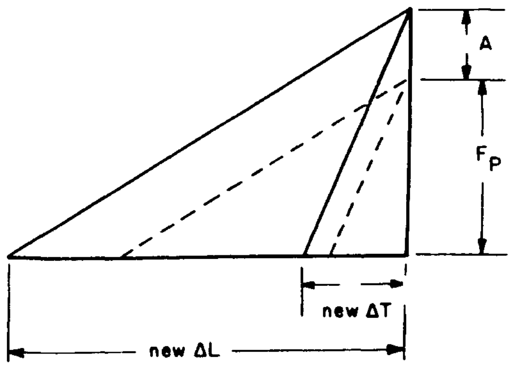


Fig. 35.27 The external load applied to the joint interface has exceeded the critical load by an amount = A.

This suggests that a joint designed to the above equation might have larger and/or more numerous bolts than necessary to support pressure loads the bolts will never see. The ASME Boiler and Pressure Vessel Code takes an even more conservative point of view than that described by the above equation to introduce a factor of safety. This code assumes that the bolts see 100% of external load L_X, not an amount reduced by the stiffness ratio.

35.9 EVALUATION OF SLIP CHARACTERISTICS

A slip-resistant joint is one that has a low probability of slip at any time during the life of the structure. In this type of joint, the external applied load usually acts in a plane perpendicular to the bolt axis. The load is completely transmitted by frictional forces acting on the contact area of the plates fastened by the bolts. This frictional resistance is dependent on (1) the bolt preload and (2) the slip resistance of the fraying surfaces.

Slip-resistant joints are often used in connections subjected to stress reversals, severe stress fluctuations, or in any situation wherein slippage of the structure into a "bearing mode" would produce intolerable geometric changes. A slip load of a simple tension splice is given by

$$P_{\text{slip}} = k_s m \sum_{l=1}^{n} T_i$$

where

$$k_s = \text{slip coefficient}$$
$$m = \text{number of slip planes}$$
$$\sum_{l=1}^{n} T_i = \text{the sum of the bolt tensions}$$

If the bolt tension is equal in all bolts, then

$$p_{\text{slip}} = k_s \, m \, n \, T_i$$

where

$$n = \text{the number of bolts in the joint}$$

The slip coefficient K_s varies from joint to joint, depending on the type of steel, different surface treatments, and different surface conditions, and along with the clamping force T_i shows considerable variation from its mean value. The slip coefficient K_s can only be determined experimentally, but some values are now available, as shown in Table 35.1.

35.10 INSTALLATION OF HIGH-STRENGTH BOLTS

Prior to 1985, North American practice had been to require that all high-strength bolts be installed and provide a high level of preload, regardless whether or not it was needed. The advantages in such an arrangement were that a standard bolt installation procedure was provided for all types of con-

Table 35.1 Summary of Slip Coefficients

Type of Steel	Treatment	Average	Standard Deviation	Number of Tests
A7, A36, A440	Clean mill scale	0.32	0.06	180
A7, A36, A440, Fe37, Fe.52	Clean mill scale	0.33	0.07	327
A 588	Clean mill scale	0.23	0.03	31
Fe 37	Grit blasted	0.49	0.07	167
A36, Fe37, Fe52	Grit blasted	0.51	0.09	186
A514	Grit blasted	0.33	0.04	17
A36, Fe37	Grit blasted, exposed	0.53	0.06	51
A36, Fe37, Fe52	Grit blasted, exposed	0.54	0.06	83
A7, A36, A514, A572	Sand blasted	0.52	0.09	106
A36, Fe37	Hot-dip galvanized	0.18	0.04	27
A7, A36	Semipolished	0.28	0.04	12
A36	Vinyl wash	0.28	0.02	15
	Cold zinc plated	0.30	–	3
	Metallized	0.48	–	2
	Galvanized and sand blasted	0.34	–	1
	Sand blasted treated with linseed oil (exposed)	0.26	0.01	3
	Red lead paint	0.06	–	6

nections and that a slightly stiffer structure probably resulted. Obviously, when a slip-resistant bolted structure was not needed, the disadvantages were the additional cost and inspection time for this type of installation. Since 1985, only fasteners that are to be used in slip-critical connections or in connections subject to direct tension loading have needed to be preloaded to the original preload, equal to 70% of the minimum specified tensile strength of the bolt. Bolts to be used in bearing-type connections only need to be tightened to the snug-tight condition.

When the high-strength bolt was first introduced, installation was primarily by methods of torque control. Approximate torque values were suggested, but tests performed and field experience confirmed the great variability of the torque–tension relationship, as much as ±30% from the mean tension desired. This variance is caused mainly by the variability of the thread conditions, surface conditions under the nut, lubrication, and other factors that cause energy dissipation without inducing tension in the bolt.

For a period of five years, the calibrated wrench method was banned in favor of turn-of-nut method or by use of direct tension indicators that depend on strain or displacement control versus torque control. However, in 1985, the RCSC (Research Council on Riveted and Bolted Structural Joints of the Engineering Foundation) specification again permitted the use of the calibrated wrench method, but with a clearer statement of the requirements of the method and its limitations.

The calibrated wrench method still has a number of drawbacks. Because the method is essentially one of torque control, factors such as friction between the nut and bolt threads and between the nut and washer are of major importance, as well as the type of lubricant used and the method of application, presence of dirt. These problems are not reflected in the calibration procedures.

To overcome the variability of torque control, efforts were made to develop a more reliable tightening procedure and testing began on the turn-of-nut method. (This is a strain-control method.) Initially it was believed that one turn from the snug position was the key, but because of out-of-flatness, thread imperfections, and dirt accumulation, it was difficult to determine the hand-tight position (the starting point—from the snug position). Many believe that turn control is better than torque control, but this is not true. In fact pure turn control is no more accurate than pure torque control. Current practice is as follows: run the nut up to a snug position using an impact wrench rather than the finger-tight condition (elongations are still within the elastic range). From the snug position, turn the nut in accordance with Table 35.2, provided by the RCSC specification.

Nut rotation is relative to bolt, regardless of the element (nut or bolt) being turned. For bolts installed by ⅔ turn and less, the tolerance should be ±30°; for bolts installed by ⅔ turn and more, the tolerance should be ±45°. All material within the grip of the bolt must be steel.

No research work has been performed by the council to establish the turn-of-nut procedure when bolt length exceeds 12 diameters. Therefore, the required rotation must be determined by actual tests in a suitable tension device simulating the actual conditions.

A325 bolts can be reused once or twice, providing that proper control on the number of reuses can be established. For A490 bolts, reuse is not recommended.

Washers are not required for A325 bolts because the galling in bolts that are tightened directly against the connected parts is not detrimental to the static or fatigue strength of the joint. If bolts are

Table 35.2 Nut Rotation from Snug-Tight Condition

Bolt Length (as measured from underside of head to extreme end of point)	Both Faces Normal to Bolt Axis	One Face Normal to Bolt Axis and Other Face Sloped Not More Than 1:20 (bevel washer not used)	Both Faces Sloped Not More Than 1:20 from Normal to Bolt Axis (bevel washers not used)
Up to and including 4 diameters	⅓ turn	½ turn	⅔ turn
Over 4 diameters but not exceeding 8 diameters	½ turn	⅔ turn	⅚ turn
Over 8 diameters but not exceeding 12 diameters	⅔ turn	⅚ turn	1 turn

tightened by the calibrated wrench method, a washer should be used under the turned element—that is, the nut or the bolt head. For A490 bolts, washers are required under both the head and nut when they are used to connect material with a yield point of less than 40 ksi. This prevents galling and brinelling of the connected parts. For higher strength steel assembled using high-strength bolts (higher than 40 ksi yield point), washers are only required to prevent galling of the turned element.

When bolts pass through a sloping interface greater than 1:20, a beveled washer is required to compensate for the lack of parallelism. As noted in Table 35.2, bolts require additional nut rotation to ensure that tightening will achieve the required minimum preload.

35.11 TORQUE AND TURN TOGETHER

Measuring of torque and turn at the same time can improve our control over preload. The final variation in preload in a large number of bolts is closer to ±5% than the 25–30% if we used torque or turn control alone. For this reason the torque–turn method is widely used today, especially in structural steel applications.

