What Structural Engineers and Fabricators Need to Know About Weld Metal

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INTRODUCTION

To supply structural engineers and fabricators with the mechanical properties data needed to ensure good weldment design, manufacturers of consumables utilize standard filler metal qualification tests developed by the American Welding Society. Tensile properties are thus reported. Too frequently, engineers expect the results of these tightly controlled tests to be directly applicable to the properties of welded connections made in the shop or in the field. They are not. Both the structural engineer and the fabricator need to be aware of the ways in which many variables may affect the properties of the weld deposit. This paper will examine the purpose of filler metal qualification tests, the controls for these tests, and how production welds may deviate from the tests. Finally, guidelines will be discussed to enable the engineer to predict trends and assure that required strength levels are achieved.

DESIGNING WELDS

When a structural engineer is designing a welded connection, that weld will typically be a fillet weld, a full penetration weld, or a partial penetration weld. It is designed for a particular strength requirement. The fillet weld strength will be proportional to the leg size, the length, and the strength of the filler metal. A complete penetration groove weld will be proportional to the cross-sectional area, and the strength of the filler metal. A partial penetration groove weld will have a strength proportional to the depth of penetration, the length, and the strength of the filler metal used. So in any of these three situations, the strength of the filler metal used is critical to the performance of the particular joint.

PROPERTIES REQUIRED

The word "strength" is used here specifically, because in some cases yield strength is more important, and sometimes tensile strength is more important. Most welded connections are designed around the tensile strength, but the yield strength is very often the controlling factor, in that permanent deformation is not desirable. The modulus of elasticity, used for designing structure stiffness, is not a structure-sensitive property. That is, it is not dependent on the microstructure to gain the various levels of modulus. As this does not change with weld metal, modulus of elasticity is not within the scope of this discussion.

Another strength factor is toughness. Toughness would not figure into the strength equations mentioned above. Toughness is a very difficult property to use in design. Fracture mechanics is required in order to utilize the property of toughness. However, impact resistance measured by the Charpy specimen, is frequently used, and to that extent, this paper will discuss the effects of variables on toughness. Note, however, that toughness properties are not required by AWS D1.1 structural code, unless specified in contract documents.

The structural engineer requiring the properties of yield strength and tensile strength, may go immediately to the electrode classification to try to discern these. Using an example of a typical low-hydrogen electrode, an E7018, he may look at the 70 designation, knowing that 70 stands for a minimum tensile strength of 70,000 psi, and use that for design purposes. The same strength level may not be seen in the actual weld joint selected by the engineer. To understand why, it is necessary first to review filler metal specifications and qualification tests.

FILLER METAL SPECIFICATIONS

Mechanical properties requirements spelled out in the AWS classification include specific yield, tensile strength, and elongation properties. Charpy values for toughness may or may not be specified. Certain chemical properties are specified, indicating key alloy levels. Finally, there may be welding performance criteria such as the percentage of moisture in the coatings of low-hydrogen electrodes. A look at a typical certification demonstrates that electrodes exceed the minimums that are specified. However, it is important to note that the appendix to the filler metal specification includes restrictions on the use of this information, as follows:

> "Weld metal properties may vary widely, according to site of the electrode and amperage used, size of the beads in the weld, plate thickness, joint geometry, preheat and interpass temperatures, surface condition, base metal composition, dilution, etc."[1]

Since the properties may vary due to all of these specific influences, what can the engineer or fabricator rely upon? To answer that question, first consider the philosophy be-

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hind the filler metal testing procedures. Again, to quote from the appendix:

> "Because of the profound effect of these variables, a test procedure was chosen for this specification which would represent good welding practice and minimize variation of the most potent of these variables."[2]

The test plate was never designed to duplicate the actual welding properties. It would be impossible to duplicate all of the properties that may be encountered. The purpose is for classification or qualification of a particular product to a specific filler metal type. It does permit comparisons within the specification. That is, one E7018 electrode can be compared to another. But technically, an E7018 electrode cannot be compared to a deposit of submerged arc, for example, because there are differences between the tests. The comparisons must be made within the specification.

