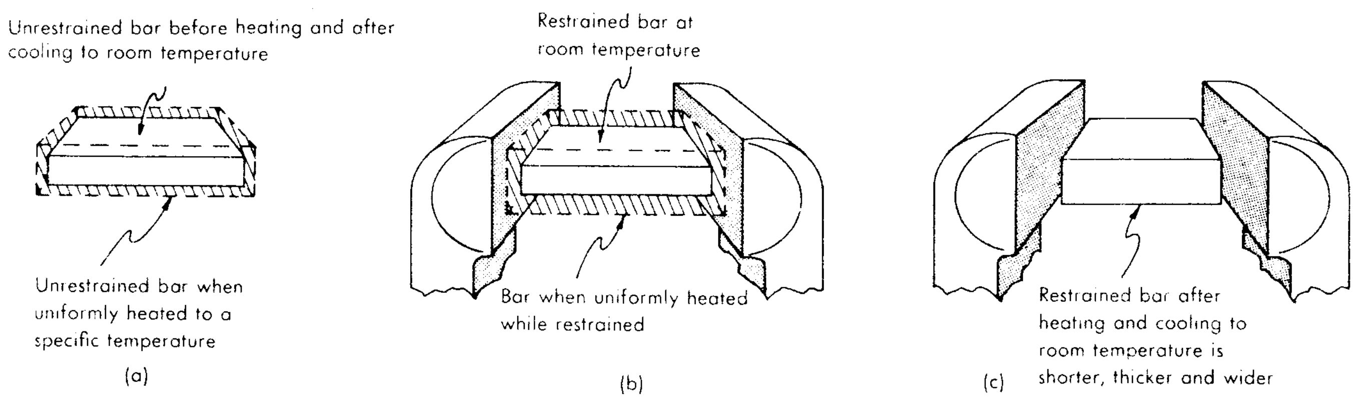
Interpass Temperature

The interpass temperature, i.e., the temperature between passes in multipass welds, should be considered along with preheat. In order to maintain the desirable conditions developed by preheat, the interpass temperature should never be below the preheat temperature. The interpass temperature can safely exceed the preheat temperatures by 100 to 200°F, depending on the particular casting, and frequently does. The interpass temperature should not be allowed to go so high that the side walls of the weld groove will be severely undercut. Reference 35 contains suggested interpass temperatures for carbon and low alloy cast steels.

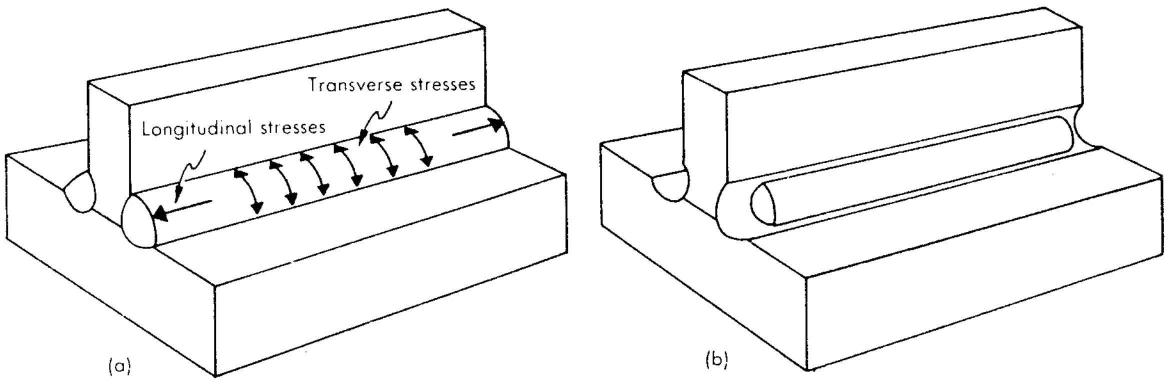
Residual Stress, Distortion, and Restraint Problems

Steel castings being repaired or fabricated by welding undergo considerable thermal and transformation stresses resulting from the welding process. These stresses produce residual tensile stresses in the weld and combined tension, compression and sometimes bending stresses in the weldment. These may result in significant distortion that can produce dimensional problems in weld fabrications. Distortion is of more concern in weld fabrication than in casting repair; it has been discussed in detail in various welding texts (20, 37). The behavior of weld metal under the restraint of the surrounding casting is illustrated in Figure III-11A (37). The resulting residual stress on a simple fillet weld is demonstrated in Figure III-11B; the weld bead in this and in most other welds are in biaxial or even triaxial tension because the as deposited weld is larger than the weld after it has solidified and cooled to room temperature. The distortion produced by welding is indicated in Figure III-11C.

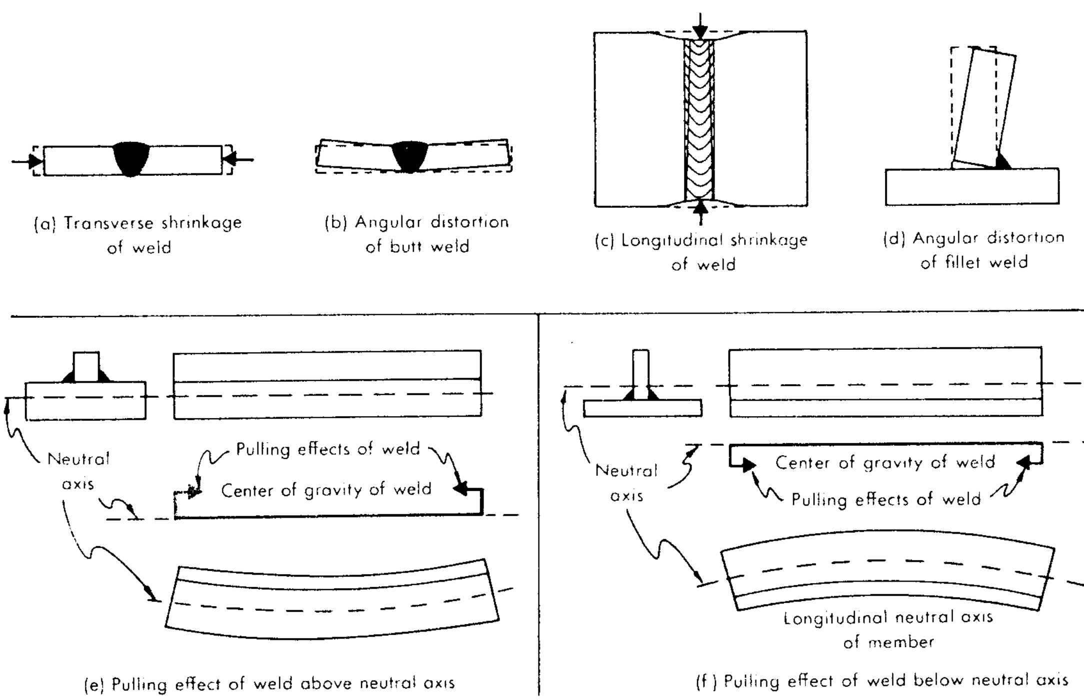
In repair welding, the casting is usually considerably larger than the weld and frequently surrounds the weld deposit except for the open face. Under these conditions, distortion is usually not great but the residual stresses obtained can contribute to cracking in the weld or even in the surrounding metal. The more severe the restraint of the free contraction of the weld, the higher the tensile stress state in the weld. Reference to Figures III-11A and B illustrate this fact. This condition makes many weld repairs, particularly the larger repairs in thick walled castings, subject to cracking because of this restraint; various means of lowering the stresses and cracking susceptibility are employed. The more severe the restraint, the greater the necessity for employing welding procedures that reduce the residual stresses. The various techniques used for this purpose include: higher preheating temperatures to lower thermal differences between the casting and weld, reduced size of the deposited weld beads, the relief of stresses in a weld by the thermal effect of subsequent weld deposits, and peening the weld. The thermal stress relieving effect of subsequent weld beads and the lower stresses usually obtained with smaller weld deposits may require welding severely restrained areas with several small weld beads, as opposed to one or only a few larger weld passes to avoid cracking. The effect of different bead



A. Non Uniform Expansion and Contraction of Weld and Adjacent Base Metal.



B. Weld Metal Shrinkage Causes Longitudinal and Transverse Stresses



C. Examples of the Distortion of Various Fabrication Weldments

Figure III-11 Expansion, Contraction, Residual Stresses and Distortion in Weldments (37).

types and welding sequences on this thermal stress from subsequent welds is discussed in subsequent paragraphs. Peening the weld, as will be discussed in a subsequent paragraph, lowers residual tensile stresses in the weld, but cracking may occur before peening can be accomplished.

Distortion as demonstrated in Figure III-11C is more of a problem in weld fabrication as employed in cast-weld construction. Various means of reducing this distortion are employed (20, 37). These procedures are: using a minimum of weld metal, placing welds near the neutral axis, balancing stresses by balancing welds around the center of gravity, selecting a welding sequence to offset the distortion of each weld with subsequent welds, maintaining a high temperature on the steel during welding, and using various types of mechanical restraint. Peening the weld also reduces distortion (37).

Residual Stress Relief

Since the residual stresses obtained by welding are additive to service stresses, the presence of the multiaxial tensile stresses in welds can lead to either abrupt or fatigue failures. In addition, stress relief improves dimensional stability during machining and service and reduces susceptibility to stress corrosion cracking. For this reason, some means of relieving these stresses is desirable before the castings are placed in service. Thermal stress relieving treatments lower the hardness of the HAZ as well as stress relieving. Several means of lowering residual stresses in welded steel castings exist as listed below:

a. Thermal stress relieving treatments in the range of 1100-1150°F are employed to reduce the stress levels significantly (20). Temperatures as high as 1250°F are required for essentially complete removal of the stresses but this low a stress level is frequently not needed and the higher strength steels would be softened by this high a temperature.

b. Other heat treatments such as normalizing, austenitizing for quenching or tempering in the stress relief temperature range after welding remove residual stresses.

c. Multipass welds are generally low in residual stresses because the latter welds thermally treat the prior welds. The effect of deposition technique on the relief of stress is discussed under a following heading.

d. Peening weld deposits converts residual tensile stresses to compressive stresses; it is used on single pass welds or the last passes of multipass welds for that purpose.

e. Vibratory stresses can be used to reduce residual stress levels under some limited conditions of shape, size, and capacity of the vibratory unit. This process is less costly and more rapid than thermal stress but the process requires further development (38).

f. Mechanical stress relief by employing a small amount of permanent deformation across the part also is very effective means under specific condition of shape and equipment.

Welding Current and Heat Input

Some classes of electrodes require higher welding current for a given diameter than others. Also, larger diameter electrodes of a given class require more current than smaller ones, Increasing the current increases the welding heat input. This acts, to a lesser degree, like preheating, flattening out the temperature differential in the weld area and lowering the cooling rate. Therefore, other things being equal (which they frequently are not), the "hotter", larger diameter electrodes should be selected for repair welding.