In this procedure, the nut is first snugged with a torque that is expected to stretch the fastener to a minimum of 75% of its ultimate strength. The nut is then turned (half a turn) or the like, which stretches the bolt well past its yield point. See Fig. 35.28.

This torque–turn method cannot be used on brittle bolts, but only on ductile bolts having long plastic regions. Therefore, it is limited to A325 fasteners used in structural steel work. Furthermore, it should never be used unless you can predict the working loads that the bolt will see in service. Anything that loads the bolts above the original tension will create additional plastic deformation in the bolt. If the overloads are high enough, the bolt will break.

A number of knowledgeable companies have developed manual torque–turn procedures that they call "turn of the nut" but that do not involve tightening the fasteners past the yield point. Experience shows that some of these systems provide additional accuracy over turn or torque alone.

Other methods have also been developed to control the amount of tension produced in bolts during assembly, namely *stretch* and *tension control.*[1] All of these methods have drawbacks and limitations, but each is good enough for many applications. However, in more and more applications,

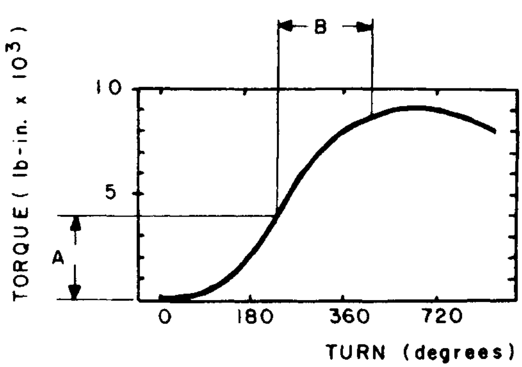


Fig. 35.28 In turn-of-nut techniques, the nut is first tightened with an approximate torque (A) and then further tightened with a measured turn (B).

we need to find a better way to control bolt tension and/or clamping forces. Fortunately, that better way is emerging, namely *ultrasonic measurement of bolt stretch or tension.*

35.12 ULTRASONIC MEASUREMENT OF BOLT STRETCH OR TENSION

Ultrasonic techniques, while not in common use, allow us to get past dozens of the variables that affect the results we achieve with torque and/or torque and turn control.

The basic concepts are simple. The two most common systems are *pulse-echo* and *transit time* instruments. In both, a small acoustic transducer is placed against one end of the bolt being tested. See Fig. 35.29. An electronic instrument delivers a voltage pulse to the transducer, which emits a very brief burst of ultrasound that passes down the bolt, echoes off the far end, and returns to the transducer. An electronic instrument measures precisely the amount of time required for the sound to make its round trip in the bolt.

As the bolt is tightened, the amount of time required for the round trip increases for two reasons:

1. The bolt stretches as it is tightened, so the path length increases.
2. The average velocity of sound within the bolt decreases because the average stress level in the bolt has increased.

Both of these changes are linear functions of the preload in the fastener, so that the total change in transit time is also a linear function of preload.

The instrument is designed to measure the change in transit time that occurs during tightening and to report the results as

1. A change in length of the fastener
2. A change in the stress level within the threaded region of the fastener
3. A change in tension within the fastener

Using such an instrument is relatively easy. A drop of coupling fluid is placed on one end of the fastener to reduce the acoustic impedance between the transducer and the bolt. The transducer is placed on the puddle of fluid and held against the bolt, mechanically or magnetically. The instrument is zeroed for this particular bolt (because each bolt will have a slightly different acoustic length). If you wish to measure residual preload, or relaxation, or external loads at some later date, you record the length of the fastener at zero load at this time. Next the bolt is tightened. If the transducer can remain in place during tightening, the instrument will show you the buildup of stretch or tension in the bolt. If it must be removed, it is placed on the bolt after tightening to show the results achieved by torque, turn, or tension.

If, at some later date, you wish to measure the present tension, you dial in the original length of *that* bolt into the instrument and place the transducer back on the bolt. The instrument will then show you the difference in length or stress that now exists in the bolt.

Because ultrasonic equipment is not in common use at this time, it is used primarily in applications involving relatively few bolts in critically important joints or quality control audits. Operator training in the use of this equipment is necessary and is a low-cost alternative to strain-gaged bolts in all sorts of studies.

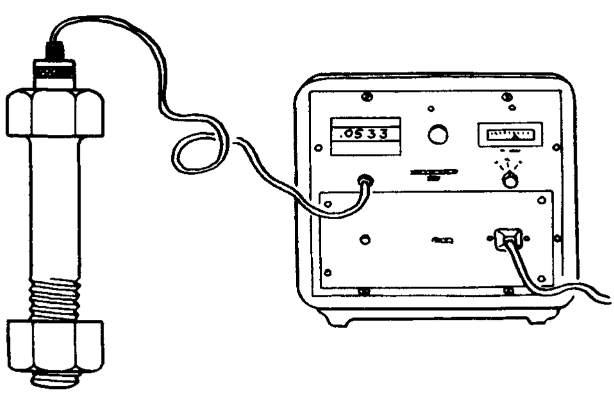


Fig. 35.29 An acoustic transducer is held against one end of the fastener to measure the fastener's change in length as it is tightened.

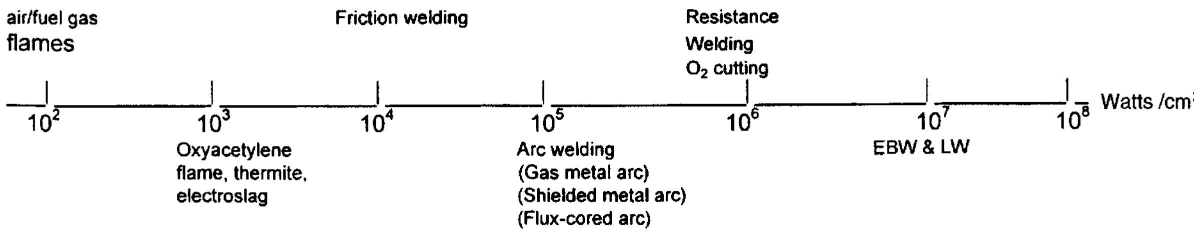


Fig. 35.30 Spectrum of practical heat intensities used for fusion welding.

These instruments are new to the field, so you must be certain to find out from the manufacturers exactly what the equipment will or will not do as well as precise information needed for use or equipment calibration. Training is essential not only for the person ordering the equipment, but for all who will use it in the field or laboratory. Proper calibration is essential. If the equipment can only measure transit time, you must tell it how to interpret transit time data *for your application.*

35.13 FATIGUE FAILURE AND DESIGN FOR CYCLICAL TENSION LOADS

A fastener subjected to repeated cyclical tension loads can suddenly break. These failures are generally catastrophic in kind, even if the loads are well below the yield strength of the material.

Three essential conditions are necessary for a fatigue failure: cyclical tensile loads; stress levels above the endurance limit of the material; and a stress concentration region (such as a sharp corner, a hole, a surface scratch or other mark on the surface of the part, corrosion pits, an inclusion and/or a flaw in the material). Essentially no part is completely free of these types of defects unless great care has been taken to remove them.

The sequence of events leading up to a fatigue failure is as follows:

1. Crack initiation begins after about 90% of the total fatigue life (total number of cycles) has occurred. This crack always starts on the surface of the part.
2. The crack begins to grow with each half-cycle of tension stress, leaving beach marks on the part.
3. Growth of the crack continues until the now-reduced cross section is unable to support the load, at which time the part fails catastrophically (very rapidly).

A bolt is a very poor shape for good fatigue resistance. Although the average stress levels in the body may be well below the endurance limit, stress levels in the stress concentration points, such as thread roots, head to body fillets, and so on can be well over the endurance limit. One thing we can do to reduce or eliminate a fatigue problem is to attempt to overcome one or more of the three essential conditions without which failure would not occur. In general, most of the steps are intended to reduce stress levels, reduce stress concentrations, and/or reduce the load excursions seen by the bolt.

