Exploring Temper Bead Welding

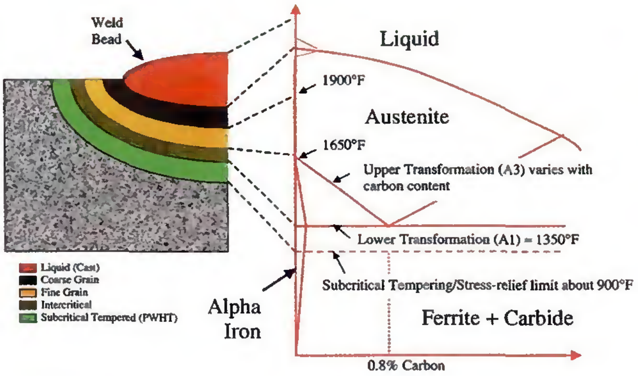

Fig. 1 — Heat-affected zone transition points for various parts of the HAZ as related to the iron-carbon equilibrium diagram.

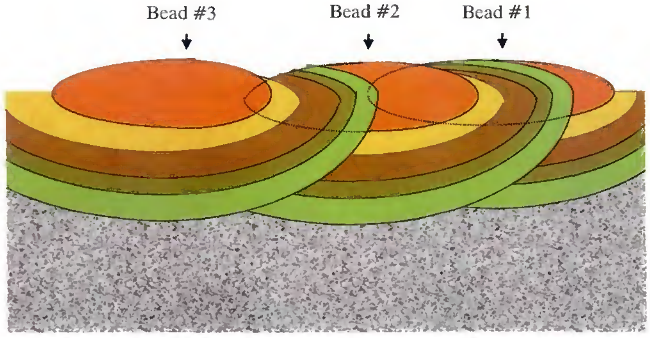

Fig. 2 — The effect of overlap of subsequent beads on the extent of the HAZ of the previously deposited bead. The dotted lines show the previous weld bead locations. Note that the middle bead overlaps the right-hand bead by about 50% of the bead width, and that the remaining HAZ of the first bead is much smaller than the remaining HAZ of the middle bead. The left-hand bead overlaps the middle bead by about 10%, resulting in very little effect on the HAZ of the middle bead.

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With this welding technique, tight control over subsequent weld beads is used to control the properties of previously deposited beads and the heat-affected zone

BY WALTER J. SPERKO

For many years, metallurgists have recognized that welding can have both positive and negative effects on the properties of the base metals being joined, as well as on previously deposited weld metal. Historically, one way of ameliorating some of the deleterious effects was postweld heat treatment of welds. Postweld heat treatment was sometimes known as stress relieving because it lowered residual stress in welds from yield-point order of magnitude to about one-third of yield. For high-carbon steels or low-alloy steels, postweld heat treatment also tempered hard microstructures containing martensite, improving resistance to cracking by improving the toughness of the weld metal or heat-affected zone (HAZ).

Modern steels have changed much of this. Postweld heat treatment is no longer a universal good as it was when steel properties were controlled by solution strengthening mechanisms. In fact, many high-performance steels are designed to be used in the as-welded condition. Microalloyed steels, particularly those containing vanadium, will lose toughness if postweld heat treated.

To optimize the properties of welds in modern steels where postweld heat treatment is not performed, or to optimize properties of steels where postweld heat treatment might be desirable but is not practical, special welding techniques are used. Foremost among these is temper bead welding.

The 2004 edition of the ASME *Boiler and Pressure Vessel Code*, Section IX: Welding and Brazing Qualifications, added requirements for qualification when using temper bead welding. It defines temper bead welding as the following: "A weld bead placed at a specific location in or at the surface of a weld for the purpose of affecting the metallurgical properties of the heat-affected zone or previously deposited weld metal."

