TOOLS FOR REVIEWING WELDING PROCEDURES

Analytical aids based on documented welding procedures are offered to engineers for evaluating WPSs

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For structural steel projects, AWS D1.1 *Structural Welding Code — Steel* is typically the governing code, and welding procedure specifications (WPSs) are central to controlling weld quality in these applications. Although the contractor writes the WPSs for the primary purpose of instructing the welder, the Engineer of Record may be required to review them for comment and approval. This paper contains some tools to help the engineer in this process. It is not the authors' intention to provide a comprehensive lesson on how to review WPSs, but rather to deliver a few new analytical tools for use by the reviewer. While based on AWS D1.1 principles, these "tools" are applicable to other welding situations as well.

These analytical tools are based on approximately 270 different documented welding procedures (Refs. 2, 3). Included were procedures for shielded metal arc welding (SMAW), gas metal arc welding (GMAW), self-shielded flux cored arc welding (FCAW-S), gas-shielded flux cored arc welding (FCAW-G) and submerged arc welding (SAW) with single, parallel and multiple electrodes. This database is generally representative of typical structural steel fabrication procedures and was used to develop the equations and general trends presented here.

Heat Input

When reviewing welding procedures, perhaps the most difficult aspect is determining which combination of amperage, voltage and travel speed will be acceptable for a given application. These three variables directly affect heat input, which is a measure of the amount of energy transferred during the welding process. Heat input is calculated as follows:

$$H = \frac{60EI}{1000S} \qquad (1)$$

where, E = arc voltage, I = current, S = travel speed, in./min (mm/min), H = heat input, kJ/in. (kJ/mm)

Heat input is usually associated with cooling rates of the weld and heat-affected zone (HAZ). However, heat input is also directly proportional to the individual weld bead cross-sectional size. Figure 1 shows the size of a fillet weld increases as the heat input increases.

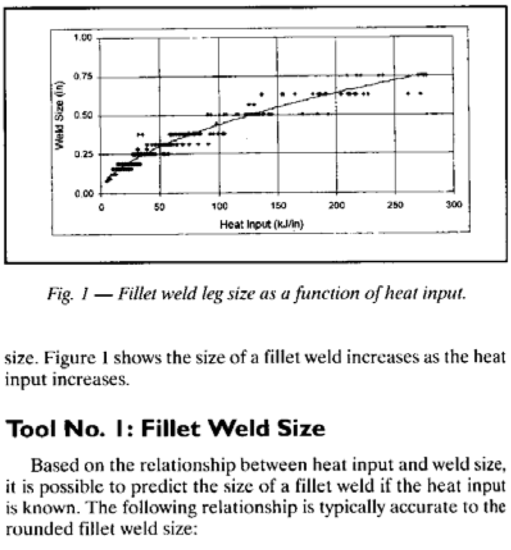

Fig. 1 — Fillet weld leg size as a function of heat input.

Tool No. 1: Fillet Weld Size

Based on the relationship between heat input and weld size, it is possible to predict the size of a fillet weld if the heat input is known. The following relationship is typically accurate to the rounded fillet weld size:

$$\omega = \sqrt{\frac{H}{500}} \quad \text{U.S. customary}$$

$$\omega = 5.5\sqrt{H} \quad \text{metric} \qquad (2)$$

where, ω = leg size, in. (mm) and H = heat input, kJ/in. (kJ/mm)

When the calculated decimal value is converted to the nearest fillet weld size in standard increments, typically ¹⁄₁₆ in. (1 mm), the predicted leg size is typically equal to the actual weld size.

The same equation can be used to predict heat input levels for various fillet weld sizes.

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$$H = 500\,\omega^2 \quad \text{U.S. customary}$$

$H = \frac{\omega^2}{32.5}$

$$H = \frac{\omega^2}{30.3} \quad \text{metric} \tag{3}$$

This allows for a quick prediction of the heat input that will be achieved based upon the requisite weld size. If, for example, a ½-in. (12.7 mm) fillet weld is made in a single pass, the heat input would be approximately 125 kJ/in. (5 kJ/mm).

Following is an example of how one would check a proposed procedure to determine if the electrical values could produce the expected fillet weld size.

Example 1

A contractor proposes to use submerged arc to make a 5/16-in. fillet weld using the following parameters: electrode diameter, 5/32 in.; polarity, DC –; current, 575 A; voltage 34 V; travel speed, 22 in./min.

Is this a viable combination of variables for this size of fillet weld?

$$H = \frac{60EI}{1000S} = \frac{60(34)(575)}{1000(22)} = 53.3 \text{ kJ/in.}$$

$$\omega = \sqrt{\frac{H}{500}} = \sqrt{\frac{53.3}{500}} = 0.326 \text{ in. or } \frac{5.2}{16} \tag{4}$$

Therefore, the proposed procedure should be capable of producing a 5/16-in. fillet weld.