The welding current used with different sizes of electrodes may also be varied somewhat when welding in a given position such as flat, as required by the weld being produced. It usually has to be varied for welding in other positions, e.g., vertical, or overhead. Manufacturers usually print the recommended current ranges for their electrodes on the containers. These ranges tend to be fairly wide and will vary somewhat even for electrodes of the same class. The higher current is for downhand welding under favorable conditions. Those on the lower side are for situations where careful control of the weld metal is needed, such as in vertical or overhead welding, or where the preheat is high. Experienced welders can select the proper current. A tendency exists to use higher current to increase productivity; however poor quality welds may result. While higher welding currents obviously increase the rate and temperature of welding, only a relatively small variation is allowed for making a good weld with a given size and type of electrode in a given position.

Deposition Technique

Weld beads can be deposited in the repair cavity or fabrication groove by several techniques. The optimum procedure depends on the size of the groove, the thickness of the casting section, the properties of the casting and weld metal, and the position in which the weld is to be made. It is possible in some cases to position the repaired casting or fabrication, so that welding is conducted in the flat or downhand position. Two basic factors that have to be considered in selecting the proper deposition technique are the speed of welding and the volume of the weld. These two factors may be varied to help control welding heat effects. For a given size of weld bead, the higher the welding speed, the more rapid the cooling rate. This increases the under-bead hardness and tendency for under-bead cracking. On the otherhand, it reduces the tendency to distortion by minimizing the volume of heat-affected base metal. When preheating is used, the welding speed is not as important--provided a sound, well-contoured bead is laid.

The effects of volume of the weld are similar to those of speed; a small weld produces effects similar to those with high speed, because, again, the cooling rate of the weld zone is relatively fast. Conversely, a large volume of weld metal deposited in a single pass results in considerably more heat in the weld zone. This results in a slower rate of cooling in the weld zone but higher shrinkage stresses. Unless the shrinkage stresses are sufficiently high to cause cracking in the weld metal or base metal, they are of no particular importance in repair welds because the castings will usually be at least stress relieved after welding.

The two main types of weld beads are the stringer and weave beads. The stringer bead is laid in a continuous pass in one direction as shown in Figure III-12. The weave bead also progresses in one direction, but has a side-to-side motion. Many patterns of weave bead are employed including simple ones such as illustrated in Figure III-13 and others that form figure eights, ellipses, etc. A modification of the weaving technique which can be used with many of the weave patterns is whipping that is illustrated in Figure III-14. This is used to control the molten weld pool by removing the arc heat, while still maintaining the arc.

Stringer and weave beads are used in single layers, when the groove can be filled in a single pass. Where the groove is too deep or too wide to be filled in one pass, multiple layers are used. These may be laid with either stringer or weave beads, or a combination of the two. Nearly all repair welds in castings can be made with string or weave beads laid from start to finish in single or multiple layers. The width of weaving is limited to 2.5 times the diameter of the coated electrode.

Still another way of controlling the welding heat effects by deposition technique is the welding sequence. This can be varied even in single-layer welds. The most common sequence for single-layer welds is simple string or weave beads laid in one direction.

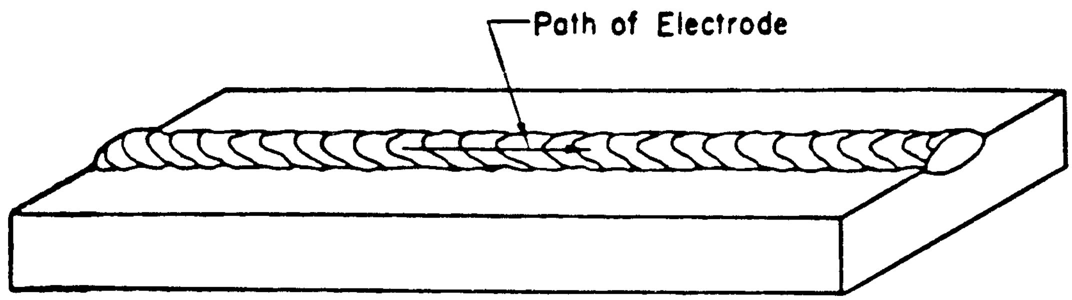


Figure III-12 String Bead Deposit

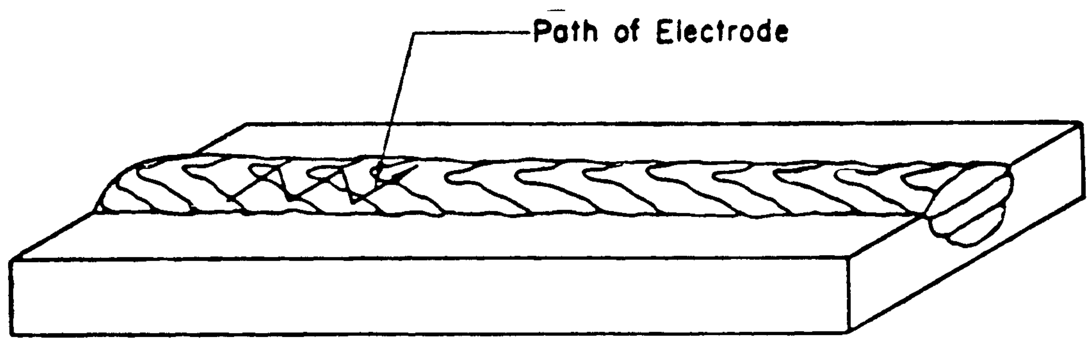


Figure III-13 Weave Bead Deposit

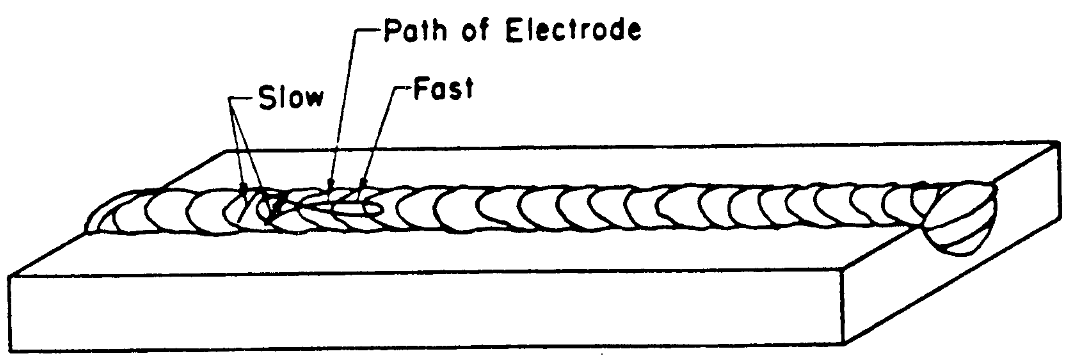


Figure III-14 Weave Bead Deposit with Whipping

These are started at one end of the weld and continued to the other. Where the weld is long, several electrodes may be used. In this case, the beads are laid one after the other in the same direction. In long welds where it may be desirable to minimize longitudinal and transverse weld shrinkage effects, the backstep method can be used. In this procedure, short weld beads are deposited in the sequence shown in Figure III-15. The first weld bead is deposited starting 2 to 4 in. inward from the edge of the part to be welded. Then, the next bead is deposited starting 2 to 4 in. further inward from the edge of the first weld. Succeeding weld beads are deposited in a similar manner, taking care to overlap the beginning of the previous bead.

In multiple-layer welding, a greater variety of sequences may be used. String or weave beads laid in one direction are most commonly employed. The backstep sequence (Figure III-15) can be utilized either as string beads or weave beads. Two other sequences designed primarily to minimize shrinkage in fairly large groove welds are the block sequence and the cascade sequence. In the block sequence, the weld is built up by intermittent blocks which are subsequently joined by other blocks after the first group is completed, as illustrated in Figure III-16. The chief benefit of the block sequence is to minimize longitudinal weld stresses. It does not have much effect on transverse shrinkage, except that the stresses in the lower passes are relieved by the welding heat from succeeding passes. The cascade sequence reduces both transverse and longitudinal shrinkage stresses as the weld progresses, particularly when employed with a weaving bead. The sequence is shown in Figure III-17. By using the cascade sequence the heat from the first half of any bead will temper or stress relieve the last half of the bead immediately before it. The net result is that all bead segments of the first-pass are stress relieved by the next succeeding increment so that no major stresses can remain. Both of these methods require more welding time than ordinary multilayer welds. They should not be used, except where the greater reduction of stress warrants it. Preheating would largely eliminate the need for such special techniques.

For the multilayer welding of large grooves, any one of the deposition techniques discussed can be used. Sometimes, as a matter of convenience, it is simplest to run one bead in one direction and the next bead in the opposite direction. In general, the simplest procedure is to build up the weld in horizontal layers, such as illustrated in Figure III-18. It has been claimed that the least stress is produced when the weld can be built up in spiral layers around the side, as shown in Figure III-19.