The purpose of depositing a temper bead, then, is to affect the properties of the HAZ or the weld metal beneath that

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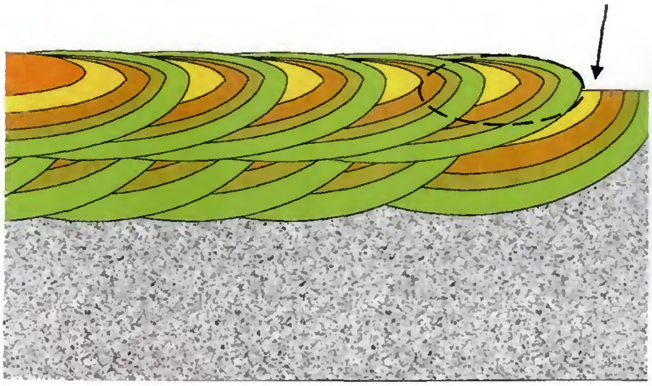

Fig. 3 — *Effect of the second layer of weld metal on the weld metal and HAZ of the first layer. The dashed oval shows the location of the first bead. Note the untempered HAZ at the arrow. The technique for tempering of this zone is shown in Fig. 4.*

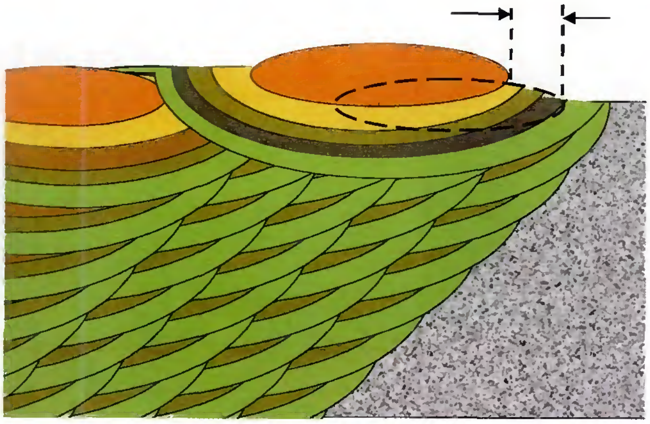

Fig. 4 — *Surface temper reinforcing bead placement. The distance from the toe of the completed weld (right vertical line) to the toe of the surface temper reinforcing bead (left vertical line) needs to be sufficiently small that the HAZ of the reinforcing bead tempers all of the unaffected HAZ in the base metal, but not so small that it creates its own untempered region. Surface temper reinforcing beads may remain in place or may be removed by grinding.*

bead that is being placed at a specific location. What the definition implies, but does not say, is that the temper bead improves the properties of the HAZ or the weld metal located under the temper bead. To understand how this happens and how to optimize the effect, a little metallurgy is necessary.

Figure 1 shows a segment of the iron-carbon equilibrium phase diagram and the locations on the diagram that mark transition points in the HAZ. Keeping it simple, any portion of the HAZ that is heated above the lower transformation temperature (A_1) is subject to changes in microstructure and mechanical properties upon cooling. Those changes can vary from minimal for a low-carbon steel that cools slowly to extreme hardening and embrittlement for a mid-carbon steel containing a few percent chromium, molybdenum, or just a little vanadium.

The factors that determine exactly what microstructures exist in the HAZ after a weld bead is deposited depend mostly on two factors.

1. The chemical composition of the base metal. This is usually expressed using a carbon equivalent (CE) formula such as that published by the International Institute of Welding (IIW): $CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$. The higher the CE, the more hardenable the steel is, and the easier it is to damage during welding. (Note that temper bead techniques normally only apply to carbon and alloy steels. Temper bead welding is not done to austenitic stainless steel, aluminum, copper, nickel, or titanium alloys.)

2. The cooling rate. Faster cooling rates cause harder and more brittle microstructures in higher CE materials.Thicker materials cool faster than thin ones. Welds made with lower heat input cool more rapidly than those made with high heat input. Welds made on cooler base metals cool more rapidly than welds made on hotter base metals.

Other areas of the HAZ are also affected during welding. The portion of the HAZ that sees temperatures above 1900°F experiences grain growth forming the coarse grain region — Fig. 1. The longer this region stays above the grain growth temperature, the more grain growth there is. The larger these grains become, the more the toughness of that region deteriorates.

What factors affect the amount of grain coarsening that occurs? The same ones that affect the cooling rate: Rapid cooling results in a smaller HAZ and less loss of toughness in the HAZ. Slow cooling results in more loss of toughness.

Optimizing Temper Bead Welding Parameters

Going back to the definition, a temper bead is a weld bead placed at a specific location for the purpose of affecting the metallurgical properties of the HAZ or previously deposited weld metal. Once one deposits the first bead, the properties of that bead and its associated HAZ can be changed by weld beads that are deposited next to that bead; the energy flowing from the weld pool raises the temperature of the previously deposited weld and HAZ to "temper" it.

