Design File

Use Undermatching Weld Metal Where Advantageous

Practical Ideas for the Design Professional by Duane K. Miller, P.E.

How Strong Does a Weld Have To Be?

The answer is fairly simple: strong enough to transfer the loads that are passed between the two interconnected materials. How strong does the weld metal have to be? The answer to that question is far more complex.

In order to make a weld of sufficient size, the designer has three variables that can be changed to affect the weld strength:

- weld length,
- weld throat, and
- weld metal strength.

Since three variables are involved, there are many combinations that are suitable for obtaining the correct weld strength. It may be necessary to also consider the loads imposed on the base metal to ensure that the complete welded joint has sufficient strength. This edition of "Design File" will focus on the variable of weld metal strength.

For purposes of this discussion, "weld metal strength" is defined as the yield and tensile strength of the deposited weld metal, as measured by an all-weld metal tensile coupon extracted from a welded joint made in conformance with the applicable AWS filler metal specification. "Matching" weld metal has minimum specified yield and tensile strengths equal to or higher than the minimum specified strength properties of the base metal. Notice that the emphasis is placed on minimum specified properties because, in the case of both the filler metal and the base metal, the actual properties are routinely higher. An example of matching weld metal would be the use of E70XX filler metal on A572 grade 50 steel. The weld metal/base metal properties for this combination would be 60/50 ksi (414/345 MPa) yield strength and 75/65 ksi (517/448 MPa) tensile strength. Even though the weld metal has slightly higher properties than the base metal, this is considered to be a matching combination.

All too often, engineers see filler metal recommendations provided in codes that reference "matching" combinations for various grades of steel and assume that this is the only option available. While this will never generate a nonconservative answer, it may eliminate better choices. Matching filler metal tables were designed to give the recommendations for one unique situation where matching weld metal is required, that is, Complete Joint Penetration (CJP) groove welds in tension applications. All other applications permit some degree of undermatching, and undermatching may be a very desirable, cost-effective alternative for applications such as Partial Joint Penetration (PJP) groove welds and fillet welds.

The significance of weld metal strength, as compared to base metal strength, has increased in recent years, as the number of higher strength steels continues to grow. When A36 was the predominant steel, commercially available filler metals would routinely overmatch the weld deposit. As steels with a 50 ksi (345 MPa) minimum specified yield strength became more popular (e.g., A572 grade 50 and A588), the use of the E70XX grades of filler metals provided for a matching relationship. Steels with minimum specified yield strengths of 70 ksi (483 MPa) through 100 ksi (690 MPa) have become more and more popular. Although matching strength filler metals are available, the option of using undermatched weld metal, where applicable, is increasingly attractive.

When undermatching weld metal is utilized, the designer must ensure that weld strength is achieved, but this is easily done with the standard equations used to determine the allowable stress on the weld.

For fillet welds in 90° T-joints, the maximum allowable load on the weld can be determined from the following equation:

$$F = (0.3)\,(0.707)\,\omega\,(EXX)\,L$$

where,

ω	=	weld leg size
EXX	=	minimum specified tensile strength of the filler metal
L	=	length of the weld

By substituting in the strength level of the undermatched filler metal, the weld strength can be determined. Undermatching may be used to reduce the concentration of stresses in the base metal. Lower strength weld metal will generally be more ductile than higher strength weld metal. In Figure 1, the first weld was made with matching filler metal. The second weld utilizes undermatching weld metal. To obtain the same capacity for the second joint, a large fillet weld has been specified. Since the residual

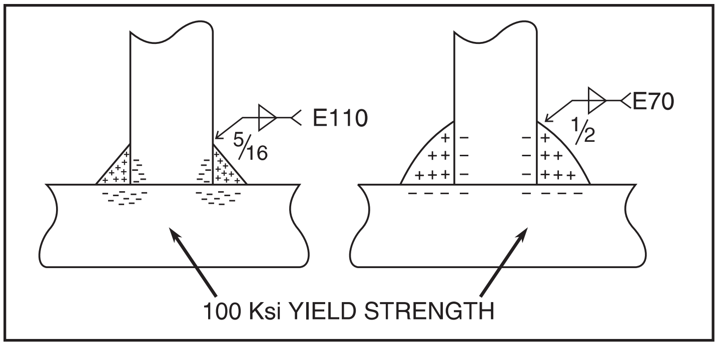


Figure 1. Matching and undermatching filler metal.

stresses are assumed to be of the order of the yield point of the weaker material in the joint, the first example would have residual stresses in the weld metal and in the base metal of approximately 100 ksi (690 MPa) level. In the second example, the residual stresses in the base metal would be approximately 60 ksi (20 MPa), since the filler metal has a lower yield point. These lower residual stresses will reduce cracking tendencies, whether they might occur in the weld metal, in the heat affected zone, or as lamellar tearing in the base metal.