Tool No. 2: Square Groove Welds

In order to minimize joint preparation costs, square groove welds may be employed. This complete joint penetration (CJP) detail is not prequalified according to AWS D1.1. To successfully achieve complete fusion through the cross section, a balance must be achieved to obtain adequate penetration and yet avoid melt-through. If no backing is applied to the joint, it is generally difficult to avoid melt-through if the level of penetration exceeds approximately 60% of the cross section, particularly when welding from the first side. The second side weld is more resistant to melt-through; the 60% factor is still a good rule of thumb. Obviously, if less than 50% penetration is achieved from each side, a CJP weld cannot be achieved. With 60% from each side, there will be an approximate 20% overlap between the two passes, adequate to provide repeatability. The maximum heat input that can be applied by a first-pass weld without melt-through can be estimated from the following:

$$H_{max1} = 130\,t - 15 \quad \text{U.S. customary}$$

$$H_{max1} = 0.23\,t - 0.60 \quad \text{metric} \tag{5}$$

where, H = heat input, kJ/in. (kJ/mm) and t = plate thickness, in. (mm)

While the second side weld can tolerate heat inputs up to the following:

$$H_{max2} = 140\,t - 15 \quad \text{U.S. customary}$$

$$H_{max2} = 0.22\,t - 0.60 \quad \text{metric} \tag{6}$$

When reviewing WPSs, one can simply use the following equation to determine the absolute maximum heat input to prevent melt-through:

$$H_{max} = 150\,t \quad \text{U.S. customary}$$

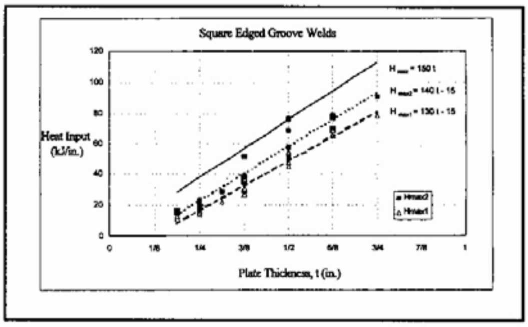

Fig. 2 — Plots of 42 submerged arc welding procedures.

$$H_{max} = 0.23\,t \quad \text{metric} \tag{7}$$

The preceding relationships are based upon SAW with DC+ polarity, the process typically employed when deep penetration is necessary for achieving CJP welds in square edge butt joints. Plotted in Fig. 2 are 42 submerged arc welding procedures and joints from Ref. 3, and below are three applicable equations.

This provides some insight into the maximum heat inputs that can be tolerated to avoid melt-through, but in order to achieve adequate penetration, the heat input should be at least 70% of the maximum value. Below is an example.

Example 2

A proposed WPS involves a CJP weld on a square-edge butt joint involving ½-in. steel. Submerged arc welding is to be used with the following proposed parameters: electrode diameter, 3/16 in.; polarity, DC+; current, side 1 — 750 A, side 2 — 850 A; volts, side 1 — 35 V, side 2 — 36 V; travel speed 32–38 in./min.

The range of travel speed would be within a ± 10% range of a nominal 35 in./min. Will melt-through occur?

The heat input for the first side is calculated with the lowest proposed travel speed that will give the highest heat input.

$$H = \frac{60EI}{1000S} = \frac{60(35)(750)}{1000(32)} = 49.2 \text{ kJ/in.} \tag{8}$$

$$\begin{aligned} H_{max1} &= 130\,t - 15 \\ &= 130\left(\frac{1}{2}\right) - 15 \\ &= 50 \text{ kJ/in.} \end{aligned} \tag{9}$$

Melt-through is not expected with the highest first side parameters.

A similar series of calculations show the maximum second side heat input to be 57.4 kJ/in.

$$\begin{aligned} H_{max2} &= 140\,t - 15 \\ &= 140(1/2) - 15 \\ &= 55 \text{ kJ/in.} \end{aligned} \tag{10}$$

This would predict that melt-through might be a possibility. An increase to 34 in./min decreases the heat input to 54 kJ/in., an acceptable level. This proposed WPS could not be prequalified due to the base-metal thickness, so a procedure qualifica-

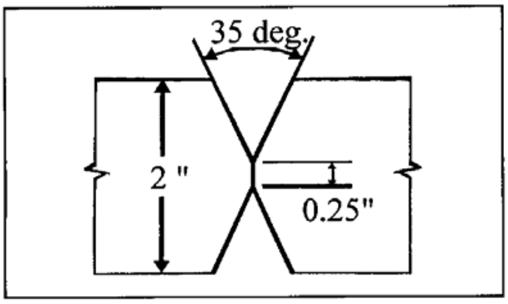

Fig. 3 — Joint detail for Example 5.

tion record (PQR) should accompany the proposed WPS. A review of the actual travel speeds used would be advisable. It would be best to control the minimum travel speed to prevent melt-through.

