Taking Your Weld's Temperature

R. Scott Funderburk is a Welding Design Engineer with The Lincoln Electric Company in Cleveland. This article is excerpted from a paper he is scheduled to present at the 2000 North American Steel Construction Conference in Las Vegas.

A successful welded connection requires properly monitoring and sometimes adjusting the temperature of both base metal and weld metal before, during, and after welding. The heating and cooling of the weld metal and its adjacent base metal will affect the mechanical properties of the weld. Improper rates of heating and cooling can result in weld cracking. To measure and adjust the temperature effectively, the engineer must: calculate heat input (the energy transferred during the process of welding); determine whether or not to apply preheat; measure and adjust the interpass temperature; and decide whether—and how—postweld heat treatment (PWHT) should be applied.

Fundamentals of Pre-Heat

Preheating involves heating the base metal, either in its entirety or just the region surrounding the joint, to a specific desired temperature, called the preheat temperature, prior to welding. Heating may be continued during the welding process, but frequently the heat from welding is sufficient to maintain the desired temperature without a continuation of the external heat source. The interpass temperature, defined as the base metal temperature at the time when welding is to be performed between the first and last welding passes, cannot be permitted to fall below the preheat temperature. Interpass temperature is discussed more fully in the next section of this paper. Preheating can produce many beneficial effects; however, without a working knowledge of the fundamentals involved, one risks wasting money, or even worse, degrading the integrity of the weldment.

Why Preheat?

There are four primary reasons to utilize preheat: it slows the cooling rate in the weld metal and base metal, producing a more ductile metallurgical structure with greater resistance to cracking; the slower cooling rate provides an opportunity for hydrogen that may be present to diffuse out harmlessly, reducing the potential for cracking; it reduces the shrinkage stresses in the weld and adjacent base metal, which is especially important in highly restrained joints; and it raises some steels above the temperature at which brittle fracture would occur in fabrication. Additionally, preheat can be used to help ensure specific mechanical properties, such as weld metal notch toughness.

When Should Preheat Be Used?

In determining whether or not to preheat, the following should be considered: code requirements, section thickness, base metal chemistry, restraint, ambient temperature, welding consumable hydrogen content, and previous cracking problems. If a welding code must be followed, then the code generally will specify the minimum preheat temperature for a given base metal, welding process and section thickness. This minimum value must be attained regardless of the restraint or variation in base metal chemistry; however, the minimum value may be increased if necessary.

When there are no codes governing the welding, one must determine whether preheat is required, and if so, what preheat temperature will be appropriate. In general, preheat usually is not required on low carbon steels less than 1" (25 mm) thick. However, as the chemistry, diffusible hydrogen level of the weld metal, restraint or section thickness increases, the need for preheat also increases.

What Preheat Temperature Is Required?

Welding codes generally specify minimum values for the preheat temperature, which may or may not be adequate to prohibit cracking in every application. For example, if a beam-to-column connection made of ASTM A572 Gr. 50 jumbo sections (thicknesses ranging from 4 to 5 in [100-125 mm]) is to be fabricated with a low-hydrogen electrode, then a minimum prequalified preheat of 225°F (107°C) is required (AWS D1.1-96, Table 3.2). However, for making butt splices in jumbo sections, it is advisable to increase the preheat temperature beyond the minimum prequalified level to that required by AISC for making butt splices in jumbo sections, namely 350°F (175°C) (AISC LRFD J2.8). This conservative recommendation acknowledges that the minimum preheat requirements prescribed by

AWS D1.1 may not be adequate for these highly restrained connections.

When no welding code is specified, and the need for preheat has been established, how does one determine an appropriate preheat temperature? Consider an approach outlined in the American Welding Society's Structural Welding Code, AWS D1.1, Annex XI: "Guideline on Alternative Methods for Determining Preheat." Two procedures are presented for establishing a preheat temperature. These techniques, developed primarily from laboratory cracking tests, are beneficial when the risk of cracking is increased due to the chemical composition, a greater degree of restraint, higher levels of hydrogen or lower welding heat input.