Overmatching is undesirable and should be discouraged. Caution must be exercised when overmatching weld metal is deliberately used. The strength of a fillet weld or PJP groove weld is controlled by the throat dimension, weld length, and strength of the weld metal. In theory, overmatching filler metal would enable smaller weld sizes to be employed and yet create a weld of equal strength. However, the strength of a connection is dependent not only on the weld strength, but also on the strength of the fusion zone. As the weld size decreases, the fusion zone is similarly reduced in size. The capacity of the base metal is not affected by the selection of the filler metal, so it remains unchanged. The reduction in weld size may result in overstressing the base metal.

Consider the three PJP groove welds shown in Figure 2. A load is applied parallel to the weld, that is, the weld is subject to shear. The allowable stress on the groove weld is 0.30 times the minimum specified tensile strength of the

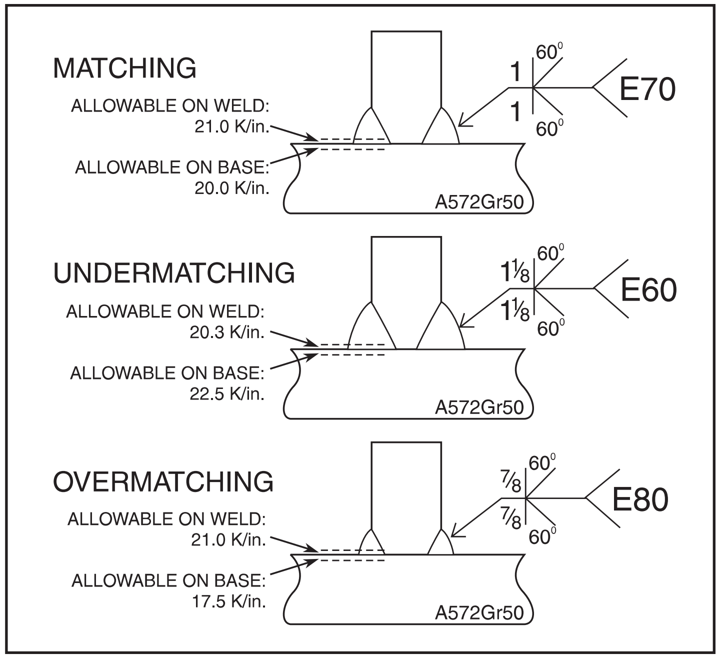


Figure 2. Effect of filler metal strength level.

electrode (i.e., the "E" number). The allowable stress on the base metal is required not to exceed 0.40 times the yield strength of the base metal. The first weld employs a matching combination, namely A572 grade 50 welded with E70 electrode. The second example examines the same steel welded with undermatching E60 electrodes, and the final example illustrates overmatching with an E80 electrode.

As shown in Figure 2, the allowable stress on the weld and the allowable stress on the base metal have both been calculated. In the case of undermatching weld metal, the weld metal controls the strength of the joint. For matching weld metal, the allowable load on both the weld and the base metal is approximately the same. In the case of the overmatching weld metal, however, the base metal is the controlling variable. For this situation, it is important to check the capacity of the base metal to ensure that the connection has the required strength.

Practical Applications

Although it is relatively easy to determine which situations are suitable for the use of undermatching weld metal, some designers may simply choose to use the "conservative" approach and specify matching weld metal for all situations. However, matching weld metal may actually reduce overall weld quality, increasing distortion, residual stresses, and cracking tendencies, including lamellar tearing. The use of undermatched weld metal is an important option for successfully joining higher strength steels.