TEST CONTROLS

In relying on test results, the engineer again will do well to heed the appendix to the filler metal specification:

> "Properties of production welds may vary accordingly, depending on the particular welding conditions. Weld metal properties may not duplicate, or even closely approach, the values listed and prescribed for test welds."[3]

These tests were actually designed to minimize variations in results due to testing from one manufacturer to another, from one year to another, and from one product to another.

An in-depth look at one test, for a low-hydrogen stick electrode, will help to clarify the purpose of the tests. That product, a shielded metal arc welding electrode, is covered in AWS A5.1. The mechanical properties are those with which structural engineers are most concerned. The first step is to find out what tests are required by the specification. Table 8 in that specification indicates that, for an E7018 electrode, 3/32 in. diameter and 1/8 in. diameter electrodes do not require mechanical testing. For the 5/32 in. diameter electrode, however, an all-weld-metal tension test is required, with the plate to be welded in the flat position. Out of the same plate, impact specimens are to be taken, and also a fillet weld test is to be performed in the vertical and overhead position to ensure weld soundness.

The 3/16 in. diameter electrode has the same requirements for mechanical testing as for the 5/32 in. diameter. However, the fillet weld is to be made in the horizontal position, as opposed to the vertical and overhead position of the 5/32 in. A 7/32 in. diameter electrode does not require any mechanical tests.

The 5/32 in. electrode can be subjected to a closer look, since it does require mechanical testing. The next step is that the particular test plate to be used must be made of one of the three grades of steel listed: A285 Grade C; A36; or A283 Gr D. Typically, A36 is used. The plate is to be configured as per Fig. 1. That is, a 45-degree included angle, with a ½ in. root opening, a plate thickness dependent on the electrode size, typically a ¾ in. or a 5/32 in. electrode, and a backing bar appropriate to the size of electrode being used. The plate is to be pre-heated to 225 degrees F, plus or minus 25 degrees. Interpass temperature is to be maintained at 225 to 350 degrees F. The amperage is suggested to be run between 150 and 220 amps. The welding sequence is specified. The first layer is to be made with a full weave, with one layer for the entire half inch of the root opening. The second and all subsequent layers are to be welded with two passes per layer. A total of seven to nine layers could be used to make this weld specimen. Dictating the amperage and welding sequence restricts the travel speed. Whereas travel speed is not explicitly controlled, it cannot be too fast, or the weld will not be completed in the nine layers.

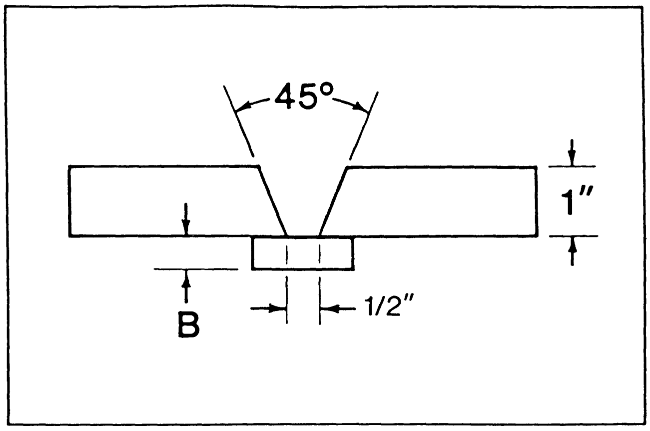

Figure 1

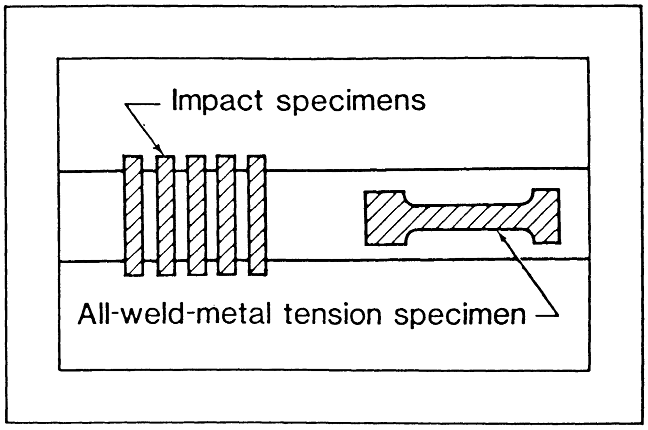

Figure 2

Alternately, it cannot be too slow, or less than seven layers will result. Note that the test plate will always be multiple pass, with a minimum of 13 relatively small beads.