The two methods outlined in Annex XI of AWS D1.1 are: heat affected zone (HAZ) hardness control and hydrogen control. The HAZ hardness control method, which is restricted to fillet welds, is based on the assumption that cracking will not occur if the hardness of the HAZ is kept below some critical value. This is achieved by controlling the cooling rate. The critical cooling rate for a given hardness can be related to the carbon equivalent of the steel, which is defined as:

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

From the critical cooling rate, a minimum preheat temperature can then be calculated. AWS D1.1-96 states that "Although the method can be used to determine a preheat level, its main value is in determining the minimum heat input (and hence minimum weld size) that prevents excessive hardening" (Annex XI, paragraph 3.4).

The hydrogen control method is based on the assumption that cracking will not occur if the amount of hydrogen remaining in the joint after it has cooled down to about 120°F (50°C) does not exceed a critical value dependent on the composition of the steel and the restraint. This procedure is extremely useful for high strength, low-alloy steels that have high hardenability. However, the calculated preheat may be somewhat conservative for carbon steels. The three basic steps of the hydrogen control method are: (1) calculate the composition parameter; (2) calculate a susceptibility index as a function of the composition parameter and the filler metal diffusible hydrogen content; and (3) determine the minimum preheat temperature from the restraint level, material thickness, and susceptibility index.

How Is Preheat Applied?

The material thickness, size of the weldment and available heating equipment should be considered when choosing a method for applying preheat. For example, small production assemblies may be heated most effectively in a furnace. However, large structural components often require banks of heating torches, electrical strip heaters, or induction or radiant heaters.

Preheating carbon steel to a precise temperature generally is not required. Although it is important that the work be heated to a minimum temperature, it usually is acceptable to exceed that temperature by approximately 100°F (40°C). However, this is not the case for some quenched and tempered (Q&T) steels such as A514 or A517, since welding on overheated Q&T steels may be detrimental in the heat affected zone. Therefore, Q&T steels require that maximum and minimum preheat temperatures be established and closely followed. Specific recommendations should be obtained from the steel producer.

When heating the joint to be welded, the AWS D1.1 code requires that the minimum preheat temperature be established at a distance that is at least equal to the thickness of the thickest member, but not less than 3 in (75 mm) in all directions from the point of welding. Finally, the interpass temperature should be checked to verify that the minimum preheat temperature has been maintained just prior to initiating the arc for each pass.

Interpass Temperature

"Interpass temperature" refers to the temperature of the material in the weld area immediately before the second and each subsequent pass of a multiple pass weld. In practice, the minimum interpass temperature is often equal to the minimum specified preheat temperature, but this is not required according to the definition.

Why Is Interpass Temperature Important?

Interpass temperature is just as important as, if not more important than, preheat temperature, with regard to the mechanical and microstructural properties of weldments. For instance, the yield and ultimate tensile strengths of the weld metal are both a function of the interpass temperature. High values of interpass temperature tend to reduce the weld metal strength. Additionally, higher interpass temperatures will generally provide a finer grain structure and improved Charpy V notch toughness transition temperatures. However, when interpass temperatures exceed approximately 500°F (260°C), this trend may be reversed. For example, the American Welding Society (AWS) Position Statement on the Northridge Earthquake recommends that the interpass temperature should not exceed 550°F (290°C) when notch toughness is a requirement.

Why a Maximum?

It may be important to impose control over the maximum interpass temperature when certain mechanical weld metal properties are required. As described in the previous paragraph, weld metal notch toughness is one example. If a designer expects a minimum strength level for a particular component that could experience extremely high interpass temperatures (i.e., due to its size or welding procedures), a maximum interpass temperature should be specified. Otherwise, the weld metal strength could be unacceptably low.

A maximum interpass temperature is also necessary for quenched and tempered (Q&T) steels, such as ASTM A514. Due to the base metal heat treatment, it is critical that the interpass temperature be controlled within limits which will help provide adequate mechanical properties in the weld metal and the heat affected zone. Keep in mind, however, that maximum interpass temperature control is not always required. In fact, the AWS D1.1-98 Structural Welding Code – Steel does not impose such control.