35.13.1 Rolled Threads

Rolling provides a smoother thread finish than cutting and thus lowers the stress concentrations found at the root of the thread. In addition to overcoming the notch effect of cut threads, rolling induces compressive stresses on the surface rolled. This compressive "preload" must be overcome by tension forces before the roots will be in net tension. A given tension load on the bolt, therefore, will result in a smaller tension excursion at this critical point. Rolling the threads is best done after heat treating the bolt, but it is more difficult. Rolling before heat treatment is possible on larger-diameter bolts.

35.13.2 Fillets

Use bolts with generous fillets between the head and the shank. An elliptical fillet is better than a circular one and the larger the radius the better. Prestressing the fillet is wise (akin to thread rolling).

35.13.3 Perpendicularity

If the face of the nut, the underside of the bolt head, and/or joint surfaces are not perpendicular to thread axes and bolt holes, the fatigue life of the bolt can be seriously affected. For example, a 2° error reduces the fatigue life by 79%.[3]

35.13.4 Overlapping Stress Concentrations

Thread run-out should not coincide with a joint interface (where shear loads exist) and there should be at least two full bolt threads above and below the nut because bolts normally see stress concentrations at (1) thread run-out; (2) first threads to engage the nut, and head-to-shank fillets.

35.13.5 Thread Run-Out

The run-out of the thread should be gradual rather than abrupt. Some people suggest a maximum of 15° to minimize stress concentrations.

35.13.6 Thread Stress Distribution

Most of the tension in a conventional bolt is supported by the first two or three nut threads. Anything that increases the number of active threads will reduce the stress concentration and increase the fatigue life. Some of the possibilities are

1. Using so-called "tension nuts," which create nearly uniform stress in all threads.

2. Modifying the nut pitch so that it is slightly different than the pitch of the bolt, i.e., thread of nut 11.85 threads/in. used with a bolt having 12 threads/in.
3. Using a nut slightly softer than the bolt (this is the usual case); however, select still softer nuts if you can stand the loss in proof load capability.
4. Using a jam nut, which improves thread stress distribution by preloading the threads in a direction opposite to that of the final load.
5. Tapering the threads slightly. This can distribute the stresses more uniformly and increase the fatigue life. The taper is 15°.

35.13.7 Bending

Reduce bending by using a spherical washer because nut angularity hurts fatigue life.

35.13.8 Corrosion

Anything that can be done to reduce corrosion will reduce the possibilities of crack initiation and/or crack growth and will extend fatigue life. Corrosion can be more rapid at points of high stress concentration, which is also the point where fatigue failure is most prevalent. Fatigue and corrosion aid each other and it is difficult to tell which mechanism initiated or resulted in a failure.

35.13.9 Surface Conditions

Any surface treatment that reduces the number and size of incipient cracks will improve fatigue life significantly, so that polishing of the surface will greatly improve the fatigue life of a part. This is particularly important for punched or drilled holes, which can be improved by reaming and expanding to put the surface in residual compression. Shot peening of bolts or any surface smooths out sharp discontinuites and puts the surface in residual compression. Handling of bolts in such a way as not to ding one against the other is also important.

35.13.10 Reduce Load Excursions

It is necessary to identify the maximum safe preload that your joint can stand by estimating fastener strength, joint strength, and external loads. Also do whatever is required to minimize the bolt-to-joint stiffness ratio so that most of the excursion and external load will be seen by the joint and not the bolt. Use long, thin bolts even if it means using more bolts. Eliminate gaskets and/or use stiffer gaskets.

While there are methods available for estimating the endurance limit of a bolt, it is best to base your calculations on actual fatigue tests of the products you are going to use or your own experience with those products.

For the design criteria for fatigue loading of slip resistant joints, see Refs. 1 and 2.

35.14 WELDED JOINTS

In industry, welding is the most widely used and cost-effective means for joining sections of metals to produce an assembly that will perform as if made from a single solid piece.

A perfect joint is indistinguishable from the material surrounding it, but a perfect joint is indeed a very rare case. Diffusion bonding can achieve results that are close to this ideal, but are either expensive or restricted to use on just a few materials. There is no universal process that performs adequately on all materials in all geometries. Nevertheless, any material can be joined in some way, although joint properties equal to those of the bulk material cannot always be achieved.

Generally, any two solids will bond if their surfaces are flat enough that atom-to-atom contact can be made. Two factors exist to make this currently impossible.

1. Even the most carefully machined, polished, and lapped surfaces have random hills and valleys differing in elevation by 100–1000 atomic diameters.
2. Any fresh surface is immediately contaminated by formation of a nonmetallic film a few atomic diameters thick, consisting of a brittle oxide layer, a water vapor layer, a layer of absorbed CO_2, and hydrocarbons, which forms in about 10^{-3} seconds after cleaning.

If large enough compressive forces were applied to the surfaces, the underlying aspirates (regions where two hills, one on each surface, meet) would flow plastically, fragmenting the intermediate, brittle oxide layer. On increasing the compressive force, isolated regions of metal-to-metal contact would occur, separated by volumes of accumulated debris from the oxide and absorbed-moisture films. Upon release of the compressive load, the isolated regions of coalescence would be ruptured by the action of the compressive residuals in unbonded areas. In diffusion bonding, the compressive forces are maintained while heating the material very near to its melting temperature, causing the aspirates to grow by means of recrystallization and grain growth. But this still leaves regions where the fragmented oxides remain, thus reducing the overall bonded joint length.

In order to produce a satisfactory metallic bond between two metal objects, it is first necessary to dissipate all nonmetallic films from the interface. In fusion welding, intimate interfacial contact is achieved by placing a liquid metal, of essentially the same composition as the base metal, between the two solid pieces. If the surface contamination is soluble, it is dissolved in the liquid; if not then it will float away from the liquid solid interface. While floating away the oxide is an attractive procedure, it does not preclude cleaning all surfaces to be welded as well as you possibly can before applying the heat source to the joint to be welded.

One distinguishing feature of all fusion welding processes is the intensity of the heat source used to melt the solid into a liquid. It is generally found that heat source power densities of approximately 1000 watts/cm^2 are necessary to melt most metals.

At the high end of the power densities, heat intensities of 10^6 or 10^7 watts/cm^2 will vaporize most materials within a few microseconds and all of the solid that interacts with the heat source will vaporize. Around the hole thus created, a molten pool is developed that will flow into the hole once the beam has moved ahead, allowing the weld to be made. This is the case for electron-beam and laser welding. Power densities of the order of 10^3 watts/cm^2, such as oxyacetylene or electroslag welding, require interaction times of 25 seconds with steel. This is why welders begin their training with the oxyacetylene process. It is inherently slow and does not require a rapid response from the new welder in order to control the molten puddle. Much greater skill is needed to control the arc in the faster arc processes.

The selection of materials for welded construction applications involves a number of considerations, including design codes and specifications, where they exist. In every design situation, economics—choosing the correct material for the life cycle of the part and its cost of fabrication—is of prime importance. Design codes or experience frequently offer an adequate basis for material selection. For new or specialized applications, the engineer encounters problems of an unusual nature and thus must rely on basic properties of the material, such as strength, corrosion or erosion resistance, ductility, and toughness. Welding processes may be significant in meeting the design goals.

The processes that are most frequently used in the welding of large structures are normally limited to four or five fusion welding methods. These methods will be discussed starting from the most automatic, cheapest method progressing to semiautomatic and finally to those methods that are manual only.

35.14.1 Submerged Arc Welding (SAW)

This method is the workhorse of heavy metal fabrication and used as a semi-automatic or fully automatic operation, although most installations are fully automatic. Its cost per unit length of weld is the lowest of all the processes, but it has the disadvantage of operating only in the downhand position. Thus, it requires manipulation of the parts into positions where welding can be accomplished in the horizontal position. It is suitable for shop welding, but not field welding.

Heat is provided by an arc between a bare solid metal consumable electrode and the workpiece. The arc is maintained in a cavity of molten flux or slag, which refines the weld deposit and protects it from atmospheric contamination. Alloy ingredients in the flux may be present to enhance the mechanical properties and crack resistance of the weld deposit. See Fig. 33.31.

A layer of granular flux, deep enough to prevent flash-through, is deposited in front of the arc. The electrode wire is fed through a contact tube. The current can be ac, dc reverse, or straight polarity. The figure shows the melting and solidification sequence. After welding, the unfused slag and flux may be collected, crushed, and blended back into the new flux. To increase the deposition and welding rate, more than one wire (one in front of the other) can be fed simultaneously into the same weld pool. Each electrode has its own power supply and contact tip. Two, three, or even four wire feeds are frequently used.