The specimen is to be tested, per ASTM specifications. The test specimens are to be removed from the plate configuration, as shown in Fig. 2. The machining of the test plate, the accuracy of the test instruments, etc., are all covered in

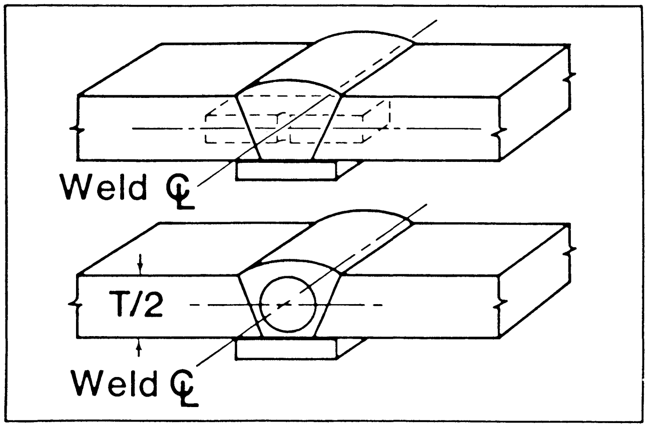

Figure 3

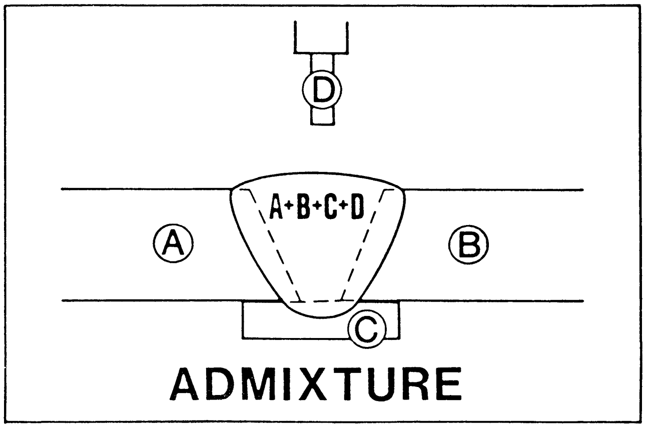

Figure 4

the ASTM specifications. For the E7018 electrode, the all-weld-metal tensile strength must be a minimum of 72,000 psi. Yield must be 60,000 psi minimum. Elongation must be 22 percent minimum. The impact energy must be a minimum of 20 ft-lbs at minus 20 degrees F. In addition, there are chemical and performance tests that are not discussed here, but if all these other criteria are met, it may be classified as an E7018 SMAW stick electrode.

Other consumables may be tested in a different form. For instance, consider the example of an E6010 electrode, which is still within the A5.1 specification. In this case, the specimen can be aged at 200 to 220 degrees F for 48 hours, plus or minus two hours. This permits any hydrogen to escape from the weld metal. This test is not designed to hide the fact that hydrogen may be present in the weld metal; its purpose is rather to present a very consistent way of comparing products that may have hydrogen in the weld metal. If, for example, the weld specimens are not tested for two to four weeks after welding, most of the hydrogen has escaped from the sample. This is an accelerated way of letting the hydrogen escape, in order to ensure the consistency of test results.

A different filler metal specification, A5.20, for flux-cored arc welding, shows that the ambient or starting temperature for the test plate is room temperature, vs. the low hydrogen test under 5.1, which called for an initial temperature of 225 degrees F. Here, the initial temperature is specified as 70 degrees F. In addition, flux-cored arc welding may utilize externally supplied shielding gas. When required, the controlling gas is to be carbon dioxide. Actual welding can be done with a different gas, but this is the specified gas for flux-cored arc consumable qualification.

A consideration of specification 5.17 for submerged arc welding demonstrates that the procedure is tightly controlled for testing. The $\frac{5}{32}$ in. diameter electrode should be used at 550 amps and 28 volts. There can also be post-weld heat treatment, or stress relieving, of submerged ard welds and other products as well. The stress relief temperature is 1150 degrees F., plus or minus 25 degrees, and the weld should be stress relieved for one hour.