As shown in Fig. 2, a portion of the weld metal and HAZ of the first bead is remelted by the heat from the second bead. If the second bead overlaps the first bead a lot, much of the weld metal and HAZ of the first bead is gone, as shown in the figure; if it only overlaps a little as the third bead overlaps the second, little of the HAZ of the second bead will be affected.

Obviously, the successive beads cannot completely overlap the earlier beads because that would result in a lump of weld metal that would not be very useful; tempering occurs when successive weld beads overlap previous weld beads by 30 to 70%, the optimum being 50%. This is most easily done by having the welder run a stringer bead or a small weave with the electrode pointed at the toe of the previously deposited weld bead. It is also important to make the beads consistent in width and thickness to ensure uniformity of tempering by the next bead and next layer of weld metal.

Once the first layer of weld metal has been deposited over an area, the second layer is deposited. The energy from each bead of the second layer not only affects neighboring beads just like in the first layer, but that energy penetrates into the weld layer below the second layer where it further tempers that weld metal and some of the HAZ beneath the layer — see Fig. 3. Note how the second layer HAZ overlaps the coarse-grain regions of the first layer completely as well as a large portion of the fine-grain regions. Multiple thinner layers provide more uniform tempering than a couple of thick layers.

In the old days, the effectiveness of the second layer on tempering the first layer was enhanced by grinding off part of the first layer — the so-called "half-bead technique." The difficulty with this technique was accurately controlling removal of the first layer weld metal. One could not easily tell if enough or too much of the first

Table 1 — Example of Calculating Heat Input Ratios between Weld Layers

Layer Number	PQR Heat Input*	Ratio	WPS Heat Input 1	WPS Heat Input 2	WPS Heat Input 3	WPS Heat Input 4
1	30		25	30	40	60
2	45	1.5	37.5	45	60	90
3	55	1.22	45.8	55	73.3	110

*All heat inputs shown are in kJ/in., but could be expressed as bead size or deposit length per unit length of electrode.

layer was removed. Later research showed that one could optimize the effectiveness of the second layer by only grinding enough to clean and slightly smooth the first layer, then depositing the second layer using heat input that was about 30 to 70% greater than the heat input used on the first layer. This resulted in optimum overlap of the second layer HAZs over those of the first layer without the labor, aggravation, and uncertainty of grinding off a lot of otherwise perfectly good weld metal. For shielded metal arc welding (SMAW), increasing the electrode size by one size while keeping the same welding technique generally accomplishes this.

Once the second weld layer has been deposited, controlling subsequent weld layers remains critical to control the HAZ properties until at least $\frac{3}{16}$ in. (5 mm) of weld metal has been deposited over the base metal.

Measuring Heat Input

Heat input can be measured three ways. First is the classic heat input formula

$$\text{Heat input} = \frac{\text{Volts} \times \text{Amps} \times 60}{\text{Travel speed}}$$

In this formula, heat input is measured in Joules/inch (J/in.) or Joules/mm (J/mm) depending on whether the travel speed is measured in inches per minute or millimeters per minute. Because the numbers are large, this product is usually divided by 1000 and expressed in kilojoules per unit length (i.e, kJ/in. or kJ/mm).

The second way to measure heat input is by the length of weld deposit per unit length of electrode consumed. This method is particularly easy to use with SMAW because it does not require the welder to measure the amperage, voltage, or travel speed when making production welds. The basis for this method is simply that it takes a certain amount of energy (Joules) to melt a given length of electrode. It does not matter whether the amperage used was at the high end of the electrode's operating range or the low end — the amount of energy consumed is the same at both extremes for all practical purposes. If that energy is spread out over a given length as a weld bead, and that length is divided into measurement units, the energy per unit length will be constant. For example, if it took 120 kJ of energy to melt a ⅛-in. (3.2-mm) electrode from a 14 in. length to a 2-in. stub, and that energy was spread out over a 4 in. length, the equivalent heat input would be 30 kilojoules per inch of weld length. If that energy were spread out over a 3 in. length, the heat input would be 40 kilojoules per inch of weld length. One does not need to calculate the energy that it takes to melt the electrode when using this method; one only needs to measure the length of weld beads deposited for each unit length of electrode consumed. Heat inputs qualified using this method are valid for only the size electrode used, although by measuring both deposit length per unit length electrode and the heat input using the formula for various electrode sizes, one can easily develop correlations between different electrode sizes.