A Delicate Balance

Particularly on sensitive base metals, the minimum interpass temperature must be sufficient to prevent cracking, while the maximum interpass temperature must be controlled to provide adequate mechanical properties. To maintain this balance, the following variables must also be considered: time between passes, base metal thickness, preheat temperature, ambient conditions, heat transfer characteristics, and heat input from welding.

For example, weldments with smaller cross-sectional areas naturally tend to "accumulate" interpass temperature: as the welding operation continues, the temperature of the part increases. As a general rule, if the cross-sectional area is less than 20 in² (130 cm²), then the interpass temperature will tend to increase with each sequential weld pass if normal production rates are maintained.

However, if the cross-sectional area is greater than 40 in^2 (260 cm^2), then the interpass temperature generally decreases throughout the welding sequence unless an external heat source is applied.

How Is Interpass Temperature Measured and Controlled?

One accepted method of controlling the interpass temperature is to use two temperature indicating crayons. A surface applied temperature indicating crayon (often referred to by the trade name Tempilstik) melts when the material to which it is applied reaches the crayon's melting temperature. The crayons are available in a variety of melting temperatures, and each individual crayon is labeled with its approximate melting point. One temperature indicating crayon is typically used to measure both the minimum specified preheat temperature and the minimum specified interpass temperature, while the second is a higher temperature crayon used to measure the maximum specified interpass temperature (if required).

The welder first heats the joint to be welded and checks the base metal temperature at the code-designated location (see "How is Preheat Applied?") by marking the base metal with the first temperature-indicating crayon. When the minimum specified preheat temperature is reached (when the first crayon mark melts), the first welding pass can commence. Immediately before the second and subsequent passes, the minimum and maximum (if specified) interpass temperature should be checked in the proper location. The lower temperature crayon should melt, indicating that the temperature of the base metal is greater than the melting temperature of the crayon, while the higher temperature crayon should not melt, indicating that the base metal temperature is not above the maximum interpass temperature.

If the lower temperature crayon does not melt, additional heat should be applied to the joint until the crayon mark on the base metal melts. And if the upper temperature crayon melts, the joint should be allowed to slowly cool in the ambient air until the upper temperature crayon no longer melts, while the lower temperature crayon does melt. Then the next welding pass can begin.

Where Should Interpass Temperature Be Measured?

There are both codes and industry standards that specify where the interpass temperature is to be checked. Both the AWS D1.1-98 Structural Welding Code – Steel and the AWS D1.5 Bridge Welding Code require that the interpass temperature be maintained "for a distance at least equal to the thickness of the thickest welded part (but not less than 3 in [75 mm]) in all directions from the point of welding." This makes sense, and is conservative when controlling the minimum interpass temperature. However, if maximum interpass temperature is also to be controlled, then the actual interpass temperature in the adjacent base metal may significantly exceed the maximum specified interpass temperature. If this is the situation, it is more appropriate to measure the temperature 1 in (25 mm) away from the weld toe.

In other cases, specific industries have adopted self-imposed regulations. For example, in the ship building industry, the interpass temperature is typically maintained 1 in (25 mm) away from the weld toe and within the first foot (300 mm) of its start. In this particular case, the preheat is applied from the back side of the joint so as to completely "soak" the base metal.

Although there is some debate as to where the interpass temperature should be measured, most experts agree that it must be maintained for some reasonable distance away from the welded joint. Since this decision may greatly influence the fabrication cost, a reasonable and practical location must be determined. One foot away from the joint is probably excessive, while a tenth of an inch, or on the weld itself, is probably excessively conservative. However, one inch from the weld toe seems appropriate.

Postweld Heat Treatment

Postweld heat treatment (PWHT), defined as any heat treatment after welding, is often used to improve the properties of a weldment. In concept, PWHT can encompass many different potential treatments; however, in steel fabrication, the two most common procedures used are post heating and stress relieving.

When is PWHT Required?

The need for PWHT is driven by code and application requirements, as well as the service environment. In general, when PWHT is required, the goal is to increase the resistance to brittle fracture and relaxing residual stresses. Other desired results from PWHT may include hardness reduction, and material strength enhancements.