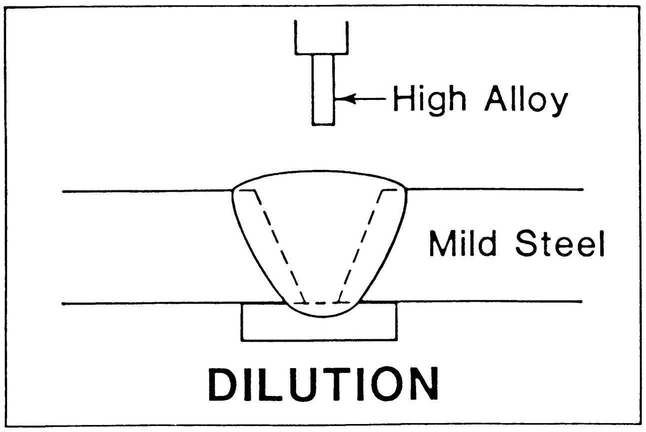

Figure 5

THE EFFECTS OF DEVIATIONS

These test configurations and controls may or may not represent the actual welding conditions. Indeed, in the majority of situations, there will be deviations. Such deviations as amperage, weld bead placement, plate thickness, and so forth, have already been noted. These can be classified, however, into two broad categories: chemical and thermal changes.

CHEMICAL EFFECTS

Chemical changes are due to two key influences: first, the plate chemistry, and secondly, the amount of admixture. Three terms may need definition here: admixture, dilution, and pickup.

Figure 4 helps to illustrate admixture. As the illustration shows, this weld is joining plate A to plate B. A backing strip

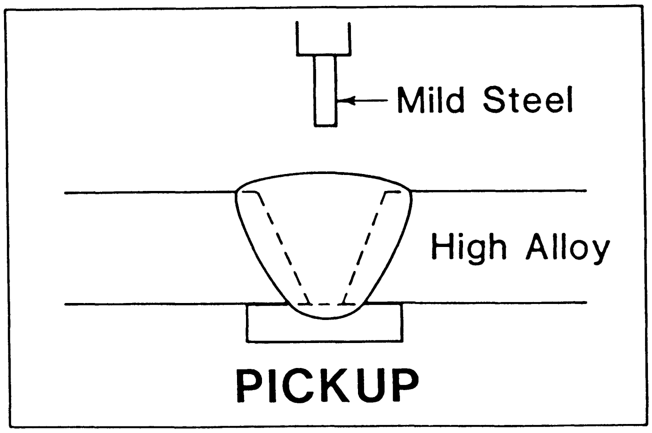

Figure 6

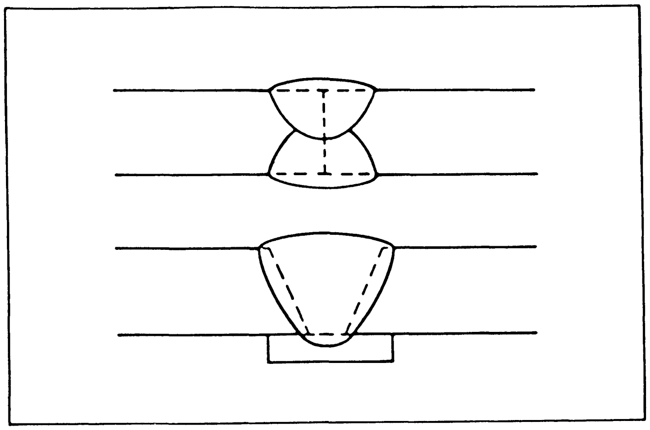

Figure 7

labeled C is included. The joint is to be filled with a filler metal labeled D. The arc force and energy of the electrode will melt some of plate A, some of plate B, and some of plate C. The final composition of the weld metal will be A, B, C, and D. This conglomeration of material is called "admixture."

Figure 5 illustrates dilution. Dilution occurs when a high alloy electrode is used to weld on lower alloy plate. Thus, as the high alloy is mixed wih the lower alloy, creating an admixture, the high alloy is diluted. For example, using a stainless steel electrode with high chrome and high nickel to weld on mild steel, will result in lower chrome and nickel content in the weld than in the electrode. The result is called "dilution."