In the section on preparation for welding, the use of backings

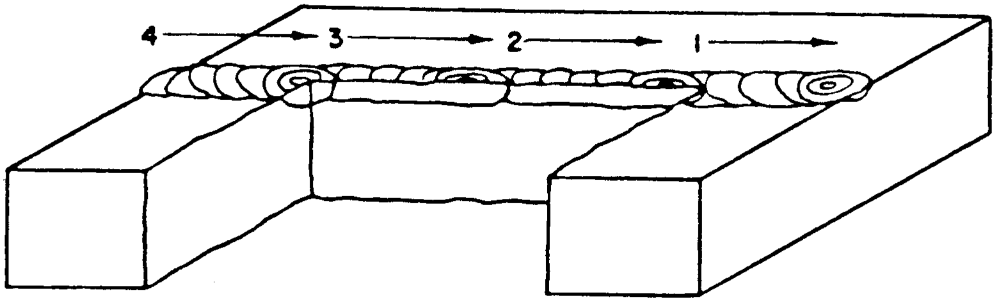


Figure III-15 Backstep Welding Sequence

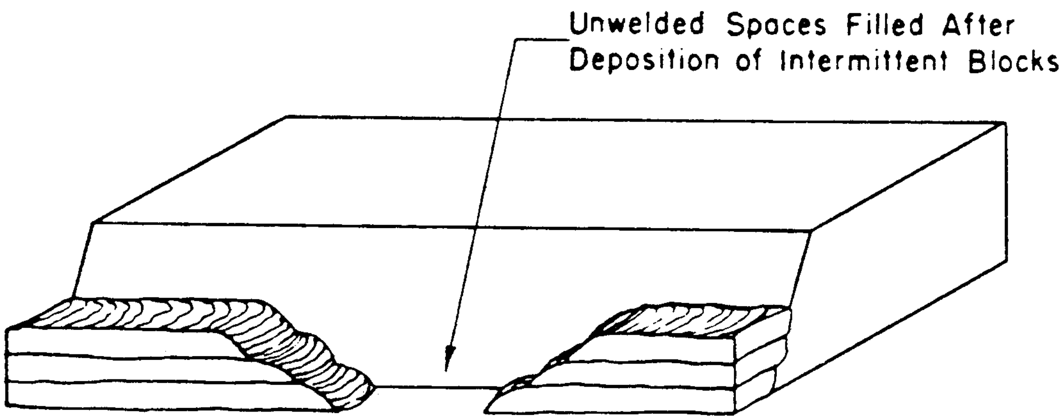


Figure III-16 Block Welding Sequence

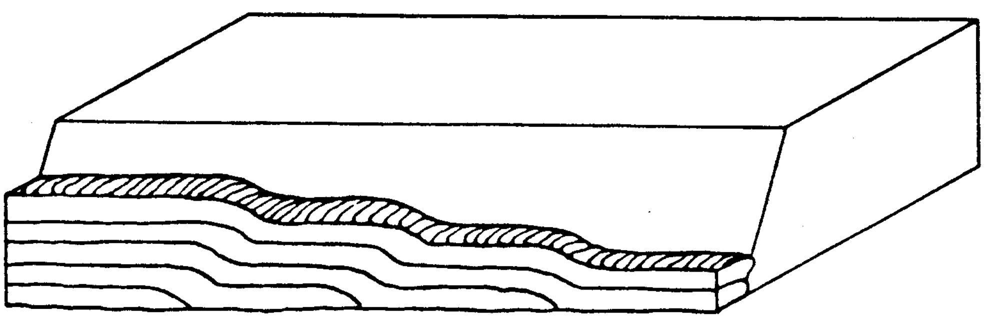


Figure III-17 Cascade Welding Sequence

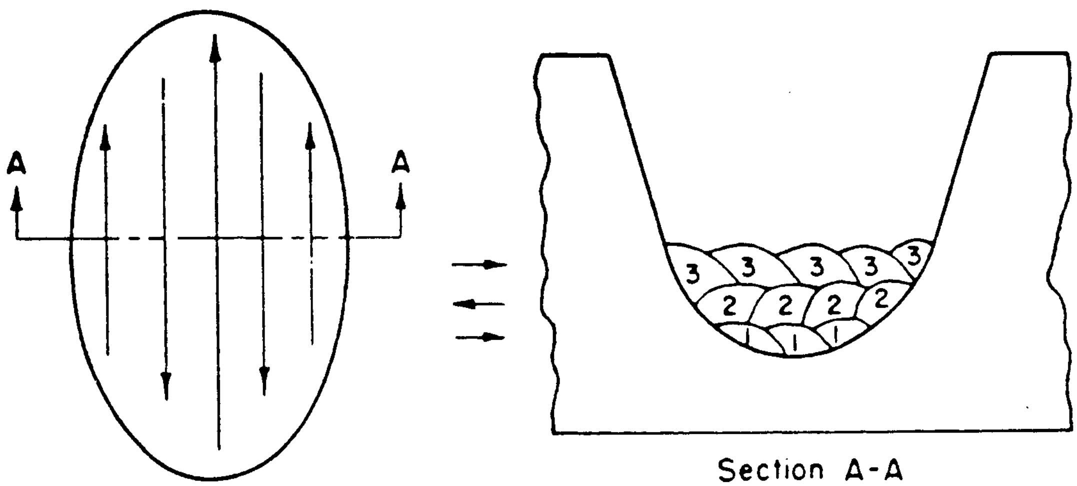


Figure III-18 Horizontal-weld layer deposition

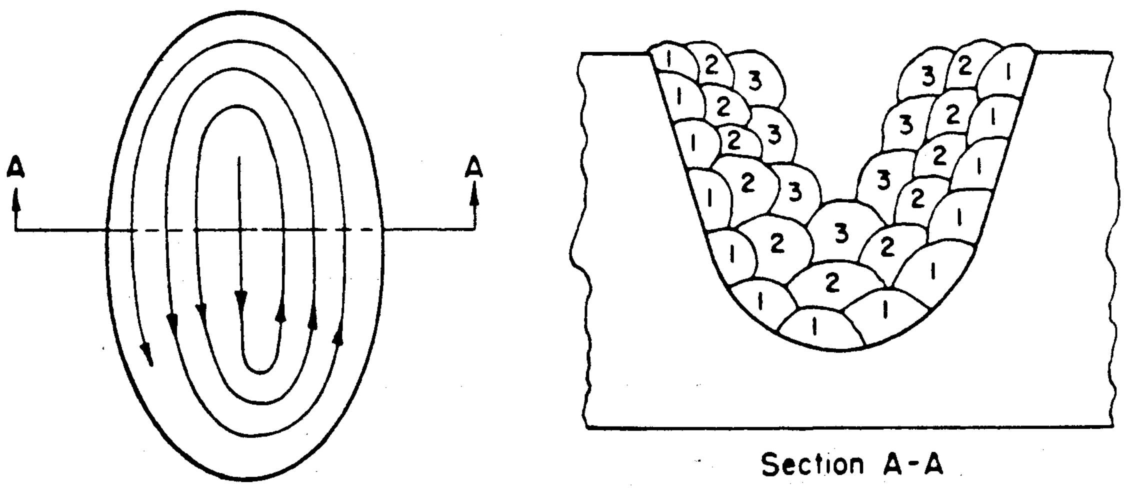


Figure III-19 Spiral-weld layer deposition was discussed. In general, the presence of a backing does not markedly change the required deposition technique. However, particular care must be taken in laying the root passes. Where a backing is to become a part of the assembly, it is very important to obtain full penetration into the backing. Where a temporary backing of either ceramic or ceramic-washed metal is used, particular care should be taken to insure good fusion between the root pass and the side walls of the groove. If lack of fusion exists between the root pass and the side walls, the unfused sections will act as stress raisers and increase the possibility of cracking.

Arc length is also an important consideration in weld deposition. Ordinarily, a good welder automatically holds a proper, or "normal" arc length. For the low-hydrogen type electrodes, the arc required for depositing high-quality weld metal is shorter than for other classes of electrodes. This important difference may be overlooked even by good welders, whose experience has been with the other classes of electrodes. The use of flux cored arc welding and gas-shielded metal-arc welding requires some dexterity and experience on the part of the operator. However, the arc length is determined by the equipment and the skill is no greater than that required for manual welding. The additional heat from the processes compared to shielded metal arc welding may require more shielding for the operator.

Peening

Distortion can be minimized by peening the weld. Heavy peening after each pass will reduce distortion by offsetting the tensile stresses in the weld, thus counter-balancing its natural shrinkage. For castings thick enough to resist distortion, deep peening provides a mechanical stress relief. However, peening must be carefully controlled, because over-peening causes weld-metal cracking and is, therefore, worse than not peening at all. The permissible amount of peening is somewhat dependent on the mass of the casting. Heavier peening forces are required for heavier castings. Reference 35 indicates the conditions when peening may be necessary. Where severe distortion during welding may occur, for example, in filling a relatively large groove in a thin rangy casting, peening may be helpful in minimizing distortion. For castings which are to be at least stress relieved after welding, peening is not generally used. Peening and slag removal can be combined into one operation.

Post-Weld Heat Treatment

Post-weld heat treatment, PWHT, reduces residual stresses, and, provided the PWHT temperature is sufficiently high, it can increase the strength of the weld or lower the hardness and improve the tcughness of the weld metal and heat affected zone. The various types of PWHT normally used are: stress relief (discussed in the previous section II), temper, normalize and temper, or quench and temper. Casting material specifications usually specify the PWHT required after repair welding. Reference 35 contains suggested PWHT temperatures for carbon and low alloy cast steels. In general, PWHT of low carbon steels is intended to reduce the residual stresses rather than temper the weld metal or heat affected zone. PWHT for the hardenable low alloy steels is intended to improve toughness and ductility, in addition to reducing residual stresses.

The great majority of castings can be cooled to room temperature in still air after welding, but those of higher alloy content, which are more sensitive to cracking, should be cooled gradually from the welding temperature. This is primarily to provide greater insurance against cold cracking. Such retarded cooling may be accomplished in a furnace or oven, by heating with a flame or by burying the casting in some insulating material. However, inasmuch as crack-sensitive steels require preheating as well, one of the best practices is to put the castings back in the preheating furnace as soon as they are welded.

Many castings are heat treated with their regular final heat treatment, such as normalizing or quenching and tempering after welding. Either of these treatments will eliminate the heat-affected zone and make the stress-relieving unnecessary. Though normalizing or quenching and tempering generally improves the base metal, they may reduce the weld metal properties, unless proper electrodes are chosen as discussed in Section II.

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35).

Steel Specification	Suggested Welding Conditions: For Carbon Range, % Note (1)	For Thickness Range, Inch Note (2)	Minimum Preheat and Interpass Temperature, °F: Low-Hydrogen	Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
ASTM A27-73 Mild to medium strength carbon steel castings for general application	Up to 0.25, Inc. (Total residual alloys less than 0.50%)	Up to 1, Incl.	Ambient, Above 10F	100	Desirable 1100/1250	--
		Over 1 to 2, Incl.	Ambient, Above 10F	200	Desirable 1100/1250	--
		Over 2 to 4, Incl.	100	300	Desirable 1100/1250	Yes
	0.26 - 0.30, Inc. (Total residual alloys less than 0.50%)	Up to 1/2, Incl.	Ambient, Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	Ambient, Above 10F	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	100	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200	300	Desirable 1100/1250	Yes
	0.31 - 0.35, Incl. (Total Residual alloys less than 0.50%)	Up to 1/2, Incl.	Ambient, Above 10F	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	100	300	Desirable 1100/1250	--
		Over 1 to 2,Incl.	200	300	Desirable 1100/1250	Yes
		Over 2 to 4,Incl.	300	300	Desirable 1100/1250	Yes
	Up to 0.25, Incl. (Total residual alloys between 0.50 and 1.00%)	Up to 1, Incl.	Ambient, Above 10F	200	Desirable 1100/1250	--
		Over 1 to 2,Incl.	100	300	Desirable 1100/1250	Yes
		Over 2 to 4,Incl.	200	300	Desirable 1100/1250	Yes
	0.26 - 0.30,Incl. (Total residual alloys between 0.50 and 1.00%)	Up to 1/2,Inc.	Ambient, Above 10F	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	100	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300	300	Desirable 1100/1250	Yes
	0.31 - 0.35, Incl. (Total residual alloys between 0.50 and 1.00%)	Up to 1/2, Incl.	100	300	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400	400	Desirable 1100/1250	Yes
	Note: 1. If total Mn + Si + Cu + Ni + Cr + Mo exceeds 2.0%, compare analysis to nearest matching AISI specifications for selecting welding conditions. 2. Thickness refers to that at point of welding.					
ASTM A148-73 High-strength steel castings for structural purposes	Compare analysis to nearest matching AISI specifications for selecting welding conditions. Notes: 1. Thickness measured at point of welding. 2. Specification limits defect depths which may be repair welded without consent of purchaser and requires stress relief or other heat-treatment after welding.					
1% Cr - 1% Mo-V ASTM A356-75 A389-74 A405-70 (1976)	Up to 0.15, Incl.	Up to 1/2, Incl.	150	300	Required 1150/1350	--
		Over 1/2 to 1,Incl.	200	350	Required 1150/1350	--
		Over 1 to 4, Incl.	300	450	Required 1150/1350	Yes
	0.16 - 0.20,Incl.	Up to 1/2, Inc.	300	350	Required 1150/1350	--
		Over 1/2 to 1,Incl.	400	450	Required 1150/1350	--
		Over 1 to 4, Incl.	500	550	Required 1150/1350	Yes
	Note: 1. Post-weld Heat-Treatment of these grades of steel should be done with caution. 2. Use chromium-molybdenum electrodes where compatible high-temperature properties are required in weld metal.					