Post Heating

Post heating is used to minimize the potential for hydrogen induced cracking (HIC). For HIC to occur, the following variables must be present (see Figure 1): a sensitive microstructure, a sufficient level of hydrogen, or a high level of stress (e.g., as a result of highly constrained connections). In structural steels, hydrogen embrittlement occurs at temperatures close to the ambient temperature. Therefore, it is possible to avoid cracking in a susceptible microstructure by diffusing hydrogen from the welded area before it cools. After welding has been completed, the steel must not be allowed to cool to room temperature; instead, it should be immediately heated from the interpass temperature to the post heat temperature and held at this temperature for some minimum amount of time. Although various code and service requirements can dictate a variety of temperatures and hold times, 450°F (230°C) is a common post heating temperature to be maintained for 1 hour per inch (25 mm) of thickness.

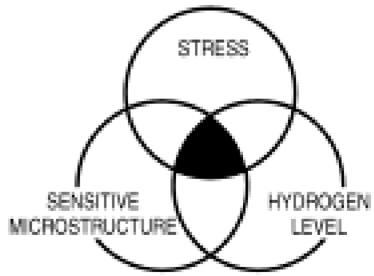

Figure 1. *Criteria for hydrogen induced cracking (HIC).*

The need for post heating assumes a potential hydrogen cracking problem exists due to a sensitive base metal microstructure, high levels of hydrogen, and/or high stresses, and is not necessary for most applications. It may, however, be a code requirement. For example, post heating is often required for critical repairs, such as those defined under the Fracture Control Plan (FCP) for Nonredundant Members of the AASHTO/AWS D1.5 Bridge Welding Code. The FCP provision is 450 to 600°F (230 to 315°C) for "not less than one hour for each inch (25 mm) of weld thickness, or two hours, whichever is less." When it is essential that nothing go wrong, post heating can be used as "insurance" against hydrogen cracking. However, when the causes of hydrogen cracking are not present, post heating is not necessary, and unjustifiable costs may result if it is done.

Stress Relief

Stress relief heat treatment is used to reduce the stresses that remain locked in a structure as a consequence of manufacturing processes. There are many sources of residual stresses, and those due to welding are of a magnitude roughly equal to the yield strength of the base material. Uniformly heating a structure to a sufficiently high temperature, but below the lower transformation temperature range, and then uniformly cooling it, can relax these residual stresses. Carbon steels are typically held at 1,100 to 1,250°F (600 to 675°C) for 1 hour per inch (25 mm) of thickness.

One commonly overlooked detail is that after welding, the component must be allowed to cool to room temperature before stress relieving. If the weldment is not allowed to cool, the residual stresses never get "locked" into place. The residual stresses must be established in order to relieve them.

Stress relieving offers several benefits. For example, when a component with high residual stresses is machined, the material tends to move during the metal removal operation as the stresses are redistributed. After stress relieving, however, greater dimensional stability is maintained during machining, providing for increased dimensional reliability.

In addition, the potential for stress corrosion cracking is reduced, and the metallurgical structure can be improved through stress relieving. The steel becomes softer and more ductile through the precipitation of iron carbide at temperatures associated with stress relieving.

Finally, the chances for hydrogen induced cracking (HIC) are reduced, although this benefit should not be the only reason for stress relieving. At the elevated temperatures associated with stress relieving, hydrogen often will migrate from the weld metal and the heat affected zone. However, as discussed previously, HIC can be minimized by heating at temperatures lower than stress relieving temperatures, resulting in lower PWHT costs.

Other Considerations

When determining whether or not to implement a postweld heat treatment, the alloying system and previous heat treatment of the base metal must be considered. The properties of quenched and tempered alloy steels, for instance, can be adversely affected by PWHT if the temperature exceeds the tempering temperature of the base metal. Stress relief cracking, where the component fractures during the heating process, can also occur. Thus, the specific application and steel must be considered when determining the need, the temperature and time of treatment if applied, and other details regarding PWHT.