Figure 6 shows alloy pickup, which is just the opposite of dilution. Here, a mild steel electrode is used to weld on high alloy plate. The weld deposit will contain nickel that was never present in the mild steel filler. When the deposit contains a greater amount of alloy than the electrode, the situation is referred to as alloy "pickup."

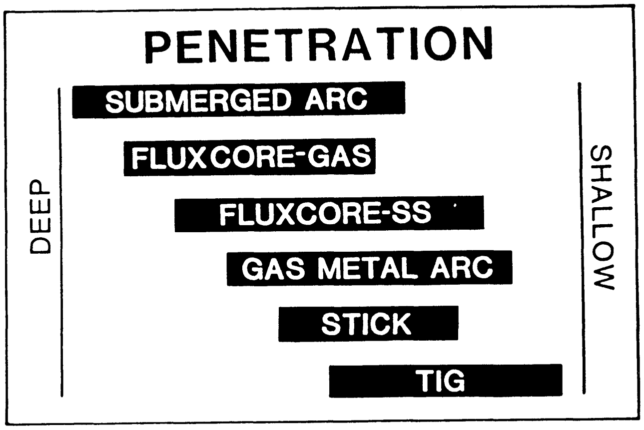

Figure 8

As base plate is introduced into the admixture, the weld chemistry changes. If the plate chemistry is different from that used for filler metal qualification, the weld chemistry may be different. The significance of this will be considered later.

The extent of admixture is a function of joint geometry, the process used, and procedures. Since few people weld AWS filler metal qualification plates in production, the test plate is not typical of most production joints.

Figure 7 shows two different butt joints. The plate thickness is the same in both cases. One involves a penetration weld, welding from two sides. In this example, the bottom side was welded first, then the plate was turned, the top side was welded, and full joint strength was achieved. The artwork shows that there would be a tremendous influence of base material in this particular weld, as shown by the dotted lines. A high percentage of the base metal would be contained in the weld metal. This admixture would be composed primarily of base material.

The second butt joint in Fig. 7 shows a beveled joint with a back-up that comes close to approaching that of a filler metal specification. Here, minimum amounts of base material are melted. The admixture is composed primarily of the filler metal. So the joint geometry plays an important role in determining the composition of the admixture.

The process selected is very important with respect to penetration. Figure 8 delineates six major arc welding processes; the degree of penentration will vary, according to the process. The deepest penetrating process is submerged arc welding. Base material would have the most significant effect on a submerged arc weld. At the other extreme, gas tungsten arc welding or TIG welding has relatively shallow penetration, still giving adequate fusion, but the base material has a lesser effect. Between these two extremes are: the flux-cored gas process, which gives relatively deep penetration; the self-shielded flux-cored process, which can have