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --2

Steel Specification	Suggested Welding Conditions: For Carbon Range, %	For Thickness Range, Inch	Minimum Preheat and Interpass Temperature, °F: Low-Hydrogen	Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
ASTM A216-75 Carbon Steel Casting Suitable For Fusion Welding for High Temperature Service		For Total Residual Alloys Less Than 0.50%				
	Up to 0.20, Incl.	Up to 1, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 1 to 2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 2 to 4, Incl.	100	200	Desirable 1100/1250	Yes
	0.21 - 0.25, Incl.	Up to 1, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 1 to 2, Incl.	100	200	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200	300	Desirable 1100/1250	Yes
ASTM A660-76 Centrifugally Cast Carbon Steel Pipe For High Temperature Service	0.26 - 0.30, Incl.	Up to 1/2, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 1/2 to 1,Incl.	100	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	100	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200	400	Desirable 1100/1250	Yes
		For Total Residual Alloys Over 0.50%				
	Up to 0.30, Incl.	Up to 2, Incl.	100	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200	400	Desirable 1100/1250	Yes
	Notes: 1. Thickness refers to that at point of welding. 2. For welding and post-weld heat-treatment requirements for boilers or pressure vessels fabricated from this material, refer to appropriate section of ASME Boiler & Pressure Vessel Code.					
ASTM A217-75 Alloy steel Castings for Pressure Containing Parts Suitable for High-Temperature Service	WC1 Up to 0.20, Incl.	Up to 2, Incl.	100	300	Required 1150/1350	--
		Over 2 to 4, Incl.	200	300	Required 1150/1350	Yes
	WC1 0.21 - 0.25, Incl.	Up to 2, Incl.	200	300	Required 1150/1350	Yes
		Over 2 to 4, Incl.	300	400	Required 1150/1350	Yes
	WC4 Up to 0.20, Incl.	Up to 1/2, Incl.	200	300	Required 1150/1350	--
		Over 1/2 to 1,Incl.	300	350	Required 1150/1350	--
		Over 1 to 4, Incl.	400	450	Required 1150/1350	Yes
	WC6 Up to 0.15, Incl.	Up to 1/2, Incl.	100	300	Required 1150/1350	--
		Over 1/2 to 1,Incl.	200	300	Required 1150/1350	--
		Over 1 to 4, Incl.	300	400	Required 1150/1350	Yes
	WC6 0.16 - 0.20, Incl.	Up to 1/2, Incl.	300	350	Required 1150/1350	--
		Over 1/2 to 1,Incl.	300	350	Required 1150/1350	--
		Over 1 to 4, Incl.	400	450	Required 1150/1350	Yes
	WC5 Up to 0.15, Incl.	Up to 1/2, Incl.	200	300	Required 1150/1350	--
		Over 1/2 to 1,Incl.	300	350	Required 1150/1350	Yes
		Over 1 to 4, Incl.	400	450	Required 1150/1350	Yes
	WC5 0.16 - 0.20, Incl.	Up to 1/2, Incl.	300	350	Required 1150/1350	Yes
		Over 1/2 to 1,Incl.	400	450	Required 1150/1350	Yes
		Over 1 to 4, Incl.	500	550	Required 1150/1350	Yes
	WC9 Up to 0.15, Incl.	Up to 4, Incl.	500	550	Required 1150/1350	Yes
	WC9 0.15 - 0.18, Incl.	Up to 4, Incl.	600	650	Required 1150/1350	Yes
	C5 Up to 0.20, Incl.	Up to 4, Incl.	Note (2)	Not Available	Transfer Directly to Post-Weld Heat-Treatment At 1350/1400	Yes
	C12 Up to 0.20, Incl.	Up to 4, Incl.	Note (2)	Not Available	Transfer Directly to Post-Weld Heat-Treatment at 1350/1400	Yes
	Notes: 1. Thickness refers to that at point of welding. 2. Use electrodes of compatible composition where compatible high-temperature properties are required in weld metal. 3. For welding and post-weld heat-treatment requirements for boilers or pressure vessels fabricated from this material, refer to appropriate section of ASME Boiler & Pressure Vessel Code					

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --3

Steel Specification	For Carbon Range, %	For Thickness Range, Inch	Suggested Welding Conditions: Minimum Preheat and Interpass Temperature, °F: Low-Hydrogen	Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
ASTM A352-76 Ferritic Steel Castings for Pressure Containing Parts Suitable for Low Temperature Service	LCA, LCB, LCC Up to 0.25, Incl.	Up to 1, Incl.	Ambient, Above 10F	Ambient, Above 10F	Optional 1150/1250	--
		Over 1 to 2, Incl.	50	100	Optional 1150/1250	--
		Over 2 to 4, Incl.	100	200	Desirable 1150/1250	Yes
	LCB 0.26 - 0.30, Incl.	Up to 1/2, Inc.	Ambient, Above 10F	Ambient, Above 10F	Optional 1150/1250	--
		Over 1/2 to 1, Incl.	50	100	Optional 1150/1250	--
		Over 1 to 2, Incl.	100	200	Desirable 1150/1250	Yes
		Over 2 to 4, Incl.	200	300	Desirable 1150/1250	Yes
ASTM A356-75 Heavy-Walled Carbon and Low Alloy Steel Castings for Steam Turbines	Grade 1 Up to 0.25, Incl.	Up to 1, Incl.	Ambient, Above 10F	Ambient, Above 10F	Optional 1100/1250	--
		Over 1 to 2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 2 to 4, Incl.	150	250	Desirable 1100/1250	Yes
	Grade 1 0.26 - 0.30, Incl.	Up to 1/2, Incl.	Ambient, Above 10F	Ambient, Above 10F	Optional 1100/1250	--
		Over 1/2 to 1, Incl.	Ambient, Above 10F	Ambient, 100	Desirable 1100/1250	--
		Over 1 to 2, Incl.	100	200	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200	300	Desirable 1100/1250	Yes
	Grade 1 0.31 - 0.35, Incl.	Up to 1/2, Incl.	Ambient, Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	100	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	250	350	Desirable 1100/1250	Yes

Note:
1. Grades 2 thru 10 included in this specification are carbon-molybdenum or chromium-molybdenum grades. Welding recommendations for those grades given elsewhere in the table.

Steel Specification	For Carbon Range, %	For Thickness Range, Inch	Low-Hydrogen	Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
ASTM A486-74 Steel castings for highway service Note (2)	Up to 0.20, Incl.	Up to 2, Incl.	Ambient Above 10F	200	Optional 1100/1250	Yes Over 1 In.
		Over 2 to 4, Incl.	100	300	Optional 1100/1250	Yes
	0.21 - 0.25, Incl.	Up to 1, Incl.	100	300	Optional 1100/1250	--
		Over 1 to 2, Incl.	200	300	Optional 1100/1250	Yes
		Over 2 to 4, Incl.	250	350	Optional 1100/1250	Yes
	0.26 - 0.30, Incl.	Up to 1/2, Incl.	100	300	Optional 1100/1250	--
		Over 1/2 to 1, Incl	150	300	Optional 1100/1250	--
		Over 1 to 2, Incl.	250	350	Optional 1100/1250	Yes
		Over 2 to 4, Incl.	300	400	Desirable 1100/1250	Yes
	0.31 - 0.35. Inc.	Up to 1/2, Incl.	100	300	Optional 1100/1250	--
		Over 1/2 to 1, Incl.	200	350	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	400	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	350	450	Desirable 1100/1250	Yes

Notes:
1. Thickness refers to that at point of welding.
2. Welding conditions shown apply to Class 70 material. Class 90 and Class 120 material are low-alloy grades and welding conditions are dependent on chemical composition. Consult casting producer for welding recommendations or compare composition to nearest matching AISI specification for selecting welding conditions.

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --4

Steel Specification	For Carbon Range, %	For Thickness Range, Inch	Suggested Welding Conditions: Minimum Preheat and Interpass Temperature, °F: Low-Hydrogen	Minimum Preheat and Interpass Temperature, °F: Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
ASTM A487-76 Steel castings suitable for pressure service	1 N up to 0.20, Inc (1 Q - Use temperatures shown in parenthesis when given) Note (1)	Up to 1, Incl.	Ambient, Above 10F	100 (Ambient, Above 10F)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	Ambient, Above 10F	200 (100)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200 (100)	300 (200)	Desirable 1100/1250	Yes
	1 N 0.21 - 0.25, Incl. (1 Q - Use temperatures shown in parenthesis when given) Note (1)	Up to 1/2, Incl.	Ambient, Above 10F	100 (Ambient, Above 10F)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	Ambient, Above 10F	200 (100)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	100 (Ambient, Above 10F)	300 (200)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	250 (150)	350 (250)	Desirable 1100/1250	Yes
	1 N 0.26 - 0.30 Incl. (1 Q Use temperatures shown in parenthesis when given) Note (1)	Up to 1/2, Incl.	Ambient, Above 10F	200 (100)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	100 (Ambient, Above 10F)	300 (200)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200 (100)	300 (200)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300 (200)	400 (300)	Desirable 1100/1250	Yes
	2 N up to 0.20, Incl. (2 Q - Use temperatures shown in parenthesis when given)	Up to 1/2, Incl.	Ambient, Above 10F	100 (Ambient, Above 10F)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	Ambient, Above 10F	200 (100)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	100 (Ambient, Above 10F)	300 (200)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200 (100)	350 (250)	Desirable 1100/1250	Yes
	2N 0.21 - 0.25, Incl. (2 Q - Use temperatures shown in parenthesis when given)	Up to 1/2, Incl.	Ambient, Above 10F	200 (100)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	100 (Ambient, Above 10F)	300 (200)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200 (100)	300 (200)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300 (200)	400 (300)	Desirable 1100/1250	Yes
	2 N 0.26 - 0.30, Incl. (2 Q - Use temperatures shown in parenthesis when given)	Up to 1/2, Incl.	100 (Ambient, Above 10F)	300 (200)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	200 (100)	300 (200)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300 (200)	350 (250)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400 (300)	450 (350)	Desirable 1100/1250	Yes
	4N, 6N, 9N, 10N, up to 0.20, Incl. (4 Q, 4QA, 6Q, 9Q, 10 Q - Use temperatures shown in parenthesis when given)	Up to 1/2, Incl.	Ambient, Above 10F	200 (100)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	100 (Ambient, Above 10F)	300 (200)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200 (100)	300 (200)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300 (200)	400 (300)	Desirable 1100/1250	Yes
	4N, 6N, 9N, 10N, 0.21 - 0.25, Incl. (4Q, 4QA, 6Q, 9Q, 10Q - Use temperatures shown parenthesis)	Up to 1/2, Incl.	100 (Ambient, Above 10F)	300 (200)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	200 (100)	300 (200)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300 (200)	350 (250)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400 (300)	450 (350)	Desirable 1100/1250	Yes
	4N, 6N, 9N, 10N, 0.26 - 0.30, Incl. (4Q, 4QA, 6Q, 9Q, 10Q - Use temperatures shown in parenthesis)	Up to 1/2, Incl.	200 (100)	300 (200)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	300 (200)	350 (250)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400 (300)	450 (350)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	500 (400)	550 (450)	Desirable 1100/1250	Yes
	4N, 6N, 9N, 10N, 0.31 - 0.38, Incl. (4Q, 4QA, 6Q, 9Q, 10Q -Use temperatures shown in parenthesis)	Up to 1/2, Incl.	300 (200)	350 (250)	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	400 (300)	450 (350)	Desirable 1100/1250	--
		Over 1 to 2, Incl.	500 (400)	550 (450)	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	600 (500)	650 (550)	Desirable 1100/1250	Yes
	7 Q	Up to 1, Incl.	100	Not Recommended	Optional 1050/1100	--
		Over 1 to 2, Incl.	150	Not Recommended	Optional 1050/1100	Yes
		Over 2 to 4, Incl.	200	Not Recommended	Optional 1050/1100	Yes