Advantages of the Process

1. The arc, which is under a blanket of flux, eliminates arc flash, spatter, and fumes. This is attractive from an environmental point of view.
2. High current densities increase penetration and decrease the need for edge preparation.
3. High deposition rates and welding speeds are possible.
4. Cost per unit length of weld is low.
5. The flux deoxidizes contaminates such as O_2, N_2, and sulfur.
6. Low hydrogen welds can be produced.
7. The shielding provided by the flux is substantial and not sensitive to wind, and UV light emissions are low.
8. The training requirements are lower than for other welding procedures.
9. The slag can be collected, reground, and sized back into new flux.

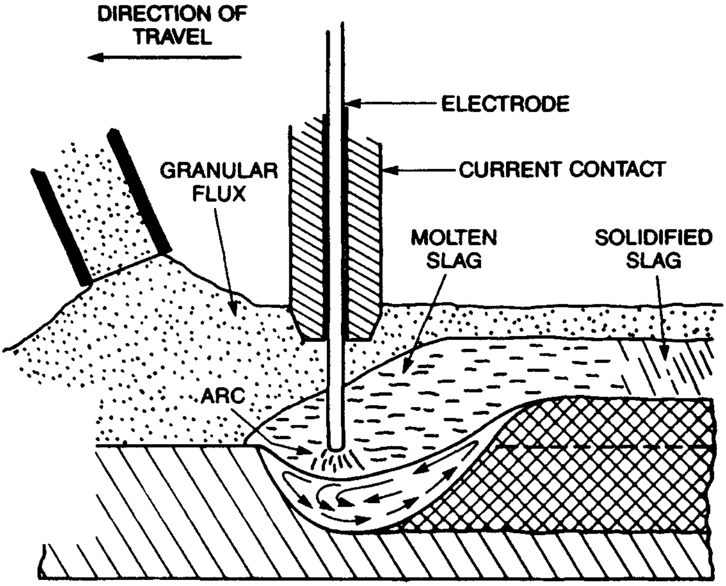


Fig. 35.31 Diagrammatic sketch of the submerged arc welding process (SAW). Sketch illustrates electrode deposition on a thick plate, Arrows drawn on weld pool show the usual hydrodynamic motion of the molten metal.

Disadvantages or Limitations of the Process

1. Initial cost of all equipment required is high.
2. Must be welded in the flat or horizontal position.
3. The slag must be removed between passes.
4. Most commonly used to join steels ¼ inch thick or greater.

This process is most commonly used to join plain carbon steels and low alloy steels, but alloy steels can be welded if care is taken to limit the heat input as required to prevent grain coarsening in the heat-affected zone (HAZ). It can also be used to weld stainless steels and nonferrous alloys or to provide overlays on the top of a base metal. To prevent porosity, the surface to be welded should be clean and free of all grease, oil, paints, moisture, and oxides.

Because SAW is used to join thick steel sections, it is primarily used for shipbuilding, pipe fabrication, pressure vessels, and structural components for bridges and buildings. It is also used to overlay, with stainless steel or wear-resistant steel, such things as rolls for continuous casting, pressure vessels, rail car wheels, and equipment for mining, mineral processing, construction, and agriculture.

Power sources consist of a dc constant voltage power supply that is self-regulating, so it can be used with a constant-speed wire feeder. No voltage or current sensing is necessary. The current is controlled by the wire diameter, the amount of stick-out, and the wire speed feed. Constant current ac machines can also be used, but require voltage-sensing variable wire speed controls. On newer solid state power supplies, the current and voltage outputs both approximate square waves, with instantaneous polarity reversal reducing arc initiation problems.

Fluxes interact with the molten steel in very similar ways to those in open-hearth refining of steel. These processes need to be understood for the best selection of the flux depending on the material being welded. For this chapter it suffices to say that acid fluxes are typically preferred for single-pass SAW welding because of their superior operating and bead wetting characteristics. In addition, these fluxes have more resistance to porosity caused by oil contamination of the material to be welded, rust, and mill scale.

Basic fluxes tend to give better impact properties, and this is evident on large multipass welds. Highly basic (see Boniszewski basicity index) fluxes produce weld metals with very good impact

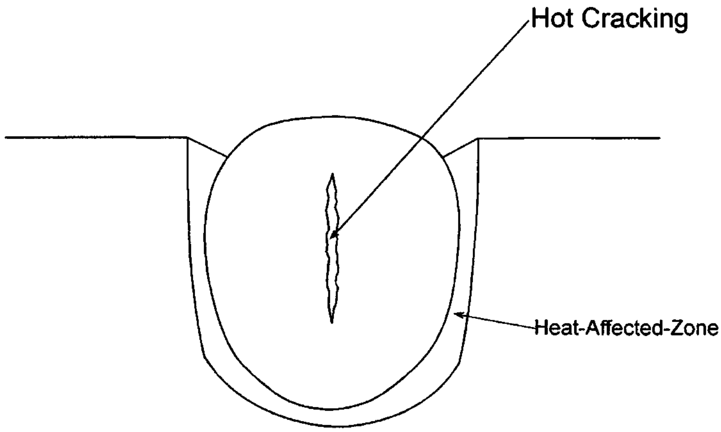


Fig. 35.32 Deeply penetrating weld made by SAW process with hot cracking.

properties. These highly basic fluxes have poorer welding characteristics than acid fluxes and are limited to cases where good weld notch toughness is required.

While SAW is the most inexpensive and efficient process for making large, long, and repetitive welds, much time is required to prepare the joint. Care must be taken to line up all joints for a consistent gap in groove welds and to provide backing plates and flux dams to prevent the spillage of molten metal and/or flux. Once all the pieces are clamped or tacked in place, welding procedures and specifications need consultation before welding begins.

The fact that SAW is a high heat input process, under a protective blanket of flux, greatly decreases the chance of weld defects. However, defects such as lack of fusion, slag entrapment, solidification cracking, and hydrogen cracking occasionally occur. See Figs. 35.32 and 35.33 for two examples of defects.

Welds with a high depth/width ratio may have unfavorable bulbous X-sectional shape that is susceptible to cracking at center from microshrinkage and segregation of low melting consituents. Note—crack does not extend to surface.

35.14.2 Gas Metal Arc Welding

See Fig. 35.34.

The GMAW process allows welds to be made with the continuous deposition of filler metal from a spool of consumable electrode wire that is pushed or pulled automatically through the torch. Thus, the process is semi-automatic and/or automatic and avoids the problem of removing the slag, which is required in the SAW process (and required in the two other processes to be mentioned in this

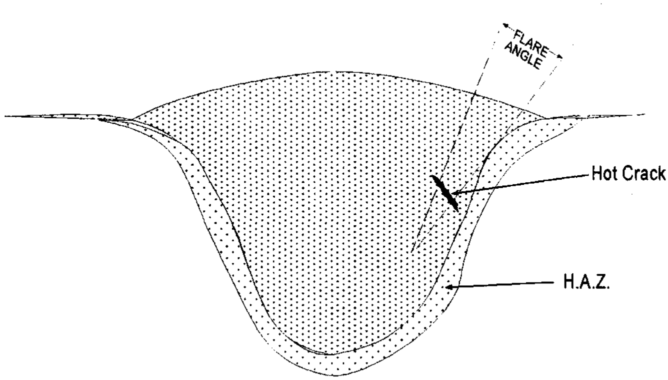


Fig. 35.33 Weld made by SAW with flare angle and hot cracking at juncture of 2 solidification fronts.