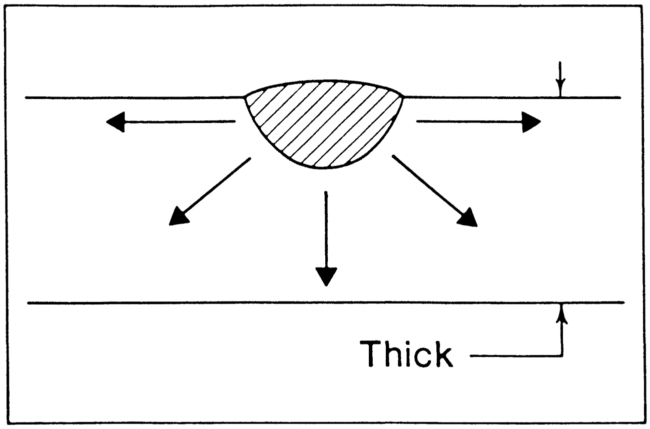

Figure 9

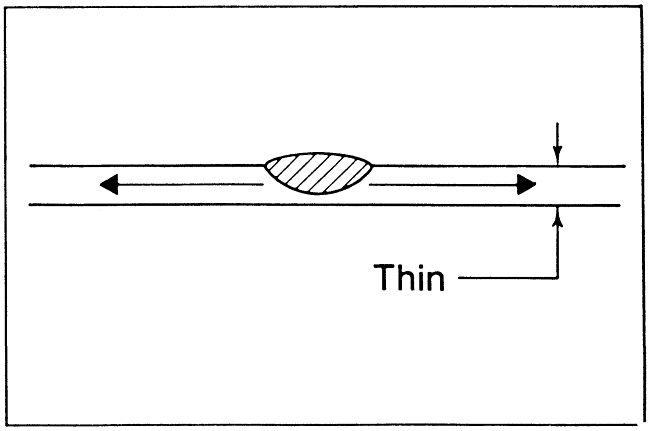

Figure 10

a tremendous range in penetration; the gas metal arc process, which features deep penetration in the spray mode and relatively shallow penetration in the short arc mode (Note: the latter is restricted on structural applications); and the stick electrode process or shielded metal arc welding, which has a tighter range. For a given process, the extent of penetration is a function of amperage and electrode size. Travel speed, polarity, and position of welding affect the penetration to a lesser extent. Because of these factors, Fig. 8 shows a significant range for each process.

ALLOY EFFECTS ON MECHANICAL PROPERTIES

Plate chemistry and the amount of plate that ends up in the admixture may change the deposit analysis from that of filler metal qualification deposits. This may in turn result in different mechanical properties. The effects of individual elements will be considered next. Alloys may be singularly introduced into the admixture and their significance evaluated on a weight percent basis. Those individual trends will be considered. However, combinations of elements may produce a synergetic effect; the potentially complicated reactions of synergetic elements are beyond the scope of this paper.

Alloy Effects: Strength

Least Significant ——►			Most Significant
Nickel	Chromium Silicon Manganese	Molybdenum Copper	Carbon Vanadium Columbium

In small percentages, those elements in the "most significant" column greatly increase the strength of an alloy. While they are still "significant," those elements listed to the left of carbon, vanadium, and columbium contribute to the strength factor in proportionally lesser degrees, as indicated by the layout of the chart. While nickel will contribute to the strength of the admixture, a much greater weight percentage of nickel will be required to provide the same degree of strength as a fractional percentage of, for instance, vanadium. Whereas A36 plate, used for qualification of many products, typically does not include vanadium and columbium, plate bearing these elements and welds having a high degree of admixture and, in this case, much alloy pickup (in that the vanadium and columbium are in the base material and not in the welding material) will be high-strength.

Alloys affecting toughness properties may be similarly evaluated. Generally, higher strength means lower toughness. To predict toughness, alloys can be categorized in three groups, as follows:

Alloy Effects: Toughness

Decreases	Inactive (Little Effect)	Improves
Vanadium	Copper	Nickel
Carbon	Silicon	Manganese
Columbium	Chromium	
	Molybdenum	

Vanadium, carbon, and columbium typically lower the impact energy. Copper, silicon, chromium, and molybdenum have very little effect either way. Nickel and manganese increase the impact energy. Nickel is a key ingredient for gaining better impact properties without significantly increasing the strength of the metal.

PROCEDURAL EFFECTS ON CHEMISTRY

Procedural changes may produce significant chemical deviations. One of those deviations is typical of the submerged arc process. Submerged arc deposit chemistry is dependent, among other things, on the effect of the flux. If an active flux is used, manganese and silicon levels in the deposit will be dependent on the arc voltage used. As previously noted, 28 volts is the voltage used for welding submerged arc filler metal qualification test plates. If a higher voltage is used,