Tool No. 3: Minimum Heat Input Levels for Multiple Pass Welds

The AWS D1.1 *Structural Welding Code — Steel* prescribes minimum fillet weld sizes as a function of material thickness. This is not for design reasons, but to ensure the heat input of welding will be in proportion to material thickness in order to avoid problems such as incomplete fusion and unacceptable hardening of the heat-affected zone. As has been previously demonstrated, it is possible to estimate the heat input required to make a given fillet weld size. Thus, for a given plate thickness, it is possible to estimate the minimum heat input necessary in order to achieve the requisite minimum fillet weld sizes.

The most straightforward approach is the method in the code, that is, to specify the minimum fillet weld size. However, for multiple-pass groove welds, it is equally important that the heat input for each given weld pass be sufficiently high so as to ensure fusion and avoid the development of unacceptably hard heat affected zones. The following relationship has been derived in order to estimate the minimum level of heat input necessary, based upon the thickness of steel being joined:

$$H_{min} = 30\,t^2 + 15\,t \quad \text{U.S. customary}$$

$$H_{min} = \frac{t^2}{550} + \frac{t}{40} \quad \text{metric} \qquad (11)$$

where, H = heat input, kJ/in. (kJ/mm) and t = plate thickness, in. (mm).

Since this is an equation to check the heat input, and since the concern here is the minimum level of heat input, the equation has been based upon the lowest level of heat input associated with the single pass fillet welds.

In no case should it be necessary to increase the heat input beyond the level of 50 kJ/in. (2 kJ/mm), providing low-hydrogen electrodes and processes are employed. This is consistent with the code mandating no greater than a 5/16 in. (8 mm) fillet weld, regardless of plate thickness, when low-hydrogen electrodes and processes are used.

Tool No. 4: Number of Weld Passes Required

When a given joint detail has been established, it is possible to estimate with reasonable accuracy the number of passes that are anticipated to complete the welded joint. To analytically determine the number of passes, the following equation can be used.

$$N = \frac{300\,Wt}{H} \quad \text{U.S. customary}$$

$$N = \frac{11\,Wt}{H} \quad \text{metric} \qquad (12)$$

where, Wt = weight of weld metal per length of weld, lb/ft (kg/mm) and H = heat input, kJ/in. (kJ/mm).

Example 3

A proposed WPS utilizes a heat input of 240 kJ/in. (9.5 kJ/mm), and suggests a 1.75-in. (44 mm) fillet weld can be made in 7 passes. Is it valid? Such a fillet weld requires approximately 5.7 lb of weld metal per foot.

$$\begin{aligned} N &= 300\,Wt/H \\ &= 300\,(5.7)/240 \\ &= 7.1 \text{ passes (ok)} \end{aligned} \qquad (13)$$

Tool No. 5: Root Pass Thickness

The root pass of a groove weld is usually the most difficult pass to make, and may be the most critical part of the weld, depending on the joint application. Excessively thick root passes often contain slag inclusions and incomplete penetration. The root-pass thickness in groove welds based upon the heat input calculated from the welding parameters can be estimated from the following relationships.

The cross-sectional area of a weld deposited in one pass is equal to

$$A = \frac{H}{1000} \qquad (14)$$

The cross-sectional area for a groove weld (no reinforcement) in a bevel or a V-groove weld is as follows:

$$A = hR + \frac{h^2\tan\alpha}{2} + \frac{h^2\tan\beta}{2} \qquad (15)$$

where, h = root pass thickness, in. (does not include any penetration); R = root opening, in.; α = bevel angle No. 1; β = bevel angle No. 2; and H = heat input, kJ/in.

Combining the two relationships results in

$$\frac{H}{1000} = hR + \frac{h^2\tan\alpha}{2} + \frac{h^2\tan\beta}{2} \qquad (16)$$

Once simplified, the root pass thickness h is estimated from

$$h = \frac{-1000R + \sqrt{(1000R)^2 + 2000H\,(\tan\alpha + \tan\beta)}}{1000\,(\tan\alpha + \tan\beta)} \qquad (17)$$

Notice h is defined as the amount of buildup of weld metal on top of the previous surface. It does not include any root penetration.