When welding on higher strength steels with undermatching weld metal, it is important that the level of diffusible hydrogen in the deposited weld metal be appropriate for the higher strength steel that is being welded. For example, whereas an E6010 electrode is suitable for welding on lower strength steels that are not subject to hydrogen assisted cracking, it would be inappropriate to utilize this as an undermatching weld metal on 100 ksi (690 MPa) yield strength A514 or A517 since these are highly sensitive to hydrogen cracking. When undermatched weld metal is used, it must not exceed the maximum levels of diffusible hydrogen appropriate for matching strength weld deposits. Also, any preheat requirements for matching strength relationships must be maintained even when undermatching weld metal is utilized.

There are economic considerations as well. While many filler metals from various welding processes are capable of delivering 70 ksi (490 MPa) weld deposits, the number of options available to the fabricator is greatly reduced when 100 ksi (690 MPa) yield strength weld metal is required (i.e., E110 class filler metals). The metallurgical characteristics necessary for the deposition of weld metal at this strength level may impose restrictions on the electrode designer which limit the attainable welding speeds and/or operational characteristics. In contrast, the requirements for lower strength filler metals give the electrode designers more latitude and may result in improved operational characteristics.

For many beam-like sections that are subject to bending, the resultant longitudinal shear that must be transmitted between the web and the flange of a built-up section is relatively small. Weld sizes that are based upon the transfer of the stress alone may result in surprisingly small welds, welds so small that they may be difficult to make on a production basis. The heat input associated with these small welds may be so small that weld cracking results. For these reasons, the D1.1 code has established minimum fillet weld sizes that, regardless of the level of stress imposed on the weld, should be maintained in order to obtain sound welds. For example, the minimum fillet weld size for 3/4 in. (18mm) steel is 1/4 in. (6mm). For materials greater than 3/4 in. (18mm), a 5/16 in. (8mm) fillet weld is the minimum acceptable size. The implications of this are that, for most structural fabrications involving built-up sections, the minimum fillet weld size is 5/16 in. (8mm). This is often greater than the required fillet weld size necessary to transfer the longitudinal shear. Particularly in these applications, undermatched weld metal offers a significant advantage because the minimum required weld size can be achieved utilizing the undermatched weld metal, and this may also satisfy design requirements.

The following welding procedures have assumed that the governing factor for the design of the members subject to bending is the minimum weld size, not the allowable stress on the connection. This will not always be the case. However, comparing the welding procedures associated with the two connections shows the benefit of utilizing the undermatched filler metal.

Example – Matching Versus Undermatching Filler Metal

Given: T-joint formed by 3/8” and 1” plates, 5/16” fillet weld, horizontal position, automatic SAW

Find: Cost savings for using undermatching versus matching filler metal

Assumptions: SAW Flux/electrode combinations – 960/L-61 (undermatching) and 880M/LAC-M2 (matching)

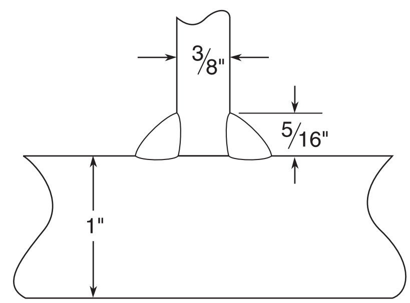
Labor & Overhead = $40.00/hr.

Equations: Cost = Labor + Materials

$$\text{Cost (\$/ft)} = \left[\frac{\text{Labor \& Overhead (\$/hr)}}{\text{Travel Speed (in/min)}} \; \frac{\text{12 in/ft}}{\text{60 min/hr}}\right]$$

$$+ \text{[electrode used (lb/ft) x electrode cost (\$/lb)]}$$

$$+ \text{[flux used (lb/ft) x flux cost (\$/lb)]}$$



	Undermatching 960/L-61	Matching 880M/LAC-M2
Labor & Overhead ($/hr.)	$ 40.00	$ 40.00
Travel Speed (in./min.)	20.0	16.0
Electrode Used (lb./ft. of joint)	0.19	0.28
Electrode Cost* ($/lb.)	$ 0.87	$ 1.84
Flux Used (lb./ft. of joint)	0.24	0.15
Flux Cost* ($/lb.)	$ 0.53	$ 0.93
COST ($/ft.)	**$ 0.69**	**$ 1.16**

*Prices based on current Industrial Prices in Lincoln Electric price book (April, 1997)

Solution:
In this particular situation, savings of 40% were achieved by utilizing the undermatching option. Design requirements were satisfied, and the likelihood of welding-related problems such as weld cracking or lamellar tearing has been reduced.