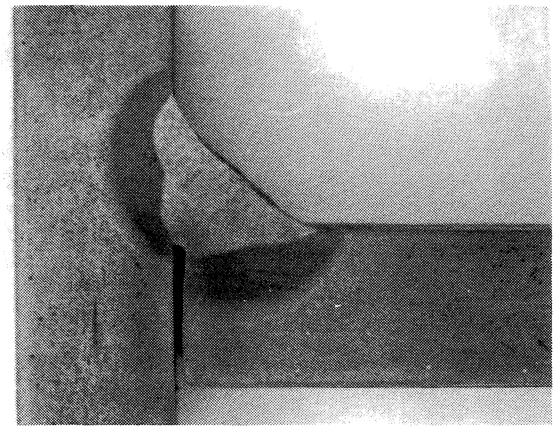

Figure 11

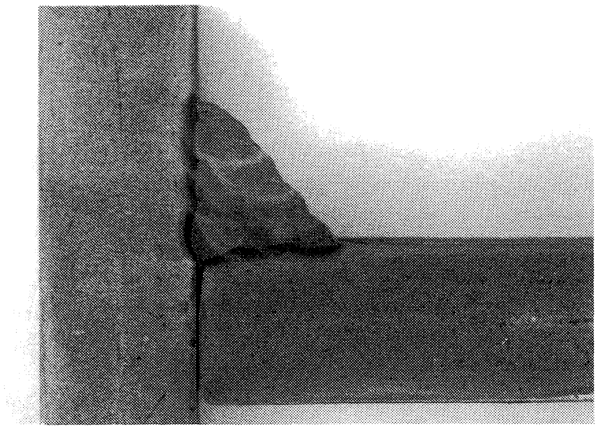

Figure 12

the level of manganese may be either increased or decreased. Voltage is a variable that is not considered in the qualification plates. Acknowledging this, the Wall neutrality number, frequently designated as *W*, has been developed. Since literally thousands of test plates have been run at 28 volts, this was used as one voltage for comparison. An identical test is run at 36 volts, an 8-volt difference. The absolute difference in the weight percent of silicon is added to the absolute difference in the weight percent of manganese. Those figures, added together, and multiplied by 100, equal the Wall neutrality number.

The American Welding Society has selected a Wall number of 40 or less and defined that to designate a neutral flux. If the Wall number is greater than 40, it is considered to be an active flux. If the Wall number is less than 40, the effect of voltage is considered insignificant. If the changes are greater than 40, the structural engineer should be aware of the fact that the silicon and manganese contents of the weld may be increased. Both silicon and manganese will increase the weld strength. While silicon will have little effect on the weld deposit in terms of toughness, manganese tends to improve it slightly.

When CO_2 gas is used in flux-cored welding, alloys may oxidize and not appear in the weld deposit. When inert gases are used for shielding, less alloy is oxidized. The deposit has a higher alloy content, meaning that the strength levels typically go up, and the impact energy typically goes down, when inert gases are used. In fact, a 5,000 to 10,000 psi increase in tensile strength is very common. Impact properties may drop by as much as 50 percent with the use of inert gas shielding.

Some testing specifications utilize the aging process to eliminate hydrogen from the weld. The structural engineer should be aware that the weld metal may contain hydrogen, even though the tested results do not show this. The time before loading may become a critical variable that should be addressed.

THERMAL EFFECTS

The second major change in welding test plates vs. real-life welding takes place in the area of thermal effects. In general, with carbon steel materials, the faster the material cools, the stronger it will be. Furthermore, as a rule, the faster the material is cooled, the lower the impact properties will be. What are the significant thermal differences between filler metal qualification plates and real life welds? First, preheat may or may not be required on the job site. If preheat is not used in either case, the first weld passes cool at a very rapid rate, increasing the strength.

Secondly, the heat input may be different. The list of variables covered by tests includes such things as electrode size, voltage, amperage, stick-out, polarity, process, travel speed, and position of welding. All of these address the heat input factor. Heat input is proportional to the voltage *E*, amperage *I*, divided by the travel speed, times the efficiency:

$$\text{Heat Input} \propto \text{(Volts) (Amps) (Eff.) / (Travel Speed)}$$

The voltage and amperage are dictated by the welding procedure, as is the travel speed. The efficiency has to do with the process. Submerged arc causes most of the heat of the arc to be put into the base material. Other processes may involve a tremendous amount of radiation, smoke, spatter, and other sources for the energy to escape, other than entering the plate. Many heat input equations do not even consider the effect of efficiency, however.

The higher the amperage, for instance, the more heat will be put into the joint. That preassumes that the same travel speed is being used. However, if travel speed increases, high deposition or high amperage welding procedures are not necessarily high heat input procedures. A case in point: if the weld nugget size is kept the same, the heat input is very often a constant.

Another factor to be considered is the interpass temperature that is maintained. In terms of welding on steel that is less than 80,000 psi tensile strength, the heat input has a limited effect. On higher tensile strength steels, heat input is more critical. In general, higher heat input will produce lower tensile strength, but better impact properties.