The filler metal composition is also important. After heat treatment, the properties of the deposited weld can be considerably different than the as-welded properties. For example, an E7018 deposit may have a tensile strength of 75 ksi (500 MPa) in the as-welded condition. However, after stress relieving, it may have a tensile strength of only 65 ksi (450 MPa). Therefore, the stress relieved properties of the weld metal, as well as the base metal, should be evaluated.

Electrodes containing chromium and molybdenum, such as E8018-B2 and E9018-B3, are classified according to the AWS A5.5 filler metal specification in the stress relieved condition. The E8018-B2 classification, for example, has a required tensile strength of 80 ksi (550 MPa) minimum after stress relieving at 1,275°F (690°C) for 1 hour. In the as-welded condition, however, the tensile strength may be as high as 120 ksi (825 MPa).

For specific PWHT recommendations, one should consult the filler metal manufacturer and/or the steel producer.

What is Heat Input?

In arc welding, energy is transferred from the welding electrode to the base metal by an electric arc. When the welder starts the arc, both the base metal and the filler metal are melted to create the weld. This melting is possible because a sufficient amount of power (energy transferred per unit time) and energy density is supplied to the electrode.

Heat input is a relative measure of the energy transferred per unit length of weld. It is an important characteristic because, like preheat and interpass temperature, it influences the cooling rate, which may affect the mechanical properties and metallurgical structure of the weld and the HAZ (see Figure 2). Heat input is typically calculated as the ratio of the power (i.e., voltage x current) to the velocity of the heat source (i.e., the arc) as follows:

$$H = \frac{60EI}{1000S}$$

where,

H = heat input (kJ/in or kJ/mm)
E = arc voltage (volts)
I = current (amps)
S = travel speed (in/min or mm/min)

This equation is useful for comparing different welding procedures for a given welding process. However, heat input is not necessarily applicable for comparing different processes (e.g., SMAW and GMAW), unless additional data are available such as the heat transfer efficiency (Linnert, 1994).

How is Heat Input Measured?

Heat input can not be measured directly. It can, however, be calculated from the measured values of arc voltage, current and travel speed.

In determining the arc voltage (E), the voltage should be measured as close to the arc as possible, as opposed to the value displayed on the welding machine voltmeter. Measuring the voltage across the arc provides the actual voltage drop across the welding arc. The welding machine voltmeter reading is always higher than the arc voltage due to the resistance of the welding cables (see Figure 3). The machine voltage, therefore, can be used only for approximate calculations and, in the case of significant voltage drops, may lead to heat input calculation errors.

The welding current (I) is measured with either an inductance meter (tong meter) or a shunt with appropriate metering equipment. The current is never fixed with respect to time, especially on a microsecond level. With SMAW, the current is also a function of the arc length, which is dependent on the welder's skill. Therefore, the current used in the heat input calculations should be the average value.

The travel speed (S) is the forward velocity of the arc measured in either inches per minute or millimeters per minute. Only the forward progress contributes to the travel speed. If a weaving technique is used, only the forward speed counts, not the oscillation rate. For vertical welding, the upward or downward speed of the arc is used. The travel speed must be in terms of minutes and not seconds for the dimensions to balance in the heat input equation.

When the travel speed is measured, the arc should be established for an amount of time that will produce an accurate average speed. A continuous welding time of 30 seconds is suggested. If this is not possible for the production

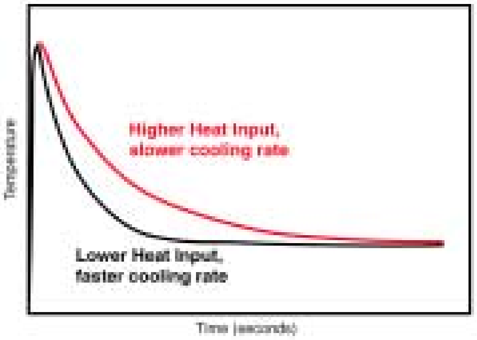

Figure 2. Heat input influences cooling rate.