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --5

Suggested Welding Conditions

Steel Specification	For Carbon Range, %	For Thickness Range, Inch Note (1)	Minimum Preheat and Interpass Temperature, °F Low-Hydrogen	Minimum Preheat and Interpass Temperature, °F Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F Note (2)	Peening May Be Necessary
ASTM A487-76 Steel Castings suitable for pressure service (Cont'd.)	8 N Up to 0.15, Incl. (8 Q - Use temperatures shown in parenthesis)	Up to 4, Incl.	400 (300)	450 (350)	Desirable 1300/1400	Yes Over 1 Inch
	8 N 0.16 - 0.20, Incl. (8 Q - Use temperatures shown in parenthesis)	Up to 4, Incl.	500 (400)	550 (450)	Desirable 1300/1400	Yes Over 1 Inch
	Notes: 1. Post-Weld Heat-Treatment of these grades of steel should be done with caution. 2. For welding and Post-Weld Heat-Treatment requirements for pressure vessels fabricated from certain grades of this steel refer to appropriate section of ASME Boiler and Pressure Vessel Code.					
ASTM A643-75 Steel castings, heavy walled, carbon and alloy for pressure vessels	Grade A Up to 0.20, Incl.	Up to 2, Incl.	100	250	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200	300	Desirable 1100/1250	Yes
	Grade A 0.21 - 0.25, Incl.	Up to 2, Incl.	200	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300	400	Desirable 1100/1250	Yes
	Grade B Up to 0.20, Incl.	Up to 2, Incl.	300	450	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400	500	Desirable 1100/1250	Yes
	Grade B 0.21 - 0.25, Incl.	Up to 2, Incl.	400	450	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400	500	Desirable 1100/1250	Yes
	Grade D Up to 0.20, Incl.	Up to 2, Incl.	150	Not Recommended	Desirable 1100/1150	Yes
		Over 2 to 4, Incl.	300	Not Recommended	Desirable 1100/1150	Yes
	Grade C of this specification is a Chromium-Molybdenum steel. Welding recommendations are, therefore, given with the Chromium-Molybdenum (2-1/4Cr - 1Mo) steels given elsewhere in this table.					
	Notes: 1. Minimum specification thickness 2 inches. 2. For welding and Post-Weld Heat-Treatment requirements for pressure vessels fabricated from this material, refer to appropriate section of ASTM Boiler and Pressure Vessel Code.					

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --6

Steel Designation	For Carbon Range, %	Suggested Welding Conditions: For Thickness Range, Inch	Minimum Preheat and Interpass Temperature, °F: Low-Hydrogen	Minimum Preheat and Interpass Temperature, °F: Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
AISI-SAE 1010 1011 1012 1013	Within Specification	Up to 2, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	150	Optional 1100/1250	Yes
AISI-SAE 1015 1016	Within Specification	Up to 2, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	200	Optional 1100/1250	Yes
AISI 1017 1018 1019	Within Specification	Up to 2, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	150	Optional 1100/1250	Yes
AISI-SAE 1020 1021 1022 1023	Within Specification	Up to 2, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 2 to 4, Incl.	200	300	Optional 1100/1250	Yes
AISI-SAE 1024 1027	0.18 - 0.25, Incl.	Up to 1, Incl.	Ambient Above 10F	100	Optional 1100/1250	--
		Over 1 to 2, Incl.	100	200	Optional 1100/1250	--
		Over 2 to 4, Incl.	200	300	Optional 1100/1250	Yes
	0.25 - 0.29, Incl.	Up to 1/2, Incl.	50	150	Optional 1100/1250	--
		Over 1/2 to 1, Incl	150	300	Optional 1100/1250	--
		Over 1 to 2, Incl.	250	300	Optional 1100/1250	--
		Over 2 to 4, Incl.	300	350	Optional 1100/1250	Yes
AISI-SAE 1025 1026	Within Specification	Up to 1, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 1 to 2, Incl.	Ambient Above 10F	100	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	200	Optional 1100/1250	Yes
AISI-SAE 1029 1030	0.25 - 0.30, Incl.	Up to 1, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1 to 2, Incl.	Ambient Above 10F	200	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	200	300	Desirable 1100/1250	Yes
	0.31 - 0.34, Incl.	Up to 1/2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1, Inc.	Ambient Above 10F	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	100	200	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	250	350	Desirable 1100/1250	Yes
AISI-SAE 1035 1037	Within Specification	Up to 1/2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1, Inc.	100	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300	400	Desirable 1100/1250	Yes
AISI-SAE 1036 1041	0.30 - 0.35, Incl.	Up to 1/2, Incl.	100	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	150	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	250	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300	350	Desirable 1100/1250	Yes
	0.36 - 0.40, Incl.	Up to 1/2, Incl.	150	200	Desirable 1100/1250	--
		Over 1/2 to 1, Inc.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	350	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	350	400	Desirable 1100/1250	Yes
	0.41 - 0.44, Incl.	Up to 1/2, Incl.	200	300	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	300	350	Desirable 1100/1250	--
		Over 1 to 2, Incl.	350	400	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400	450	Desirable 1100/1250	Yes

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --7

Steel Designation	For Carbon Range, %	Suggested Welding Conditions For Thickness Range, Inch	Minimum Preheat and Interpass Temperature, °F Low-Hydrogen	 Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
AISI-SAE 1038 1039 1040	0.34 - 0.40, Incl.	Up to 1/2, Incl.	100	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300	400	Desirable 1100/1250	Yes
	0.41 - 0.44, Incl.	Up to 1/2, Incl.	150	250	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	350	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400	450	Desirable 1100/1250	Yes
AISI-SAE 1042 1043	Within Specification	Up to 1/2, Incl.	200	300	Desirable 1100/1250	Yes
		Over 1/2 to 1, Incl.	250	300	Desirable 1100/1250	Yes
		Over 1 to 2, Incl.	300	350	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400	450	Desirable 1100/1250	Yes
AISI-SAE 1044 1045 1046	Within Specification	Up to 1/2, Incl.	300	350	Desirable 1100/1250	Yes
		Over 1/2 to 4,Incl.	400	450	Desirable 1100/1250	Yes
AISI-SAE 1048 1049 1050 1052 1053	0.43 - 0.50, Incl.	Up to 1/2, Inc.	300	350	Desirable 1100/1250	Yes
		Over 1/2 to 4,Incl.	400	450	Desirable 1100/1250	Yes
AISI-SAE 1108 1109 1110	Within Specification	Up to 2, Incl.	Ambient Above 10F	Not Recommended	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	Not Recommended	Optional 1100/1250	Yes
AISI-SAE 1116 1117 1118 1119	Within Specification	Up to 1, Incl.	Ambient Above 10F	Not Recommended	Optional 1100/1250	--
		Over 1 to 4,Incl.	200	Not Recommended	Optional 1100/1250	Yes
AISI-SAE 1132 1137 1139 1140 1141 1144 1145 1146 1151	0.27 - 0.30, Incl.	Up to 1/2, Incl.	50	Not Recommended	Optional 1100/1250	--
		Over 1/2 to 1,Incl.	100	Not Recommended	Desirable 1100/1250	--
		Over 1 to 2,Incl.	200	Not Recommended	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	250	Not Recommended	Desirable 1100/1250	Yes
	0.31 - 0.35, Incl.	Up to 1/2, Incl.	100	Not Recommended	Desirable 1100/1250	--
		Over 1/2 to 1, Incl.	150	Not Recommended	Desirable 1100/1250	--
		Over 1 to 2, Incl.	250	Not Recommended	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300	Not Recommended	Desirable 1100/1250	Yes
	0.36 - 0.40, Incl.	Up to 1/2, Incl.	150	Not Recommended	Desirable 1100/1250	--
		Over 1/2 to 1, Inc.	200	Not Recommended	Desirable 1100/1250	--
		Over 1 to 4, Incl.	300	Not Recommended	Desirable 1100/1250	Yes
	0.41 - 0.45, Incl.	Up to 1/2, Incl.	200	Not Recommended	Desirable 1100/1250	--
		Over 1/2 to 1,Inc.	300	Not Recommended	Desirable 1100/125	--
		Over 1 to 4, Incl.	350	Not Recommended	Desirable 1100/1250	Yes
	0.45 - 0.50, Incl.	Up to 1/2, Incl.	300	Not Recommended	Desirable 1100/1250	--
		Over 1/2 to 1,Inc.	400	Not Recommended	Desirable 1100/1250	--
		Over 1 to 4, Incl.	450	Not Recommended	Desirable 1100/1250	Yes
AISI-SAE 1211 1212 1213 1215 B1111 B1112 B1113	Within Specification	Up to 2, Incl.	Ambient Above 10F	Not Recommended	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	Not Recommended	Optional 1100/1250	Yes