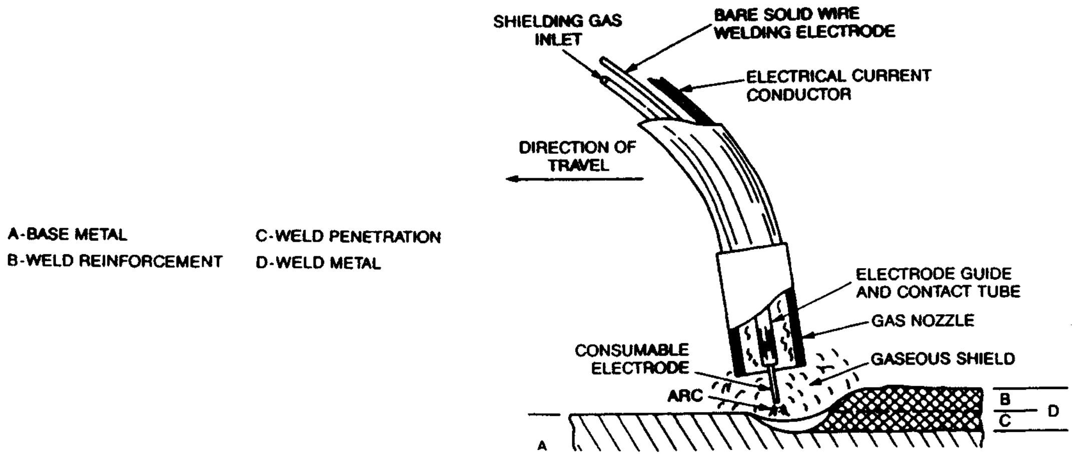


Fig. 35.34 Diagrammatic sketch of (GMA) welding process.

chapter). In addition, the process provides an inert shielding gas through nozzles in the torch or gun. The process is generally a dc method using reverse polarity. Initially the process used argon as the shielding gas, although helium was tried because the spatter was excessive using argon. Today pure argon is not used but is doped with oxygen (as little as .5% with a maximum of 2%) or carbon dioxide (no more than 10%). These additions assure confinement of the arc to a clear weld pool, which makes the arc steady and produces sound weld deposits. The reverse polarity of this process delivers enough heat input into the cathodic base metal for good penetration, and it provides a positive-ion cleaning effect. Alternating current is not used for GMAW because the arc extinguishes each ½ cycle. The preferred method is a dc constant voltage supply because the arc is self-regulating. This means that if the gun is moved in a way to shorten the arc, the voltage decreases and the current increases, as does the burn-off rate. Thus, the arc returns to its original length. The opposite effect occurs if the gun is moved away from the workpiece. The GMAW process has the following features:

1. High deposition rates
2. Good quality welds
3. Deep penetration
4. Self-regulating feature
5. Adaptability to almost any material (carbon steels, low alloy steels, stainless steels, aluminum, copper, nickel alloys, titanium, and bronzes)
6. Welding can be accomplished in all positions
7. Deposition rates significantly higher than those obtained by SMAW but less than SAW
8. Minimum post-weld cleaning required because of the absence of heavy slag
9. Welding equipment more complex, usually more costly, and less portable than in SMAW
10. With the advent of robotics, GMAW has become the predominant process choice for automatic high-production welding applications

Metal Transfer

Three types of filler metal transfer mechanisms are observed in GMAW:

1. Short-circuiting transfer
2. Globular transfer
3. Spray transfer

Short-Circuiting Transfer

This encompasses the lowest range of welding currents and electrode diameters associated with this process and is a recent process development. This type of transfer produces a small, fast-freezing weld pool that is generally suited for joining thin sections, for out-of-position welding, and for bridging of large root openings. Metal is transferred from the electrode to the workpiece only during the period that the electrode is in contact with the weld pool, and there is no metal transfer across the arc gap.

The electrode contacts the molten pool at a steady rate that can range from 20 to over 200 times per second. As the wire touches the weld metal, the current increases and the liquid metal at the top of the wire is pinched off, initiating an arc. The rate of current increase must be high enough to heat the electrode and promote metal transfer, yet low enough to minimize spatter caused by the violent separation of the molten drop. When the arc is initiated, the wire melts at the top as it is fed forward towards the next short circuit. The open-circuit voltage of the power source must be low enough so that the drop of molten metal cannot transfer until it contacts the weld metal.

Because metal transfer only occurs during short-circuiting, the shielding gas has very little effect on the transfer itself. However, the gas does influence the operating characteristics of the arc and the base metal penetration. CO_2 gas generally produces high spatter as compared to the inert gases, but allows deeper penetration in steels. As a compromise between spatter and penetration, mixtures of carbon dioxide and argon are often used. For nonferrous metals, argon–helium mixtures achieve the same compromise. See Fig. 35.35.

While less expensive CO_2 serves well for shielding low carbon and low alloy steels, argon–CO_2 mixtures improve conditions for welding thinner sections of base metal. The ease of welding in all positions is so advantageous that this variation of GMAW is applied to many different structures and the weld metal deposited displays normal strength and good toughness. One frequent defect has sharply dampened enthusiasm for this process, namely small areas of incomplete fusion between the interface of the base and weld metal. These areas occur when welding with relatively low heat input, as is the case when penetration is minimal or welding steel thicker than ¼ inch. The unfused areas are difficult to detect. Many code-writing bodies either forbade GMAW-S (short-circuit) welding on heavy sections of steel or called for stringent testing before permitting its use.

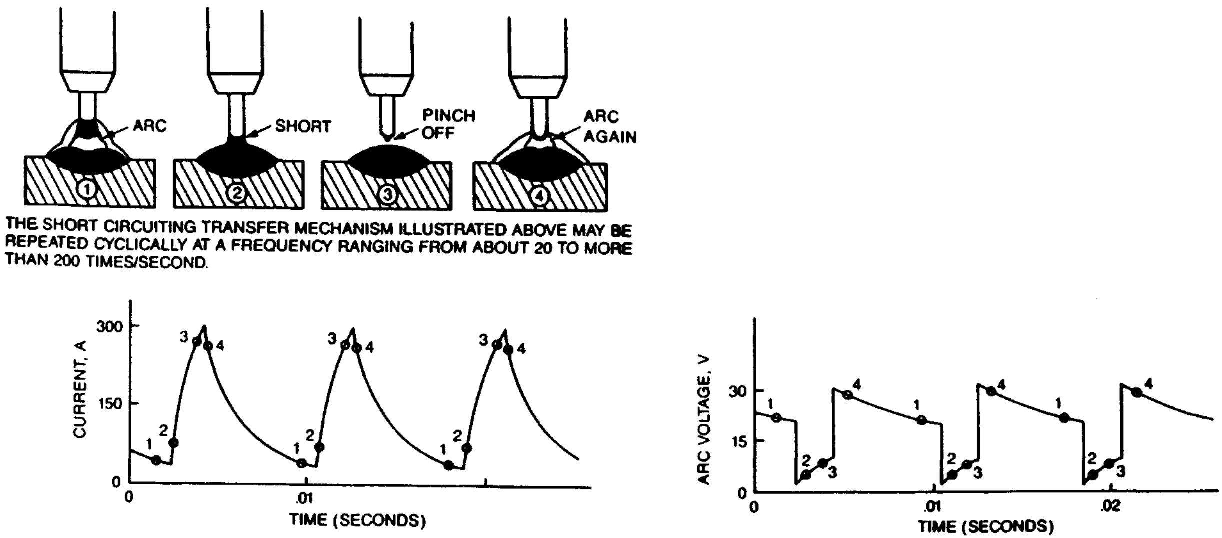


Fig. 35.35 GMAW process operating in the short-circuiting transfer mode.

Globular Transfer

With a positive electrode, globular transfer takes place when the current density is relatively low, regardless of the shielding gas used. However, the use of CO_2 or helium results in this type of transfer at all usable welding currents. Globular transfer is characterized by drop size with a diameter greater than that of the electrode. This large drop is easily acted upon by gravity, which means that transfer occurs successfully only in the flat position (downhand).

The arc length must be long enough to avoid the large droplet size from causing short-circuiting to the workpiece. If short-circuiting occurs, the droplet becomes superheated and disintegrates, producing considerable spatter. When higher voltage values are used, weld spatter causes lack of fusion, insufficient penetration, and excessive reinforcement. This limits the use of this transfer mode to very few production applications. Carbon dioxide shielding gas produces randomly directed globular transfer when welding current and voltage values are significantly higher than those used for short-circuiting transfer. CO_2 is the most commonly used shielding gas for welding carbon steels using this mode of metal transfer when the quality requirements are not too rigorous. The spatter problem is controlled by placing the arc below the weld/base metal surfaces. The resulting arc forces are adequate to produce a depression that contains the spatter. This technique requires relatively high currents and results in very deep penetration. However, good operator skills are required. Poor wetting action can result in excessive weld reinforcement.