The third method of measuring heat input is by the size of the weld bead. A larger bead will contain more energy and automatically have a higher heat input per unit length than a smaller bead. Weld bead size should be measured as width × thickness for each bead, and the product recorded as the bead area.

To measure the heat input, one simply records the heat input by any of the three methods for each pass on the first layer, then selects a representative value to record on the procedure qualification record (PQR) for that layer. This process is repeated for subsequent layers until the test coupon is welded out.

Specifying Heat Input in the WPS

When writing the welding procedure specification (WPS), the heat input for each weld layer recorded on the PQR becomes the basis for the heat input limits specified on the WPS. While it is not necessary to use the same heat input in production as was used on the test coupon, the ratio of heat input between layers must remain constant as shown in Table 1.

For production welding, if the welder selected a heat input for layer 1 (the layer against the base metal) of 60 kJ/in., the nominal heat input for the next layer is required to be 90 kJ/in. For P-1 metals, section IX sets a tolerance of ±20%, so the heat input for the second layer can be from 72 to 108 kJ/in.

One might ask if this is technically sound. Doesn't increasing the heat input against the base metal increase the size of the HAZ? Yes, that does, but by increasing the heat input in the next layer proportionally, that layer's HAZ is also increased proportionally. Imagine making the weld beads in Fig. 3 twice as large as they are on the figure; the HAZ of each bead increases proportionally, and the figure does not look any different with beads twice as large — except that it is larger.

A WPS that specifies that "the heat input for the second layer shall be between 72 and 108 kJ/in." is inadequate unless the welder has been trained how to calculate the heat input based on the amps, volts, and travel speed that he or she will be using. This means that the welder would have to have a calculator and a stop watch, and understand the math. In the author's opinion, heat input should be controlled in the WPS by appropriate nomographs or by tables showing the amperage and corresponding travel speeds for a given heat input. For example, a heat input showing 72 to 108 kJ/in. at 28 V is detailed in Table 2.

By this table, if the welder chooses to weld at 225 A, he or she has to be within the range of 3.5 to 5.2 in./min travel speed. All WPSs that specify heat input controls should provide the heat input parameters in such a manner that the welder and the QC inspector do not have to calculate anything — they just look it up and use the required parameters. This includes specifying heat input by deposit length per unit length of electrode (which would simply be a minimum and maximum deposit length per unit length of electrode) or a bead width range assuming some typical weld bead thickness.

Table 2 — Travel Speed Range for Various Amperages at 72 and 108 kJ/in. at 28 V

Amps	Minimum Travel Speed(a) (in./min)	Maximum Travel Speed(b) (in./min)
150	2.4	3.5
175	2.7	4.1
200	3.1	4.7
225	3.5	5.2
250	3.9	5.8
275	4.3	6.3
300	4.7	7.0

(a) Based on 108 kJ/in. heat input.
(b) Bsed on 72 kJ/in. heat input.

Heat Input for Fill Layers

Fill layers are those that complete the weld joint after the layers affecting the HAZ have been deposited. Because these layers are weld metal being deposited over weld metal, the welding engineer can choose appropriate filler metals to ensure that the weld metal has appropriate properties. If the basis for temper bead qualification is impact testing, the normal supplementary essential variable QW-409.1 applies. In this case, the heat input may not exceed that qualified for the fill layers. If the basis for qualification is hardness limits, the heat input may not be less than 20% below the heat input qualified.

Optimizing Properties at the Toe of a Completed Weld

After completing a weld using the temper bead technique, there is still one region where no tempering of the HAZ has occurred. That is at the toe of the weld as shown in Fig. 3. In addition, there is weld metal that is also not tempered. If necessary to obtain the desired properties, one may have to add an additional layer of weld metal to the completed weld — and then grind it off. This results in tempering of the remaining untempered weld metal and HAZ. One does, however, have to be careful when approaching the edge of the weld not to let this extra tempering layer get too close to the toe of the weld. If it does, it will create a new untempered HAZ. The trick in optimizing the properties at the toe of the weld is to place the tempering bead a short distance from the toe, typically ⅛ to 3⁄16 in. This allows the heat from the tempering bead to penetrate the weld metal and the HAZ at the weld toe, tempering both. Often, just tempering the weld toe is adequate to achieve the required properties, avoiding the extra work of overlaying the entire weld surface and then grinding it off — see Fig. 4. ♦

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