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --8

Suggested Welding Conditions

Steel Designation	For Carbon Range, %	For Thickness Range, Inch	Minimum Preheat and Interpass Temperature, °F		Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
			Low-Hydrogen	Other Than Low-Hydrogen		
AISI-SAE 12L13 12L14	Within Specification	Up to 2, Incl.	Ambient Above 10F	Not Recommended	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	Not Recommended	Optional 1100/1250	Yes
	Note: Due to lead content, manufacturing operations involving elevated temperatures in the range of those encountered in gas cutting or welding should be carried out under adequate ventilation.					
AISI-SAE 1330 1335 1340 1345	0.27 - 0.33, Incl.	Up to 1/2, Incl.	250	Not Recommended	Desirable 1025/1050	--
		Over 1/2 to 1.Incl.	300	Not Recommended	Desirable 1025/1050	--
		Over 1 to 2, Incl.	350	Not Rcecommended	Desirable 1025/1050	Yes
	0.33 - 0.38, Incl.	Up to 1/2, Incl.	300	Not Recommended	Desirable 1025/1050	--
		Over 1/2 to 1,Incl.	400	Not Recommended	Desirable 1025/1050	--
		Over 1 to 2, Incl.	400	Not Recommended	Desirable 1025/1050	Yes
	0.38 - 0.43, Incl.	Up to 1/2, Incl.	350	Not Recommended	Desirable 1025/1050	--
		Over 1/2 to 1,Incl.	450	Not Recommended	Desirable 1025/1050	--
		Over 1 to 2, Incl.	550 Note (1)	Not Recommended	Desirable 1025/1050	Yes
	0.43 - 0.49, Incl.	Up to 1/2, Incl.	400	Not Recommended	Desirable 1025/1050	--
		Over 1/2 to 1,Incl.	500	Not Recommended	Desirable 1025/1050	--
		Over 1 to 2, Incl.	600 Note (1)	Not Recommended	Desirable 1025/1050	Yes
	Note: 1. Hold at temperature for one hour after welding completed.					
AISI-SAE 1513 1518 1522 1525	Up to 0.20, Incl.	Up to 1, Incl.	Ambient Above 10F	Ambient Above 10F	Optional 1100/1250	--
		Over 1 to 2,Incl.	Ambient Above 10F	100	Optional 1100/1250	--
		Over 2 to 4, Incl.	100	200	Optional 1100/1250	Yes
	0.21 to 0.25, Incl.	Up to 1, Incl.	Ambient Above 10F	100	Optional 1100/1250	--
		Over 1 to 2, Incl.	100	200	Optional 1100/1250	--
		Over 2 to 4, Incl.	200	300	Optional 1100/1250	Yes
	0.26 to 0.29, Incl.	Up to 1/2, Incl.	50	150	Optional 1100/1250	--
		Over 1/2 to 1,Incl.	150	300	Optional 1100/1250	--
		Over 1 to 2, Incl.	250	300	Optional 1100/1250	--
		Over 2 to 4, Incl.	300	350	Optional 1100/1250	Yes
AISI-SAE 1524 1526 1527	Up to 0.25, Incl.	Up to 1, Incl.	50	100	Optional 1100/1250	--
		Over 1 to 2, Incl.	100	200	Optional 1100/1250	--
		Over 2 to 4, Incl.	200	300	Optional 1100/1250	Yes
	0.26 - 0.29, Incl.	Up to 1, Incl.	150	250	Desirable 1100/1250	--
		Over 1 to 2, Incl.	250	300	Desirable 1100/1250	--
		Over 2 to 4, Incl.	300	350	Desirable 1100/1250	Yes
AISI-SAE 1536 1541	Up to 0.35, Incl.	Up to 1/2, Incl.	100	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	150	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	250	300	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	300	350	Desirable 1100/1250	Yes
	0.36 to 0.40, Incl.	Up to 1/2, Incl.	150	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	350	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	350	400	Desirable 1100/1250	Yes
	0.41 to 0.44, Incl.	Up to 1/2, Incl.	200	300	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	300	350	Desirable 1100/1250	--
		Over 1 to 2, Incl.	350	400	Desirable 1100/1250	Yes
		Over 2 to 4, Incl.	400	450	Desirable 1100/1250	Yes

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35) --9.

Steel Designation	For Carbon Range, %	For Thickness Range, Inch	Suggested Welding Conditions: Minimum Preheat and Interpass Temperature, °F — Low-Hydrogen	Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
AISI-SAE 1547 1548	0.43 to 0.52, Incl.	Up to 1/2, Incl.	300	350	Desirable 1100/1250	--
		Over 1/2 to 4, Inc.	400	450	Desirable 1100/1250	Yes
AISI-SAE 4012	0.09 - 0.14, Incl.	Up to 1, Incl.	Ambient Above 10F	Ambient Above 10F	Desirable 1100/1250	--
		Over 1 to 2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	Yes
AISI-SAE 4023 4024 4027 4028	0.20 - 0.25, Incl.	Up to 1/2, Inc.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1, Inc.	100	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	250	Desirable 1100/1250	Yes
	0.26 - 0.30, Incl.	Up to 1/2, Incl.	Ambient Above 10F	150	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	150	250	Desirable 1100/1250	--
		Over 1 to 2, Incl.	250	300	Desirable 1100/1250	Yes
AISI-SAE 4032	0.30 - 0.35, Incl.	Up to 1/2, Incl.	50	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	175	275	Desirable 1100/1250	--
		Over 1 to 2, Incl.	275	325	Desirable 1100/1250	Yes
AISI-SAE 4037	0.35 - 0.40, Incl.	Up to 1/2, Incl.	100	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	350	Desirable 1100/1250	Yes
AISI-SAE 4042	0.40 - 0.45, Incl.	Up to 1/2, Incl.	150	250	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	250	400	Desirable 1100/1250	--
		Over 1 to 2, Incl.	350	500	Desirable 1100/1250	Yes
AISI-SAE 4047	0.45 - 0.50, Incl.	Up to 1/2, Incl.	200	300	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	300	500	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400	600	Desirable 1100/1250	Yes
AISI-SAE 4118	0.17 - 0.23, Incl.	Up to 1/2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	100	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	300	Desirable 1100/1250	Yes
AISI-SAE 4130	0.27 - 0.33, Incl.	Up to 1/2, Incl.	300	400	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	400	500	Desirable 1100/1250	--
		Over 1 to 2, Incl.	450	550	Desirable 1100/1250	Yes
AISI-SAE 4135 4137 4140 4142 4145 4147 4150	0.32 - 0.40, Incl.	Up to 1/2, Incl.	350	450	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	450	550	Desirable 1100/1250	--
		Over 1 to 2, Incl.	500	600 Note (1)	Desirable 1100/1250	Yes
	0.41 - 0.45, Incl.	Up to 1/2, Incl.	400	500	Desirable 1100/1250	--
		Over 1/2 to 2, Incl	550	600 Note (1)	Desirable 1100/1250	Yes
	0.46 - 0.50, Incl.	Up to 1/2, Incl.	450	550	Desirable 1100/1250	--
		Over 1/2 to 2,Incl.	600	700 Note (1)	Desirable 1100/1250	Yes
	Note: 1. Hold at temperature one hour after welding completed.					
AISI-SAE 4320	0.17 - 0.22, Incl.	Up to 1/2, Incl.	200	300	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	300	400	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400	500	Desirable 1100/1250	Yes
AISI-SAE 4340 E4340	0.36 - 0.44, Incl.	Up to 2, Incl.	550	600 Note (1)	Desirable 1100/1250	Yes
	Note: 1. Hold at temperature one hour after welding completed.					

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35). --11

Suggested Welding Conditions

Steel Designation	For Carbon Range, %	For Thickness Range, Inch	Minimum Preheat and Interpass Temperature, °F Low-Hydrogen	Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
AISI-SAE 6150	0.46 - 0.50, Incl.	Up to 1, Incl.	300	500	Desirable 1100/1250 Note (1)	--
		Over 1 to 4, Incl.	450	600	Desirable 1100/1250 Note (1)	Yes
	Note: 1. Post-Weld Heat-Treatment of this grade of steel should be done with caution.					
AISI-SAE 8115	0.13 - 0.18, Incl.	Up to 2, Incl.	Ambient Above 10F	200	Optional 1100/1250	--
AISI-SAE 8615 8617 8620 8622 8625 8627 8630	Up to 0.20, Incl.	Up to 1/2, Incl.	Ambient Above 10F	150	Optional 1100/1250	--
		Over 1/2 to 2,Incl.	100	300	Optional 1100/1250	Yes
	0.21 - 0.25, Incl.	Up to 1/2, Incl.	Ambient Above 10F	200	Optional 1100/1250	--
		Over 1/2 to 1,Incl.	100	300	Optional 1100/1250	--
		Over 1 to 2, Incl.	200	350	Optional 1100/1250	Yes
	0.26 - 0.33, Incl.	Up to 1/2, Incl.	200	300	Optional 1100/1250	--
		Over 1/2 to 1,Incl.	250	350	Optional 1100/1250	--
		Over 1 to 2, Incl.	300	400	Optional 1100/1250	Yes
AISI-SAE 8637 8640 8642 8645	0.35 - 0.40, Incl.	Up to 1/2, Incl.	200	400	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	300	450	Desirable 1100/1250	--
		Over 1 to 2, Incl.	350	500	Desirable 1100/1250	Yes
	0.41 - 0.45, Incl.	Up to 1/2, Incl.	250	450	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	350	500	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400	550	Desirable 1100/1250	Yes
	0.45 - 0.48, Incl.	Up to 1/2, Incl.	300	500	Desirable 1100/1250	--
		Over 1/2 to 1,Incl	350	550	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400	600	Desirable 1100/1250	Yes
AISI-SAE 8720	0.18 - 0.23 Incl.	Up to 1/2, Incl.	Ambient Above 10F	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	100	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	350	Desirable 1100/1250	Yes
AISI-SAE 8742	0.38 - 0.46 Incl.	Up to 1, Incl.	300	500	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400	600	Desirable 1100/1250	Yes
AISI-SAE 8822	0.20 - 0.25 Incl.	Up to 1/2, Incl.	150	300	Optional 1100/1250	--
		Over 1/2 to 2,Incl.	200	400	Desirable 1100/1250	Yes Over 1 Inch
AISI-SAE E9310	Within Specification	Up to 1/2, Incl.	Ambient Above 10F	Not Recommended	Optional 1100/1150	--
		Over 1/2 to 1,Incl.	100	Not Recommended	Optional 1100/1150	--
		Over 1 to 2, Incl.	150	Not Recommended	Optional 1100/1150	Yes

Table III-4: Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications (35).--10