Figure 3. The arc voltage is always lower than the machine voltage due to the resistance of the welding cables.

joint (e.g., short welds), a test weld should be run on a mock-up joint that will provide a sufficient length to determine the travel speed. The travel speed accuracy with manual or semi-automatic welding is dependent on the welder. However, with automatic welding, the speed is set on the motor controlled travel carriage.

Transient Values

For processes in which the voltage and current vary significantly with time, such as short-circuiting GMAW, the average values of these variables are used in calculating the heat input. For example, with GMAW-pulsed arc, the current is pulsed at a specified frequency from a minimum value (background current) to the maximum value (peak current). The average value between the maximum and minimum current and voltage will provide an approximate heat input value for these welding processes.

With SMAW, the resistance of the electrode changes as it is melted, which results in a voltage change. The temperature of the electrode also increases while its length is reduced during welding, both of which influence the overall resistance. Average values are used in this case as well.

The transient nature of these factors is usually not considered when calculating heat input, and the averages are adequate for procedure qualification or simple comparison of welding procedures. However, for scientific experimentation of cooling rate and heat input a more accurate analysis procedure may be required, including instantaneously monitoring the voltage, current and travel speed to calculate the actual heat input.

Weld Size Is Related to Heat Input

The cross-sectional area of a weld is generally proportional to the amount of heat input. This intuitively makes sense, because as more energy is supplied to the arc, more filler metal and base metal will be melted per unit length, resulting in a larger weld bead. If a welder makes one weld with a fast travel speed and another with a slow travel speed, keeping current and voltage the same for both, then the weld made at the slower travel speed will be larger than the faster one. The following equation is an approximation for the fillet weld leg size based on heat input (Miller, 1998):

$$\omega = \sqrt{\frac{H}{500}}$$

where,
ω = fillet weld leg size (in)
H = heat input (kJ/in)

Although the precise relationship between heat input and fillet weld size also depends on other variables, including the process and polarity, this equation is a helpful tool, especially in creating and reviewing welding procedures. For example, if a minimum fillet weld size is specified, then the corresponding minimum heat input can be determined and controlled.

Cooling Rate is a Function of Heat Input

The effect of heat input on cooling rate is similar to that of the preheat temperature. As either the heat input or the preheat temperature increases, the rate of cooling decreases for a given base metal thickness. These two variables interact with others such as material thickness, specific heat, density, and thermal conductivity to influence the cooling rate. The following proportionality function shows this relationship between preheat temperature, heat input and cooling rate:

$$R \propto \frac{1}{T_o H}$$

where,
R = cooling rate (oF/sec or oC/sec)
T_o = preheat temperature (°F or °C)
H = heat input (kJ/in or kJ/mm)

The cooling rate is a primary factor that determines the final metallurgical structure of the weld and heat affected zone (HAZ), and is especially important with heat-treated steels. When welding quenched and tempered steels, for example, slow cooling rates (resulting from extremely high heat inputs) can soften the material adjacent to the weld, reducing the load-carrying capacity of the connection.

Table 1: *How material properties are affected by increasing heat input for SMAW*

Property*	Change
Yield Strength	under 30%
Tensile Strength	under 10%
Percent Elongation	over 10%
Notch Toughness	over 10% for 15<H<50 kJ/in. under 50% for 50<H<110 kJ/in.
Hardness	under 10%

**SMAW with heat input range of 15 to 110 kJ/in.*

How Does Heat Input Affect Mechanical Properties?

Significantly varying the heat input typically will affect the material properties in the weld. The following table shows how the listed properties change with increasing heat input. An arrow pointed up designates that the property increases as heat input increases. An arrow pointed down designates that the property decreases as heat input increases. Next to the arrow is the approximate amount that a particular property changed from the minimum to maximum value of heat input tested.

Other than notch toughness, all of the mechanical properties show a monotonic relationship to heat input, that is, the mechanical property only increases or decreases with increasing heat input. Notch toughness, however, increases slightly and then drops significantly as heat input increases. The change in notch toughness is not just tied to the heat input, but is also significantly influenced by the weld bead size. As the bead size increases, which corresponds to a higher heat input, the notch toughness tends to decrease. In multiple-pass welds, a portion of the previous weld pass is refined, and the toughness improved, as the heat from each pass tempers the weld metal below it. If the beads are smaller, more grain refinement occurs, resulting in better notch toughness, all other factors being even.

