Key Concepts in Welding Engineering

by R. Scott Funderburk

A Look at HEAT Input

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 1). 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:

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

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).

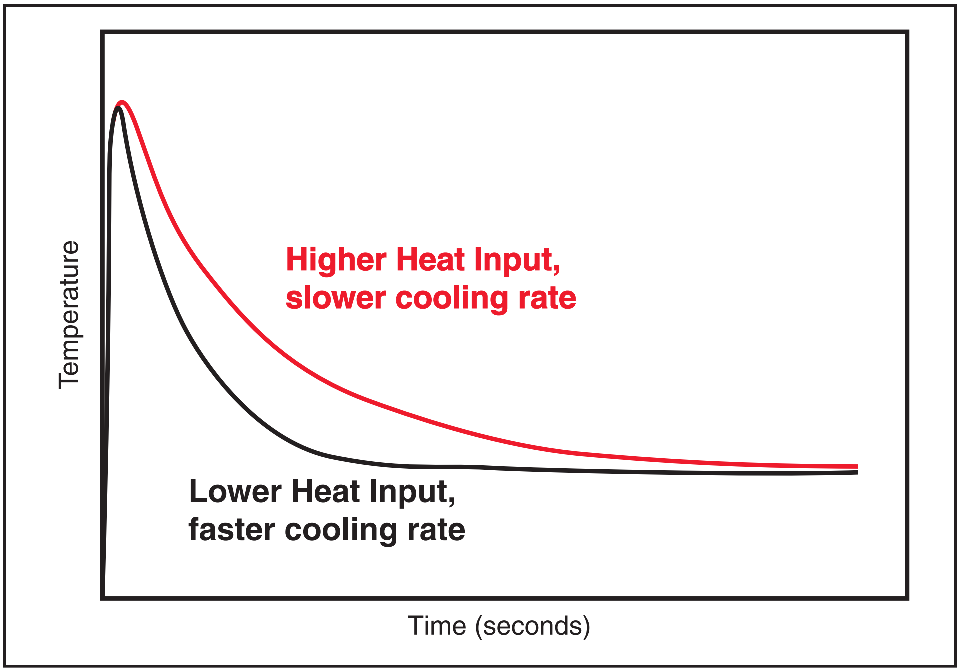

Figure 1. Heat input influences cooling rate.

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.

Arc Voltage

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 2). 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.

Heat input is a relative measure of the energy transferred during welding

Current

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.

Travel Speed

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 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 current is never fixed with respect to time

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.

Figure 2. The arc voltage is always lower than the machine voltage due to the resistance of the welding cables.

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 (°F/sec or °C/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 high heat inputs) can soften the material adjacent to the weld, reducing the load-carrying capacity of the connection.

How Does Heat Input Affect Mechanical Properties?

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 property changed from the minimum to maximum value of heat input tested.

Table 1. How Material Properties are Affected by Increasing Heat Input for SMAW

Property*	Change
Yield Strength	↓ 30%
Tensile Strength	↓ 10%
Percent Elongation	↑ 10%
Notch Toughness (CVN)	↑ 10%, for $15 < H < 50$ kJ/in ↓ 50%, for $50 < H < 110$ kJ/in
Hardness	↓ 10%

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

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 tests results did show varying properties; however, no discernable trends were established.

Welding Codes

As discussed previously, heat input can affect the mechanical properties and metallurgical structure in the weld and HAZ of weldments. The AWS Welding Codes have specific provisions related to heat input for this very reason. Below are the requirements for heat input from AWS D1.1 and D1.5.

AWS D1.1 Structural Welding Code — Steel

The AWS D1.1 Structural Welding Code — Steel controls heat input in three areas: (1) qualified Welding Procedure Specifications, (2) minimum fillet weld sizes and (3) quenched and tempered steels.

Qualified Welding Procedure Specifications (WPSs)

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.

Minimum Fillet Weld Sizes

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 requirement does 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.

Procedure Qualification

There are three different methods for qualifying procedures in 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).

D1.1-98 controls heat input in three areas

Fracture Critical Nonredundant Members

Chapter 12 of 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 D1.5 is the minimum preheat temperature, the heat input value is an equally controlling variable.

Summary

Heat input is a relative measure of the energy transferred during welding. It is a useful tool in evaluating welding procedures within a given process. The cooling rate, weld size and material properties may all be influenced by the heat input. Some welding codes place specific controls on the heat input. To ensure high quality in welded construction, it is important to understand and apply these principles when notch toughness and HAZ properties are to be controlled and when welding high alloy steels.

References

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