These relationships can also be used to determine the maximum acceptable heat input level for a specific root geometry if the root pass is held to a specific thickness. For example, D1.1-2000, Table 3.7, restricts the root pass thickness for prequalified WPSs for the various processes. Solving for the heat input for the previous equation yields the following equation:

$$H = 1000hR + 500h^2 \tan\alpha + 500h^2 \tan\beta \qquad (18)$$

If the maximum allowable bead height, h, equals 3/8 in. (9.5 mm) (*e.g.*, flat position SMAW, GMAW, FCAW per AWS D1.1), then the maximum allowable heat input can be found by solving the previous equation.

$$H_{max} = 375R + 70.3(\tan\alpha + \tan\beta) \qquad (19)$$

This equation is valid only for h equal to 3/8 in. (9.5 mm); however, one could determine the maximum heat input for other positions with varying maximum bead heights.

Example 4

Consider a B-U4a-GF prequalified joint detail with a root opening equal to 3/8 in. and an included angle of 30 deg ($\alpha = 30$, $\beta = 0$). The maximum heat input for the root pass to not exceed the 3/8-in. maximum thickness would be 180 kJ/in.

Tool No. 6: Weld Root Details

The specific geometry for a CJP groove weld that deviates from prequalified conditions should be evaluated to determine whether the geometry is conducive to sound welds that will be free of excessive discontinuities and unacceptable cracks. Acceptable combinations of the root openings and included angles are important to ensure that centerline cracking does not develop because of an inappropriate width-to-depth ratio. In general, the recommended width-to-depth ratio to prohibit centerline cracking varies from 1.0 to 1.4. The following equation can be used to evaluate any combination of V-groove or beveled groove welds to ensure this proper ratio is achieved:

$$\frac{W}{d} = \frac{R + h\left(\tan\alpha + \tan\beta\right)}{h + P} \qquad (20)$$

where, W = bead width; d = bead depth; R = root opening; α = bevel angle No. 1; β = bevel angle No. 2; P = depth of penetration; and h = bead height.

The root pass thickness (h) can be calculated from the previously presented relationship. The bead depth d is equal to h + P. Determining the depth of penetration is more difficult, but for procedure review purposes, an estimate of 0.125 in. will conservatively identify joints where width-to-depth problems may exist. This is not to imply, however, that this level of penetration is always achieved.

Achieving the proper root geometry will help preclude centerline cracking, but it does not ensure freedom from incomplete fusion or slag inclusions. This is best ascertained by careful examination of the macroetch specimen that is part of qualification testing. Acceptable results from the required nondestructive examination, as well as successful results from the requisite bend specimens, will provide assurance of a sound weld.

Example 5

A nonprequalified joint detail is to be welded with 350 A, 26 V and a travel speed of 10 in./min (heat input equals 54.6 kJ/in.). The double V-groove weld detail has an included angle of 35 deg and a root face dimension of 0.25 in., as shown in the sketch below. The design requires a complete joint penetration groove weld, and the weld is to be made without backgouging. There is some concern that this situation may result in an improper width-to-depth ratio, which could lead to centerline cracking. Determine the width-to-depth ratio. Is the potential for root cracking an issue?

Assuming a penetration of 3/16 in. is achieved, the following is calculated:

$$h = \frac{-1000R + \sqrt{\left(1000R\right)^2 + 2000H\left(\tan\alpha + \tan\beta\right)}}{1000\left(\tan\alpha + \tan\beta\right)} \qquad (21)$$

Since $\alpha + \beta$ = included angle = 35 deg and $\alpha = \beta$, then $\alpha = 17.5$ deg.

$$h = \frac{-1000(0) + \sqrt{\left(1000x0\right)^2 + 2000\left(54.6\right)\left(2\tan 17.5\right)}}{1000\left(2\tan 17.5\right)}$$

$$h = \frac{330.4}{630.6} = 0.524 \text{ in.} \qquad (22)$$

Note that this exceeds the code maximum thickness of 0.375 in. for the flat position. Next, a specific check on the width-to-depth ratio is made.

$$\frac{W}{d} = \frac{R + h\left(\tan\alpha + \tan\beta\right)}{h + p} = \frac{0 + 0.524\left(2\tan 17.5\right)}{0.524 + 0.1875}$$

$$\frac{W}{d} = \frac{0.330}{0.7115} = 0.463 \qquad (23)$$

This ratio is much less than the lowest recommendation of 1.0, and centerline cracking is a concern. The suggested procedures are suspect, and the supporting PQR should be carefully criticized.

Conclusions

Welding must be performed under conditions that can be expected to achieve high-quality results. A WPS is the primary means by which the proper welding conditions are communicated to the welder. It is essential the welder perform the actual welding in conformance with the WPS, but it is equally important the WPS provide the values necessary for achieving these goals. When welding procedures fall outside the guidelines presented, more careful scrutiny of the procedure is justified, and, when appropriate, the services of an expert welding engineer should be employed to properly evaluate the suitability of the proposed WPS. ◆

References

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