Tests have been conducted with SMAW electrodes and procedures that provided heat inputs varying from 15 kJ/in (0.6 kJ/mm) to 110 kJ/in (4.3 kJ/mm) (Evans, 1997). This represents a very large heat input range, which encompasses most applications of SMAW.

If the changes in heat input are relatively small, as opposed to those of the previous table, then the mechanical properties may not be significantly changed. In another study, no significant correlation between heat input and mechanical properties was established for submerged arc welding (SAW) with typical highway bridge fabrication heat input levels of 50 to 90 kJ/in (Medlock, 1998). In this case, the test results did show varying properties; however, no discernable trends were established.

Welding Code Requirements

As discussed previously, heat input can affect the mechanical properties and metallurgical structure in the weld and HAZ of weldments. The AWS D1.1 Structural Welding Code – Steel controls heat input in three areas: (1) qualified Welding Procedure Specifications, (2) minimum fillet weld sizes (an indirect method of controlling heat input) and (3) quenched and tempered steels.

When heat input control is a contract requirement, and if the procedure used in production has a corresponding heat input that is 10% or greater than that recorded in the Procedure Qualification Record (PQR), then the qualified WPS must be requalified (AWS D1.1-98, Table 4.5, item 18). This is primarily due to concerns regarding the potential alteration of the weld metal and HAZ mechanical properties.

The code also controls the heat input by limiting the minimum size of fillet welds (AWS D1.1-98, Table 5.8). According to the Commentary, "For non-low-hydrogen processes, the minimum size specified is intended to ensure sufficient heat input to reduce the possibility of cracking in either the heat-affected zone or weld metal" (AWS D1.1-98, para. C5.14). For multiple-pass fillet welds, the Commentary includes the following:

"Should fillet weld sizes greater than the minimum sizes be required for these thicknesses, then each individual pass of multiple-pass welds must represent the same heat input per inch of weld length as provided by the minimum fillet size required by Table 5.8." (AWS D1.1-98, para. C5.14).

Quenched and Tempered Steels

When quenched and tempered steels (e.g., A514 and A517) are to be welded, the heat input, as well as minimum preheat and maximum interpass temperatures, must conform to the steel producer's specific written recommendations (AWS D1.1-98, para. 5.7). If high heat input welding is used, the HAZ can be significantly weakened due to high temperatures and slower cooling rates. However, the AWS code requirements do not universally apply to all quenched and tempered steels. For example, with ASTM A913 Grades 60 or 65, which are quenched and self-tempered, the heat input limitations of AWS D1.1 paragraph 5.7 do not apply (AWS D1.1-98, Table 3.1 and 3.2, footnote 9 and 4, respectively).

AWS D1.5 Bridge Welding Code

The AWS D1.5-96 Bridge Welding Code has provisions for heat input in two areas: procedure qualification and fracture critical nonredundant members.

There are three different methods for qualifying procedures in AWS D1.5: the Maximum Heat Input Method, the Maximum-Minimum Heat Input Method, and the Production Procedure Method. For the Maximum Heat Input Method, the heat input must be between 60% and 100% of the value from the Procedure Qualification Record (PQR) used to qualify the WPS (AWS D1.5-96, para. 5.12.1). With the Maximum-Minimum Heat Input Method, the heat input must fall between that of the two required qualification tests. If the Production Procedure Method is used, the heat input can only deviate from the PQR by the following: an increase of up to 10% or a decrease not greater than 30% (AWS D1.5, Table 5.3, item 17).

Fracture Critical Nonredundant Members

Chapter 12 of AWS D1.5 applies to fracture critical nonredundant members (FCMs). The minimum preheat temperature for a FCM is selected based on the heat input, material grade and thickness, and filler metal diffusible hydrogen content (AWS D1.5, Tables 12.3, 12.4 and12.5). Although the focus in chapter 12 of AWS D1.5 is the minimum preheat temperature, the heat input value is an equally controlling variable.