Spray Transfer

A very stable, spatter-free "spray" transfer mode can be produced when argon-rich shielding is used. This mode requires direct current, electrode positive, and a current level above the critical "transition" value. Below this transition value transfer occurs in the globular mode at the rate of a few droplets every second. At values above the transition, current transfer occurs as very small drops are formed and detached at the hundreds per second rate. The spray-transfer mode results in a highly directed stream of discrete drops that are accelerated by arc forces to velocities that overcome the effect of gravity, thus allowing use of the process in any position. Because the drops are separated, short-circuits do not occur and the spatter level is negligible, if not eliminated.

Because of the inert characteristics of the argon shield, the spray transfer mode can be used to weld almost any metal or alloy. Sometimes thickness can be a factor, because of the relatively high currents necessary for this mode. The resultant arc forces can cut through, rather than weld, thin sheets. In addition, high deposition rates can result in a weld pool size that cannot be supported by surface tension in the vertical and overhead positions. However, the thickness and position limitations of spray transfer have been largely overcome by specially designed power supplies. These machines produce controlled current outputs that "pulse" the welding current from levels below the transition current to levels above.

35.14.3 Flux-Cored Arc Welding (FCAW) CAW

In this case, the fluxing materials are contained inside a tubular electrode wire. When combined with an automatic feeder, this process is semi-automatic. For this reason, FCAW is quickly replacing SMAW, because welding does not have to stop when the stick electrodes of SMAW are used up. Such tubes are made from thin, narrow strips of steel that is rolled into a *U*-shaped configuration, filled with the powdered fluxing material and then finished into a self-locking tube. This filling must be without gaps, because of the vital role the flux plays in providing: flux, gas coverage, deoxidants, and alloying elements.

Flux systems have been developed which provide all functions necessary for these electrodes to exhibit good behavior while welding and to produce welds of acceptable quality and mechanical properties, as required by many codes.

There are two major variations of flux-cored arc welding: *self-shielding* and *gas shielding*.

In the self-shielded process, the core ingredients protect the weld metal from the atmosphere without external shielding. Some self-shielded electrodes provide their own shielding gas through the decomposition of core ingredients. Others rely on slag shielding, where the metal droplets are protected from the atmosphere by a slag covering. Many self-shielded electrodes contain substantial amounts of deoxidizing and denitrifying ingredients to help achieve sound weld metal. These electrodes also contain stabilizers and alloying elements. Self-shielded FCAW-S electrodes are highly desirable because the cost and practical problems associated with supplying and manipulating the gas-shielded torch are eliminated. Although certain self-shielded electrodes contain gas-generating constituents in their core, primary protection from oxygen and nitrogen is provided by the addition of aluminum and possibly others, such as titanium and silicon. If added gas protection is used with these electrodes, the high aluminum content can be great enough to suppress austenite formation, producing abnormally large grains in the weld microstructure. This is not desirable because of the reduction in strength, ductility, and toughness.

The gas-shielded process uses an externally supplied gas to assist in shielding the arc from nitrogen and oxygen in the atmosphere. Generally, the core ingredients are slag formers, deoxidizers, arc stabilizers, and alloying elements. These electrodes must not be used without the gas covering because the core formulation has neither the gas-generating constituents nor the deoxidizers needed to cope with the exposure to air.

Advantages of FCAW

Because it combines the productivity of continuous welding with the benefits of having a flux present, the FCAW process has several advantages over other welding processes and has largely supplanted SMAW welding as the most popular method for welding low-carbon and low-alloy steels. These advantages are

1. High deposition rates, especially for out-of-position welding
2. Less operator skill required than for GMAW
3. Simpler and more adaptable than SAW
4. Deeper penetration than SMAW
5. More tolerant of rust and mill scale than GMAW

The disadvantages of the FCAW process are

1. Slag must be removed from each pass of the weld and disposed of.
2. More smoke and fume produced than in GMAW and SAW, requiring fume extraction.
3. Equipment is more complex and much less portable than SMAW equipment, particularly for the FCAW-G option.

Applications

This process enjoys widespread use. Both the gas-shielded and self-shielded processes are used to fabricate structures from carbon and low-alloy steels. Self-shielding is preferred for field use. Carbon steel, low-alloy steels, and stainless steels for the construction of pressure vessels and piping are welded by this process for the petroleum, refining, and power-generation industries. Some nickel-based alloys are also welded by FCAW, as well as in the heavy equipment industry for the fabrication of frame members, wheel rims, suspension components, and other parts. Automatic FCAW equipment is also common.

Figure 35.36 shows both the electrodes and the two different types of equipment.

35.14.4 Shielded Metal Arc Welding (SMAW)

This process is commonly called "stick" welding. An arc is struck between a flux-covered solid consumable electrode and the workpiece. The process uses the decomposition of the flux covering to generate a shielding gas and fluxing elements to protect the molten weld metal droplets and the weld pool with a slag covering. The flux coating on the electrode can be provided for gaseous shielding, arc stabilization, fluxing action, and slag formation.

SMAW was the most widely used welding process for steel fabrication for many years, but over the past 10 years, other, more efficient, cost-effective processes have been taking over, in particular the semi-automatic process FCAW and the GMAW process in welding robotics.

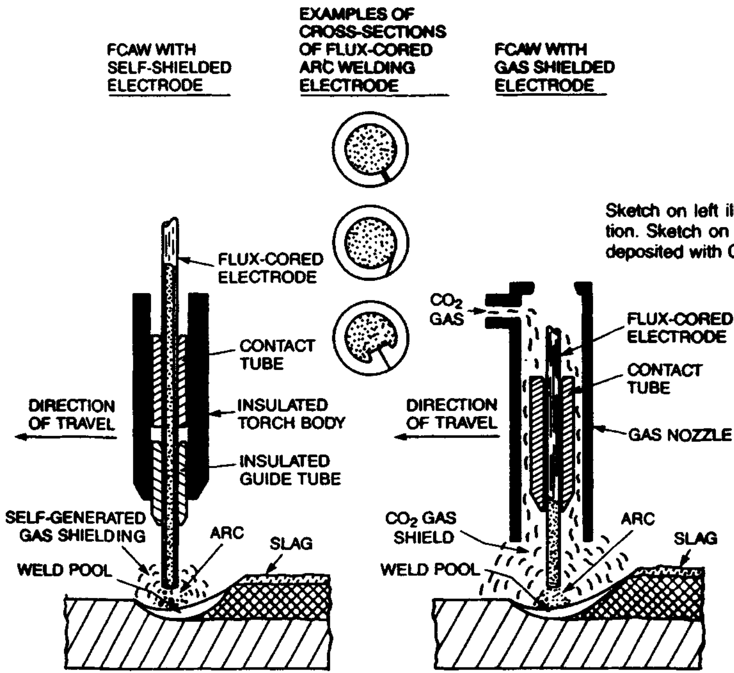
Advantages and Limitations: SMAW

The equipment investment is relatively small and welding electrodes for all but the most reactive metals, such as magnesium and titanium, are available for virtually all manufacturing, construction, or maintenance applications. The most important advantage of the process is that it can be used in all positions, with virtually all base metal thicknesses and in areas of limited accessibility.

Because this process is manual, the skill of the welder is of paramount importance in obtaining an acceptable weld. The skill level of the welder needs to be much higher than in most other processes. It is perhaps the most difficult in terms of welder training and skill level requirements of all the processes discussed in this chapter.

The SMAW process is diagrammed in Fig. 35.37.

Covered electrodes for manual welding are made in standard sizes, ranging from $\frac{3}{32}$ to $\frac{3}{8}$ in. in the United States, defined by the diameter of the metal core. The thickness of the flux covering is determined by the requirements of the specification to which the electrode is marketed and its handling characteristics. This range of electrode sizes can be used for welding base metals from thin sheet to very heavy plate. Electrodes as thick as $\frac{3}{4}$ in. are made for special applications, such as filling large cavities in castings or modifying the shape of metalworking dies. These electrodes are normally 14 in. in length, but smaller and longer sizes are available. One end of the electrode is stripped of coating for about 1 in. to allow electrical contact when gripped by the holder. The opposite end has the coating chamfered with the exposed end cleaned of flux to permit touch starting. When the arc is first struck, by touching it to the workpiece, the first small increment of filler metal deposited



Sketch on left illustrates a self-shielded electrode (FCAW-S) during deposition. Sketch on right shows a gas shielded type electrode (FCAW-G) being deposited with CO_2 shielding gas.