Steel Designation	For Carbon Range, %	For Thickness Range, Inch	Suggested Welding Conditions: Minimum Preheat and Interpass Temperature, °F: Low-Hydrogen	Other Than Low-Hydrogen	Post-Weld Heat-Treatment Range, °F	Peening May Be Necessary
AISI-SAE 4419 4422 4427	0.18 - 0.24, Incl.	Up to 1/2, Incl.	Ambient Above 10F	100	Required 1200/1350	--
		Over 1/2 to 1,Incl.	100	200	Required 1200/1350	--
		Over 1 to 2, Incl.	200	300	Required 1200/1350	Yes
	0.25 - 0.29, Incl.	Up to 1/2, Incl.	100	200	Required 1200/1350	--
		Over 1/2 to 1,Incl.	200	300	Required 1200/1350	--
		Over 1 to 2, Incl.	300	400	Required 1200/1350	Yes
AISI-SAE 4615 4617 4620 4626	Within Specification	Up to 1/2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	250	350	Desirable 1100/1250	Yes
AISI-SAE 4621	0.18 - 0.23, Incl.	Up to 1/2, Incl.	100	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	400	Desirable 1100/1250	Yes
AISI-SAE 4718	0.16 - 0.21, Incl.	Up to 1/2, Incl.	100	300	Required 1150/1300	--
		Over 1/2 to 2,Incl.	250	400	Required 1150/1300	Yes
AISI-SAE 4720	0.17 - 0.22, Incl.	Up to 1/2, Incl.	Ambient Above 10F	200	Desirable 1100/1250	--
		Over 1/2 to 2,Incl.	200	300	Desirable 1100/1250	Yes
AISI-SAE 4815 4817	Within Specification	Up to 1/2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	100	200	Desirable 1100/1250	--
		Over 1 to 2, Incl.	200	300	Desirable 1100/1250	Yes
AISI-SAE 4820	0.18 - 0.23, Incl.	Up to 1/2, Incl.	100	200	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	300	350	Desirable 1100/1250	Yes
AISI-SAE 5015	0.12 - 0.17, Incl.	Up to 2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
AISI-SAE 5046	0.43 - 0.48, Incl.	Up to 1/2, Incl.	300	400	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	350	450	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400	500	Desirable 1100/1250	Yes
AISI-SAE 5115	0.13 - 0.18, Incl.	Up to 1/2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1 to 2, Incl.	100	200	Desirable 1100/1250	--
AISI-SAE 5120	0.17 - 0.22, Incl.	Up to 1/2, Incl.	Ambient Above 10F	100	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	200	300	Desirable 1100/1250	--
		Over 1 to 2, Incl.	250	300	Desirable 1100/1250	Yes
AISI-SAE 5130 5132 5135	Within Specification	Up to 1/2, Incl.	200	300	Desirable 1100/1250	--
		Over 1/2 to 1,Incl.	300	400	Desirable 1100/1250	--
		Over 1 to 2, Incl.	400	500	Desirable 1100/1250	Yes
AISI-SAE 5140	0.38 - 0.43, Incl.	Up to 1/2, Incl.	300	400	Desirable 1100/1250	--
		Over 1/2 to 2,Incl.	400	500	Desirable 1100/1250	Yes
AISI-SAE 5145 5147 5150	0.43 - 0.50, Incl.	Up to 1/2, Incl.	350	450	Desirable 1100/1250	--
		Over 1/2 to 2,Incl.	450	550	Desirable 1100/1250	Yes
AISI-SAE 6118	0.16 - 0.21, Incl.	Up to 1, Incl.	Ambient Above 10F	100	Desirable 1100/1250 Note (1)	--
		Over 1 to 2, Incl.	100	200	Desirable 1100/1250 Note (1)	Yes

Note:
1. Post-Weld Heat-Treatment of this grade of steel should be done with caution.

SECTION IV: CAST-WELD FABRICATION

General Considerations

The welding techniques, electrode and flux selection, preheating and postheating procedures discussed in the previous sections can be employed for cast-weld fabrication as well as repair welding (3). In some cases cast-weld fabrication techniques are preferable to producing a very large or complex part as a one-piece casting. In some cases, the foundry lacks the melting, pouring or handling capacity for the large castings; in other cases, even when the size can be managed, sound castings in some configurations are difficult, even impossible to achieve because of coring, feeding, and hot-tearing problems.

Cast-weld fabrication is a logical extension of the casting process and is a practical and effective method for joining simple castings to make complex shapes. It is also used to join components of various compositions and properties or those processed by different methods, such as castings, forgings, plates, bars, and tubes. Cast-weld fabrication combines the advantages of casting and welding and eliminates some of the limitations of each. Overall advantages include greater flexibility of design, assembly of parts having different physical and chemical properties, increased strength, reduced machining and casting costs, and reduced weight (3).

Designs and Joint Preparation

Cast-weld construction can be used for many designs and configurations. Adding appendages to large cast parts and producing left-hand and right-hand components are among the simplest applications. The process is being used to an increasing extent for piping and auxiliary equipment in high-pressure, high-temperature, and nuclear-power service. Cast-weld construction also permits joining light sections to heavy sections that would be difficult to cast. One widely employed and significant use is to extend the maximum size of a component that can be produced by conventional casting equipment. Other applications involve combining different metals; for example, cladding or overlay weld deposits or separately cast sections of heat, corrosion or erosion resistant materials are welded to castings of lower alloy composition to provide special properties at selected areas (3).

Castings produced for cast-weld construction can incorporate self-locating devices to facilitate accurate assembly and tapered or "Veed out" areas into which the weld is deposited. The conventional designs of weld grooves and weld preparation as described in Section III are utilized for cast-weld construction in addition to repair welding with as much of the grooves, tapers and locating devices cast into the parts as feasible. These designs both improve quality and reduce cost. Other cost savings result from reduced coring requirements and easier machining operations

Horizontal position welding is employed more widely in cast-weld fabrications because the large sizes and awkward shapes make manipulation difficult. The weld preparation shown in Figure IV-1a has been utilized successfully for this type of position with the smaller casting located on top and no movement of the assembly during welding. In this case the gas tungsten-arc welding process was used to deposit the root pass of each butt weld. The use of the backing strips shown in Section III was avoided in this manner. A typical welding sequence for this weld (which was also employed as an ASME Section IX welder qualification test) is illustrated in Figure IV-1b.

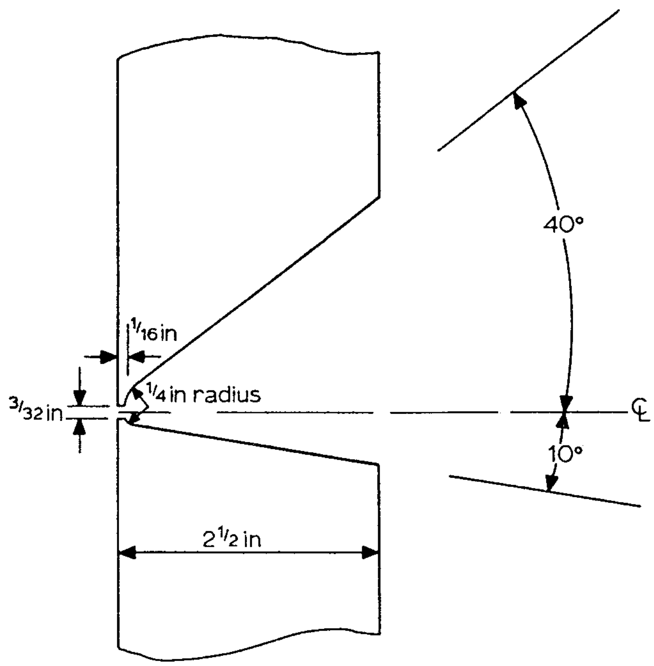
Joining of parts in cast-weld fabrication follows standard welding methods. The weld area should be free from defective metal; when required, chipping, grinding, or arc or flame-gouging are used. The standard smooth tapering of the sides of the weld toward the bottom of the groove is required for all except special welding procedures such as electroslag. Sharp inside corners and narrow grooves are apt to produce cracks, slag inclusions, or lack of penetration. Joining of thin and thick sections should be avoided, and weld seams should be located away from corners.

Grooves of the required shape are generally cast at the edges of parts to be joined to avoid the cost of removing the metal. The castings are also produced with matching contours and assembly location points to facilitate correct positioning of mating parts.

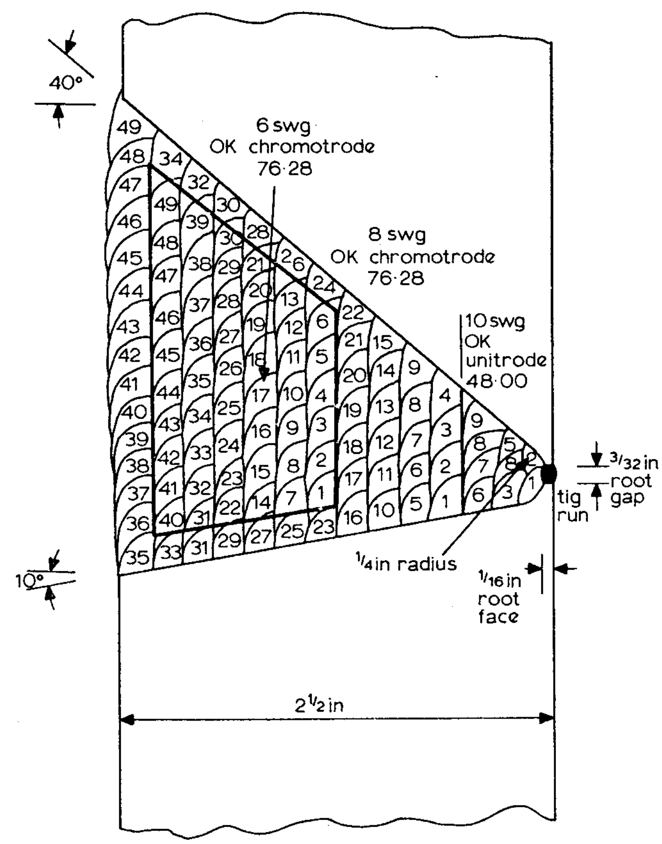
The cost of welding also deserves attention in the design stage. Manual, semiautomatic or automatic procedures are selected, depending on number of parts and contour of welds. Large production runs involving assemblies which combine centrifugally and statically cast parts are automated to as great an extent as permitted by the location, orientation, and accessibility of the weld grooves.

Welding Methods and Materials

All conventional welding methods can be used for cast-weld fabrication. The choice depends on composition of the metals and the size and configuration of the structure. Cast carbon and low, medium, and high-alloy steels respond to welding processes the same as wrought steels of similar compositions. Likewise, preheat, post-heat, and joint preparation requirements and joint backup materials are similar.



a. Horizontal-vertical butt welding profile.



b. Cross-section of a typical welding sequence (also employed as welder qualification test).

Figure IV-1 Horizontal Weld Groove and Welding Sequence Used in Cast-Weld Fabrication in the Horizontal Welding Position (39).

Welding methods that have been successfully employed for cast-weld construction include manual arc welding with coated electrodes; and automatic and semiautomatic welding with gas-metal-arc, flux-cored wire, and submerged-arc and resistance welding. Fabrication of large, heavy-section castings is often done by the electroslag process.

Manual, coated-electrode welding is generally the most economical process for welds in thin sections for overlays. Semiautomatic and automatic gas-metal-arc and flux-cored arc-welding methods are employed for more numerous or longer welds in thin and medium-thickness parts. The submerged-arc process deposits weld metal more rapidly but is limited to down-hand welding. The electroslag process is most useful for producing vertical joints in very heavy sections. Resistance welding is utilized to join simple shapes, where sufficient quantities are involved to warrant the setup costs.

As in other material applications, statically cast, centrifugally cast, forged and rolled forms are selected according to service requirements and economics for obtaining the needed shape. Carbon and low-alloy steels - the most widely used - are welded with E60XX to E120XX electrodes, depending on strength requirements of the application and strength of the base component. Heat and corrosion resistant parts can also be assembled by cast-weld fabrication. The preheat and postheating requirements follow those described in Section III. Numerous examples of cast weld fabrication are described in References 3 and 40.