Having gotten this plate up to temperature, the engineer next needs to look at the cooling rate. A fast cooling rate typically gives higher strength weld metal and lower impact properties. The cooling rate is dependent upon the heat input, the thickness of the part, the geometry of the part, and any preheat, or the ambient temperature, of the plate.

Post-weld heat treatments also require consideration. Multiple pass welding involves a thermal effect on previous beads. This thermal effect or annealing of welds, as several beads are made, significantly improves impact properties. For this reason, multiple passes are highly desirable if the goal is to achieve the ultimate in impact properties.

Stress relief typically causes the tensile strength to drop 5,000 psi, and the yield strength to drop 10,000 psi. The stress relief procedure used for AWS specimens is 1,100 degrees F for one hour. Longer term stress relief or different temperatures will affect those results. Normalizing, or thermal treatment at temperatures approaching 1,600 or 1,700 degrees F, will have a very significant effect, typically lowering yield and tensile properties.

All of these thermal effects can reinforce each other. For example, a weld may be made with an interpass temperature of 300 degrees F. If stress relieved at 1,150 degrees F for one hour, a given set of results will be obtained. The same plate, with the same welding procedure, could be welded at 200 degrees F interpass temperature, stress-relieved at 1,150 degrees F for eight hours, vs. one hour, and the same yield and tensile would be obtained from both welds.

Example: Fillet Weld

Figures 11 and 12 show photo-micrographs of two processes. Figure 11 is a single pass, very large submerged arc weld. Figure 12 is a multiple pass gas metal arc, or MIG, weld. Using the same basic analysis of filler metal, significantly different properties exist between these two. The submerged arc weld has deep penetration and an admixture with a large percentage of base material. In the MIG weld, the base material has a very limited effect. The multiple pass weld had many subsequent thermal cycles of heating and cooling, which refine the grain structure below. The submerged arc weld did not have the benefit of this. Structural engineers and fabricators need to be aware of the fact that the properties of single pass welds differ significantly from those of test plates, which are typically multiple pass welds.

CONTROLLING WELD QUALITY

Engineers have specified, and fabricators have successfully made, welds for many years without complete knowledge of the differences between actual welding conditions and filler metal test plates. This success is due, in part, to industry controls which very neatly address these differences. The filler metal manufacturer designs an electrode, tests it in a qualification plate, and certifies it to give it a classification. The fabricator takes that particular electrode, puts it into his typical welding joint, and runs a procedure qualification test. He then tests the weld metal, usually with a tensile test, and will run an impact specimen if required. The effect of all these variables is controlled in this actual performance test. The requirement of the AWS D1.1 Structural Welding Code is not that the properties of this new test meet those of the filler metal classification. Rather, it is required that the properties exceed those of the base material. For example, if A572 Grade 50 steel with a tensile strength of 65,000 psi is used, and welded with E7018 electrode, the procedure qualification test does not require meeting the 72,000 psi of the filler metal test. Instead, the 65,000 psi of the steel is the property that must be exceeded.

The information presented herein will be useful in predicting trends and making the initial selection of a filler metal. If the engineer knows, for example, that he is welding on higher carbon material with a process that will have a great deal of penetration, and the admixture will have a higher carbon content than the filler metal—due to pickup—then he may be able to predict in advance that he will have little difficulty in achieving the required strength. However, if impact properties are required, he will know that increased strength decreases toughness. Perhaps a filler metal with greater impact properties should be selected.

Finally, filler metal manufacturers typically have available test data that far exceed the certification sheets. Engineers should request that information; it can improve weld quality while reducing costs.

CONCLUSION

In conclusion, then:

- Filler metal test plates have tight controls, and do not necessarily represent actual working conditions.
- There are predictable trends, based on chemistry and thermal effects.
- The industry codes requiring qualification test plates define and bring together all of these conditions so that engineers and fabricators can be confident that they are exceeding the base metal properties.
- Knowledge of these variables permits more intelligent selection of a starting point.

REFERENCES

1. American National Standards Institute, "Specification for Covered Carbon Steel Arc Welding Electrodes," ANSI/AWS A5.1-81, Appendix, October 1981, p. 25.
2. Ibid.
3. Ibid.