Fig. 35.36 Diagrammatic sketches of the flux-cored arc welding process.

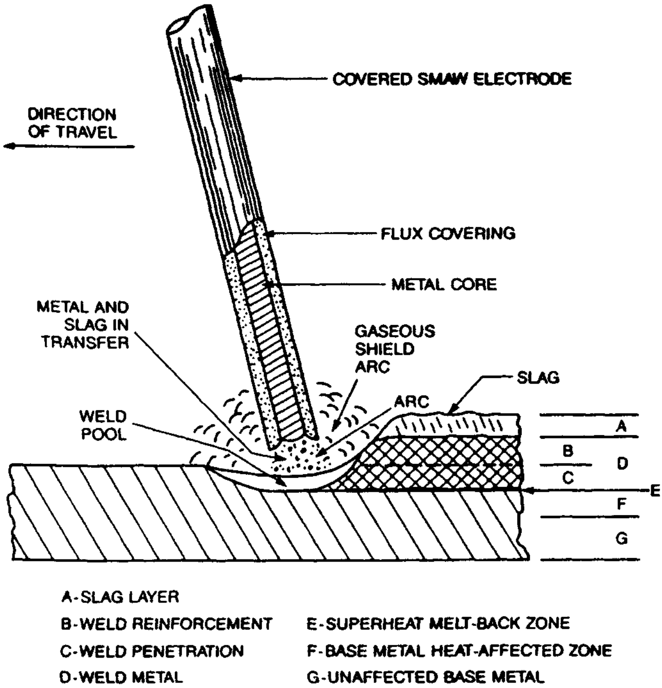


Fig. 35.37 Diagrammatic sketch of the shielded metal arc welding process (SMAW) using a consumable flux-covered electrode.

will not receive normal shielding, nor will it contain intended additions of deoxidizing and alloying elements. This can cause porosity and inadequate alloying at the very start of the weld pass. This problem can be aggravated on restarting a partially used electrode if covering fragmentation results in a bare core for a short length of the electrode. The coverings on most SMAW electrodes are formulated to resist melting just enough to form a short conical projection around and beyond the arcing core, thus accomplishing two objectives: providing greater protection of the emitting end of the metal core, which helps direct the flight of molten droplets toward the weld pool; and preventing short-circuiting of the electrode should it happen to touch the base metal surface.

Hydrogen can be troublesome in SMAW welds. Cellulose-type coverings, widely used for carbon steel electrodes, may contain as much as 30% organic materials and must be carefully baked to retain a small but important percentage of combined moisture necessary to achieve good deposition characteristics. Low-hydrogen rods are manufactured to avoid this problem, but unless very carefully packaged and handled properly after opening, they tend to pick up moisture.

Another problem with SMAW is slag entrapment in the solidifying metal. This problem is dependent on operator skill. Unless the operator can get the slag to float on the top of the molten weld pool and completely remove it by wire brushing, subsequent passes over the first pass may trap slag and become a weld defect.

Applications

Most manufacturing operations that require welding will strive to utilize mechanized processes that offer greater productivity, higher and more consistent quality, and therefore more cost-effective methods. For these reasons, the SMAW process has been replaced whereever possible. However, the simplicity and the ability of this process to achieve welds in restricted accessibility means that it still finds considerable use in certain situations and applications. Heavy construction, such as shipbuilding, and welding in the field, away from support services that would provide shielding gas, cooling water, and on-line electricity and other necessities all rely on SMAW process to a great extent. The process, while primarily designed to join steels, including low-carbon, high-strength steel, quench and tempered steels, high-alloy steels, stainless steels and many cast irons, is also used to join nickel, copper, and their alloys. While rarely used, the process will also weld aluminum.

Table 35.3 is a process selection guide for the processes just discussed above.

35.15 COOLING RATES AND THE HEAT-AFFECTED ZONE (HAZ) IN WELDMENTS[4]

Unusual combinations of time and temperature must be dealt with in welding because the temperature changes are wider and more drastic than in any other process used by industry, for the following reasons:

1. Welding sources are hotter and more intense than most commonly used by industry for heating.
2. Welding operations are carried out so rapidly that extremely steep temperature gradients are established between the weld and the base metal.
3. Both the base metal and any fixturing act as highly efficient heat sinks that promote very high cooling rates (as fast as permitted by the thermal conductivity of the metals involved).
4. Phase diagrams are based on equilibrium cooling only and do not predict the structures that will develop as a result of very fast (nonequilibrium) cooling.

For the most part, these fast heating and particularly the high cooling rates have a negative impact on the properties of the resulting weldment, depending on the material being welded. These undesirable effects occur in the heat-affected zone (HAZ) far more frequently than in the weld metal itself. (This is the zone that is not melted during welding but that lies adjacent to the molten weld zone.) For steels the most important effect of the peak temperature and the resulting fast cooling rate is the degree of hardening which may take place in the HAZ and the resulting change in the fracture toughness or in the change in susceptibility to hydrogen cold cracking. Hardening (forming martensite) is dependent on the composition of the steel and the microstructure that evolves from the fast rate of cooling.

We know that both the microstructure and its hardness are firmly determined by the rate of continuous cooling that prevails as the austenitized steel (due to welding heat) undergoes transformation. In general, faster cooling rates produce harder microstructures (up to RC 60-65 as the maximum hardness). This hardness cooling rate relationship is reliable and repeatable, and is dependent on the given steel's *hardenability.* Hardenability is a characteristic of carbon, low-alloy, and alloyed steels that is governed primarily by the composition of the steel and the austenite grain size. Classically, a guide to the hardenability of a steel can be obtained by calculating the carbon equivalent. Several carbon equivalent formulas have been developed for different classes of steel such as

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

The calculated carbon equivalent can be related to hydrogen-sensitive microstructures. That is, as the carbon equivalent increases, the microstructures that are evolved during cooling through the transformation temperature (from 800 to 500°C), become increasingly sensitive or susceptible to hydrogen induced cracking. At high levels of CE, martensitic structures can be expected. For this formula, when the carbon equivalent exceeds 0.35%, preheats are recommended to minimize susceptibility to hydrogen cracking. At higher levels of CE, both preheats and postheats may be required.

A special carbon equivalent has been developed by Yorioka to establish the critical Δt_{8-5} for a martensite-free HAZ in low-carbon alloy steels. This carbon equivalent is given as

$$CE^* = \%\,C^* + \frac{\%Mn}{3.6} + \frac{\%\,Cu}{20} + \frac{\%\,Ni}{9} + \frac{\%\,Cr}{5} + \frac{\%\,Mo}{4}$$

where

$$\%\,C^* = 5C \text{ for carbon} \leq 0.30\%$$
$$\%\,C^* = \%\,C/6 = .25 \text{ for } \%\,C \geq .3\%$$

The critical time length in seconds Δt_{8-5} for the formation of martensite is given as

$$\log \Delta t_{8-5} = 2.69\ CE^* = 0.321$$

When CE* is known, welding parameters and preheat temperatures for a given thickness of material can be established to produce cooling rates that avoid formation of martensite in the HAZ. For more details, see Ref. 5.