SECTION V: WELDER AND PROCESS QUALIFICATION

Specifications Employed

The ASTM Specification A488 or the ASME Boiler and Pressure Code Section IX provide a proven basis for a qualified welding procedure. These specifications are generally recognized and contain the essential elements for welder qualification. Even in cases where casting specifications do not require such qualification, it is advantageous to follow such procedures. Welding is a necessary part of the steel casting business. It is used for repairing castings after the defects are removed, cast-weld fabrication to simplify the casting procedure, or even to upgrade castings to meet stringent soundness levels by welding rather than using extensive padding and chills. Since welding is required to make steel castings to meet the variety of specifications, the welding process should be controlled as the casting process is controlled.

Welding Procedure

A welding procedure comprises three separate parts - a written welding procedure, a qualification of that procedure, and a performance test or qualification of the welder or operator indicating his ability to use that procedure (41). The written welding procedure consists of instructions to the welder. The weld quality depends on the variables which are in the written instructions. For this reason, the written procedure must be tested under actual shop conditions to determine that it is capable of producing sound welds insofar as the preheat, postheat, current and voltage ranges are concerned. Evidence that this has been accomplished is recorded in the qualification document. After the written procedure has been tested and found to be correct, a determination is made that each welder is capable of following that procedure. For this reason, the code requires that every welder be qualified by his current employer even though he may have been qualified to weld the same material at another employer. Constant auditing to determine that procedures are being followed is an essential part of the procedure (41). Welder qualification can be performed on rolled steel plate but actual qualification of a procedure shall be on cast steel plate.

The written welding procedure must necessarily provide limits on all the significant variables involved in welding a material. As a basis for designing such a procedure ASTM A488 or Section IX of the ASME Boiler and Pressure Vessel Code is suitable for any casting repair or fabrication and is required by ASTM and ASME specifications. The addition of a few tests will also make it suitable for military use under MIL-S-00248. These specifications provide a form which covers all the variables. While it is not necessary to use this form, it will eliminate the possibility of overlooking some important detail. A written procedure in narrative form is frequently employed because it is easier for the welders to understand (41).

Once the welding procedure has been prepared, it must be tested or qualified. This is done by simply making a weld using the procedure, and performing the required tests. Again, it is suggested that Section IX or ASTM A488 be used as a guide. Completion of the forms completes the qualification. The welding procedure qualification test establishes the ability of the welding procedure to deposit sound metal. While welder ability is a factor, the technique used is most important. The qualification indicates whether the preheat is high enough to prevent underbead cracking and establishes the ability of the combination of electrode, interpass temperature and post-weld heat treatment to meet minimum tensile and impact requirements as specified in the basic specification. The bend bars required by the qualification verify the absence of a metallurgical notch due to hardness differentials between the weld, HAZ, and parent metal.

The qualification test of the procedure should allow for ranges of the factors specified so that difficulties are not encountered during production welding. A procedure which is qualified with the variables held on the safe side of the limits may not assure good welds if production welding is subsequently performed with the variables on the unsafe side. In the welding of the hardenable grades which require preheating, the qualification of the procedure should be performed with plates whose chemical analysis is on the high side of the range using a preheat temperature on the low side of the range. Similarly, for those grades where the HAZ tends to be very hard, the post-weld heat treatment temperature should be held near the low side of the stress relief or tempering range when heat treating the plate from which the bend bars are to be taken. If the ability of the electrode to respond to higher post-weld treatments is doubtful, a section of the weld may be given an additional heat treatment on the high side of the stress relief or tempering range and checked for hardness to assure that the weld will always meet the tensile requirements (41). Rapid solidification and cooling of the weld will increase the hardness of the deposited weld metal. Harder weld deposits will result under these conditions and therefore a higher hardness after the post-weld heat treatments. A rapid solidification or effective quench of the weld metal can be obtained by the use of external heat sinks when depositing the weld.

Other Considerations

As added safeguards for a welding procedure voltmeters and ammeters that are checked regularly for accuracy should be located on the machine. A written control for electrodes is also required, including the handling or drying treatments previously discussed. Issuing only limited quantities of one type of electrode for each manual welding station will assist in preventing the use of incorrect electrodes and reduce the opportunity for moisture pickup. Frequent checks of weld quality by x-ray examination and magnetic particle inspection, even when the specifications do not require this, insure that the welds are sound and free of surface cracks. Some code requirements specify the chemical compositions of the weld deposit. In these cases, it may well be desirable to check the deposited composition of each lot of electrodes before their use.

In addition to following the specification for each casting, it is necessary to review the service and processing requirements of the casting that is being repaired or fabricated. These requirements are usually part of the purchase order. However, special considerations such as surface hardening of the casting, low temperature service and corrosive environments including possible stress corrosion cracking conditions could well alter the welding process. These factors have to be evaluated before that process is established to insure an acceptably welded casting (41).

SECTION VI: REFERENCES

1. Schaffer, George. "Welding", American Machinist, September 1977, Special Report 698.

2. Wallace, J.F., "A Review of Welding Cast Steels and Its Effects on Fatigue and Toughness Properties", Steel Founders' Society of America, December, 1979.

3. Wallace, J.F., "Redesigning for Cast-Weld Fabrication", Machine Design, May 4, 1972, Vol. 44, No. 11, p. 95-99.

4. Welding Handbook, Vol. 2, Welding Processes: Gas, Arc and Resistance, 6th Ed., American Welding Society, New York, 1969, p. 24.6.

5. Welding Handbook, Vol. 3, Part B. Welding, Cutting and Related Processes, 6th Ed., American Welding Society, New York, 1971, p. 58.28.

6. Campbell, H.C., "Revolution in Welding", Metals Review, July, 1966, Vol. 39, No. 7.

7. Brosholen, A., Skaug, E., Visser, J., "Electroslag Welding of Large Castings for Ship Construction", The Welding Journal, August, 1977, Vol. 56, No. 8, p. 28.

8. Donovan, W.P., "The Economic Application of Flux Cored Wire Welding", Steel Foundry Facts, March 1977, No. 320, p. 9-15.

9. Hinkel, J.E., "Innershield Welding of Steel Castings", Steel Foundry Facts, February 1976, No. 316, p. 42-45.

10. Schmidt, W.F., "Wire Welding for Casting Repair", Steel Foundry Facts, February 1976, No. 316, p. 46-47.

11. Kimble, W.A., "CO_2 Welding for Casting Repair", Steel Foundry Facts, June 1961, No. 217, p. 5-7.

12. Heffner, R.R., and Huntman, G.W., "Semiautomatic Submerged Arc Welding", Steel Foundry Facts, March 1977, No. 320, p. 6-9.

13. AWS A5.1-69, Specification for Mild Steel Covered Arc-Welding Electrodes, American Welding Society, 1969.

14. AWS A5.5-69, Specification for Low Alloy Steel Covered Arc-Welding Electrodes, American Welding Society, 1969.

15. AWS A5.17-76, Specification for Bare Carbon Steel Electrodes and Fluxes for Submerged Arc Welding, American Welding Society, 1976.

16. AWS A5.18-69, Specification for Mild Steel Electrodes for Gas Metal-Arc Welding, American Welding Society, 1969.

17. AWS A5.20-69, Specification for Mild Steel Electrodes for Flux-Cored Arc Welding, American Welding Society, 1969.

18. AWS A5.23-77, Specification for Bare Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding, American Welding Society, 1976.

19. AWS A5.25-78, Specification for Consumables Used for Electroslag Welding of Carbon and High Strength Low Alloy Steels, American Welding Society, 1978.

20. Linnert, G.E., Welding Metallurgy, Vol. 2, American Welding Society, New York, 1967.

21. Kammer, P.A., and Martin, D.C., "Welding High Strength Steels", DMIC Report 229, July 15, 1966.

22. Genung, D.J., "Some Practical Aspects of Repair Welding High Hardenability Steel Castings", Steel Foundry Facts, June 1961, No. 217, p. 8-10.

23. Welding and Brazing of Carbon Steels, Book 1 Arc Welding, ASM, 1976.

24. Selecting Arc Welding Electrodes for Mild and Low Alloy Steels (Data Sheet), Metal Progress, November 1974, Vol. 106, No. 6, p. 62-63.

25. AWS A5.0-78, Filler Metal Comparison Charts, American Welding Society, 1978.

26. Melilli, A.S., Biron, R.H., "Preparation, Preheat and Postheat Considerations for Welding of Steel Castings", Transactions of the American Foundrymen's Society, May 1975, Vol. 83, p. 429-436.

27. Panter, D., "Air Carbon Arc Gouging", Welding Journal, May 1977, Vol. 56, No. 5, p. 32-37.

28. AWS C5.3-74, "Recommended Practices for Air Carbon Arc Gouging and Cutting", American Welding Society, 1974.

29. The Procedure Handbook of Arc Welding, The Lincoln Electric Company, 12th Ed., p. 13.5-1 to 13.5-4.

30. Christensen, L.J., "Air Carbon Arc Gouging", The Welding Journal, December 1973, Vol. 52, No. 12, p. 782-791.

31. Levichenkov, V.I., "Surface Carburization in the Arc-Air Cutting of Cast Iron and Steel", Russian Casting Production, p. 346-7.

32. Ridal, E.J., "Welding Carbon and Low Alloy Steel Castings", (Proceedings of an International Conference) Welding of Castings, Bradford, England, September 1976, Vol. 1, p. 183-198.

33. Middleton, T., "Fettling Steel Castings with the Arcair Process", (Proceedings of an International Conference) Welding of Castings, Bradford, England, September 1976, Vol. 1, p. 67-75.

34. Welding Handbook, Vol. 1, Fundamentals of Welding, 6th Ed., American Welding Society, New York, 1968.

35. Ott, C.W., Snyder, D.J., "Suggested Arc Welding Procedures for Steels Meeting Standard Specifications", Welding Research Council Bulletin, May 1978, Revised Bulletin 191.

36. Welding of Steel Castings, Steel Castings Research and Trade Association, 1972.

37. Blodgett, O.W., "Distortion...Minimize...Welding Procedures...", Lincoln Electric Company, Pamphlet G261.

38. Irving, R.R., "Vibratory Stress Relief - Black Magic or Cure-All", Iron Age, April 17, 1978, p. 56-57.

39. Cousar, Robert, "Cast-Weld Assembly Development to Meet Increasing Engineering Requirements", British Foundryman, October 1976, p. 258-264.

40. Johnston, R.B., Welding of Castings, Vol. 1, Proceedings of an International Conference arranged by the Welding Institute, The Steel Castings Research and Trade Association, and the BNF Technology Centre, Bradford, September 21-23, 1976, available from the Welding Institute, Abbington Hall, Abbington, Cambridge, CB1 CAL, England.

41. Gross, A., "Why a Qualified Welding Procedure?", AFS Transactions, Vol. 83, 1975, p. 321-324.