The use of preheating and postheating to minimize the susceptibility to hydrogen-induced cracking is an accepted welding procedure for many steels. Preheating controls and lowers the cooling rate

Table 35.3

Parameters	SAW	GMAW	FCAW	SMAW
Usability	Limited to flat and horizontal positions. Semi-automatic version has some adaptability but is most often mechanized. Limited portability. Minimum thickness $\frac{1}{16}$ in. Joint preparation required on material $\frac{1}{2}$ in. and thicker. Process lends self to weld thicker materials.	All position process in the short-arc or pulsed mode. Moderately adaptable but use outside, where shielding can be lost. Usable for steels to 0.010 thick. Above $\frac{3}{16}$ in. thick requires joint preparation. No upper limit on plate thickness.	All-position process. Equipment similar to GMAW but self-shielded version has better portability and is usable outdoors. Minimum plate thickness 18 gage. For self-shielded material above $\frac{1}{4}$ in. requires joint prep. With CO_2 shielding metals above $\frac{1}{2}$ in. requires joint prep. No upper limit on plate thickness.	Very adaptable, all-position. Can be used outdoors. Excellent joint accessibility. Very portable. Can be used on carbon steels to 18 gage. Joint preparation required on thickness over $\frac{1}{8}$ in. Unlimited upper thickness, but other processes are usually more economical.
Cost Factors	Deposition rates are very high (over 100 LB/h) with multiwire systems. Deposition efficiency is 99% but doesn't include flux. Usually mechanized, high operator factor, cost moderate for single wire systems. High welding speeds. Higher housekeeping costs (slag and unused flux).	Deposition rates to 35 lb/h. Deposition efficiency 90–95%. Operator factor 50%. Equipment and spares cost are moderate to high. Pulsed arc power supplies are higher-cost. Welding speeds moderate to high. Cleanup minimal.	Deposition rates to 40 lb/h are higher than GMAW. Deposition efficiencies 80–90%. Operator factors 50%. Equipment cost moderate. Good out-of-position deposition rates. Welding speeds moderate to high. Slag and spatter removal and disposal required.	Low deposition rate 20 lb/h with low deposit efficiency 65%. Low operator factor. Equipment cost low. Spares minimal. Welding speeds are low. Housekeeping is required to deslag and dispose of flux and electrode stubs.
Weld metal quality	Very good with good toughness, possible. Handles rust and mill scale well with proper flux. High-dilution process.	Very good quality. Porosity or lack of fusion can be a problem. Less tolerant of rust and mill scale than flux-using processes. Very good toughness achievable.	Good quality. Weld metal toughness is fair to good (best with basic electrode). Slag inclusions are a potential problem.	Strongly dependent on skill of operator. Lack of fusion or slag inclusions are potential problems. Small beads result in high percentage of refining in multipass welding and very good toughness is achievable with some electrodes.
Effect on base metal	Higher heat inputs can result in large HAZ and possible deterioration of baseplate properties. Flux is a source of hydrogen.	Generally a low-hydrogen process.	Flux core can contribute hydrogen.	Low heat inputs can cause rapid HAZ cooling. Flux coatings are a potential source of hydrogen.
General comments	A high-deposition, high-penetration process, but thin material can be welded at high speeds. Easily mechanized. Natural for welding thick plates. Housekeeping and position limitation can be a problem.	Relatively versatile. Equipment more expensive, complex and less portable than SMAW. Easily mechanized. A clean process with high deposition rates and good efficiencies.	Relatively versatile. High deposition rates but high fumes also. Welds easily in out-of-position. Readily mechanized.	Very versatile, low-cost process. Especially strong on nonroutine jobs. Usually not economical on standard thick welds or repetitive jobs that can be mechanized.

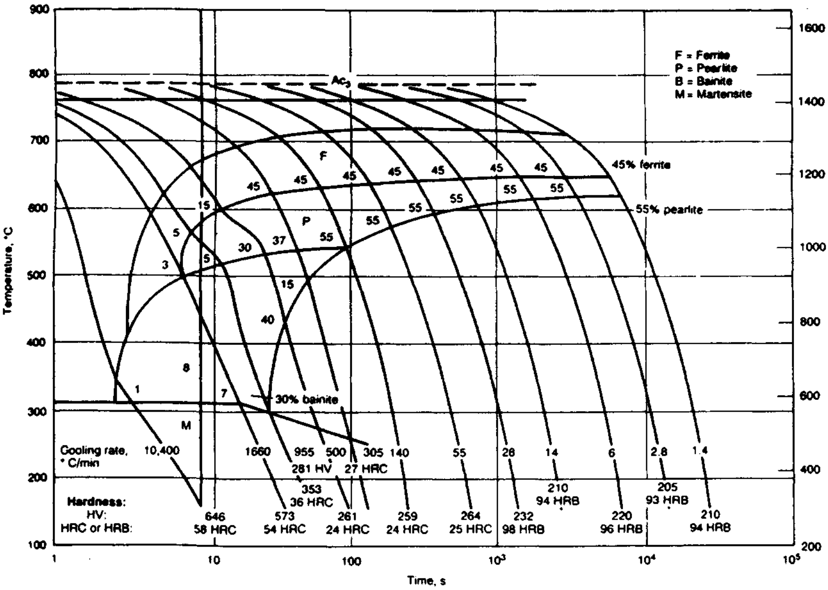


Fig. 35.38 Conventional CCT diagram for an AISI 1541 (.39 C), ASTM grain size 6, austenitized at 980°C. For each of the cooling curves the transformation start and end temperature are given as well as the hardness.

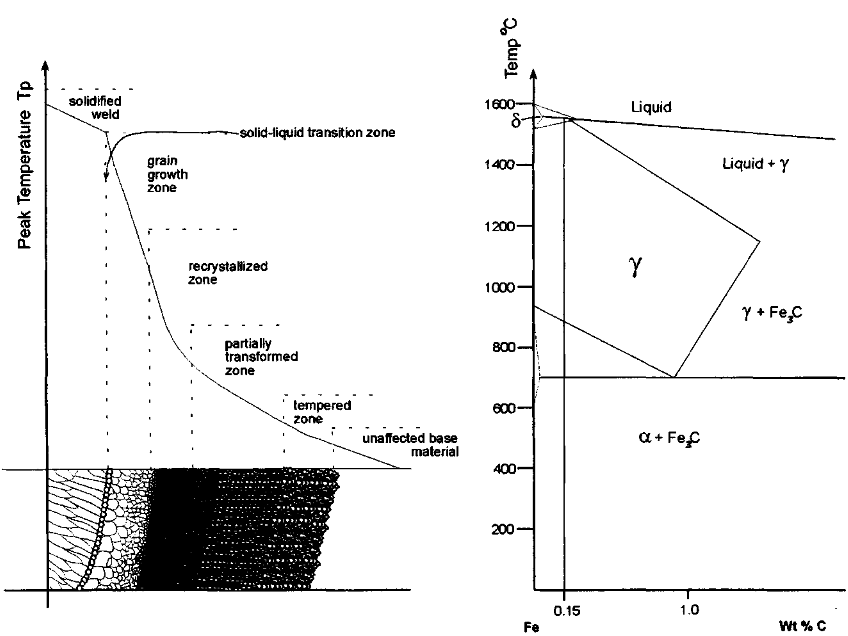


Fig. 35.39 A schematic of the various subzones of the HAZ for the alloy indicated on the Fe-Fe_3C equilibrium diagram.

through the transformation temperature range—in other words, 800 to 500°C. Thicker sections often require preheating because of the greater heat-sinking capacity of thicker sections. Preheating may also lower the level of residual stresses in the welded assembly. Preheat temperatures to 150°C (300°F) are not uncommon for low-alloy steels and may increase to 425°C (800°F) for higher-carbon equivalent steels. The practical limits to preheating are that high base metal temperatures can make welding difficult, particularly for manual welding. Furthermore, a high preheat temperature will result in a flattening of the temperature gradient, increasing the time spent in the austenite range, which will cause excessive grain growth in the HAZ and can lead to a loss of fracture toughness independent of hydrogen content.

Two graphs will give a better idea of the problem. A concise method of describing the transformation behavior of a steel is by a continuous cooling transformation diagram (CCT), as shown in Fig. 35.38. A warning needs to be issued: Fig. 35.38 cannot be used to describe the transformation behavior in a weldment of the same material because weld thermal cycles are very different from those used in generating conventional CCT diagrams.

In Fig. 35.39 we have a peak temperature–cooling time diagram. In this case, thermocouples have been embedded in the base metal at known distances from the molten pool interface. A weld is then made and the peak temperatures at each distance from the molten pool are plotted and correlated to the iron–carbon phase diagram. The HAZ is shown for the case of a single pass weld in a .15% carbon steel, showing each subzone. Each subzone refers to a different microstructure, and each is likely to possess different mechanical properties.

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