# What Every Engineer Should Know About Welding

From amperage to preheat, there's more to welding procedures than meets the eye

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Within the welding industry, the term "Welding Procedure Specification" (or WPS) is used to signify the combination of variables used to make a certain weld. At a minimum the WPS (or "Welding Procedure" or simply "Procedure") consists of: process (Shielded Metal Arc Welding [SMAW], Flux Cored Arc Welding [FCAW], etc.); electrode specification (AWS A5.1, A5.20, etc.); electrode classification (E7018, E71T-1, etc.); electrode diameter; electrical characteristics ( (AC, DC+, DC-); base metal specification (A36, A572 Gr. 50, etc.); minimum preheat and interpass temperature; welding current (amperage)/wire feed speed; arc voltage; travel speed; position of welding; post weld heat treatment; shielding gas type and flow rate; and joint design details.

The welding procedure is somewhat analogous to a cook's recipe: It outlines the steps required to make a quality weld under specific conditions.

## Effects Of Welding Variables

The effects of the variables are somewhat dependent on the welding process being employed, but general trends apply to all the processes. It is important to distinguish the difference between constant current (CC) and constant voltage (CV) electrical welding systems. Shielded metal arc welding is always done with a CC system, while flux cored welding and gas metal arc welding generally are performed with CV systems. Submerged arc may utilize either.

• Amperage is a measure of the amount of current flowing through the electrode and the work. It is a primary variable in determining heat input. Generally, an increase in amperage means higher deposition rates, deeper penetration, and more admixture. The amperage flowing through an electrical circuit is the same, regardless of where it is measured. It may be measured with a tong meter or with the use of an electrical shunt. The role of amperage is best understood in the context of heat input and current density considerations. For CV welding, an increase in wire feed speed will directly increase amperage. For SMAW on CC systems, the machine setting determines the basic amperage, although changes in the arc length (controlled by the welder) will further change amperage. Longer arc lengths reduce amperage.

• Arc voltage is directly related to arc length. As the voltage increases, the arc length increases, as does the demand for arc shielding. For CV welding, the voltage is determined primarily by the machine setting, so the arc length is relatively fixed in CV welding. For SMAW on CC systems, however, the arc voltage is determined by the arc length, which is manipulated by the welder. As arc lengths are increased with SMAW, the arc voltage will increase, and the amperage will decrease. Arc voltage also controls the width of the weld bead, with higher voltages generating wider beads. Arc voltage has a direct effect on the heat input computation.

• The voltage in a welding circuit is not constant, but is composed of a series of voltage drops. Consider the following example: assume the power source delivers a total system voltage of 40 volts. Between the power source and the welding head or gun, there is a voltage drop of perhaps 3 volts associated with the input cable resistance. From the point of attachment of the work head to the power source work terminal, there is an additional voltage drop of, say, 7 volts. Subtracting the 3 volts and the 7 volts from the original 40 leaves 30 volts for the arc. This example illustrates how important it is to ensure that the voltages used for monitoring welding procedures properly recognize any losses in the welding circuit. The most accurate way to determine arc voltage is to measure the voltage drop between the contact tip and the work piece. However, this may not be practical for semiautomatic welding, so voltage is typically read from a point on the wire feeder (where the gun and cable connection is made), to the workpiece. For SMAW welding, voltage is not usually monitored, since it is constantly changing and cannot be controlled except by the welder. Skilled welders hold short arc lengths to deliver the best weld quality.

• Travel speed, measured in inches per minute, is the rate at which the electrode is moved relative to the joint. All other variables being equal, travel speed has an inverse effect on the size of the weld beads. As the travel speed increases, the weld size will decrease. Extremely low travel speeds may result in reduced penetration, as the arc impinges on a thick layer of molten metal and the weld puddle rolls ahead of the arc. Travel speed is a key variable used in computing heat input (reducing travel speed increases heat input).

• Wire feed speed is a measure of the rate at which the electrode is passed through the welding gun and delivered to the arc. Typically measured in inches per minute (ipm), the deposition rates are directly proportional to wire feed speed and directly related to amperage. When all other welding conditions are maintained constant, an increase in wire feed speed will directly lead to an increase in amperage. For slower wire feed speeds, the ratio of wire feed speed to amperage is relatively constant and linear. For higher wire feed speeds, this ratio may increase, resulting in a higher deposition rate per amp, but at the expense of penetration.

Wire feed speed is the preferred method of maintaining welding procedures for constant voltage wire feed processes. The wire feed speed can be independently adjusted and measured directly, regardless of the other welding conditions. It is possible to utilize amperage as an alternative to wire feed speed although the resultant amperage for a given wire feed speed may vary, depending on polarity, electrode diameter, electrode type and electrode extension. Although equipment has been available for two decades that monitor wire feed speed, many codes such as AWS D1.1 continue to acknowledge amperage as the primary method for procedure documentation. D1.1 does permit the use of wire feed speed control instead of amperage, providing a wire feed speed-amperage relationship chart is available for comparison. Specification sheets supplied by the filler metal manufacturer provide data that support these relationships.

• Electrode extension, also known as "electrical stickout" or ESO, is the distance from the contact tip to the end of the electrode. It applies only to the wire fed processes. As the electrode extension is increased in a constant voltage system, the electrical resistance of the electrode increases, causing the electrode to be heated. This is known as resistance heating or "I2R heating". As the amount of heating increases, the arc energy required to melt the electrode decreases. Longer electrode extensions may be employed to gain higher deposition rates at a given amperage. When the electrode extension is increased without any change in wire feed speed, the amperage will decrease. This results in less penetration and less admixture. With the increase in electrical stickout, it is common to increase the machine voltage setting to compensate for the greater voltage drop across the electrode.

In constant voltage systems, it is possible to simultaneously increase both the ESO and the wire feed speed in a balanced manner so that the current remains constant. When this is done, higher deposition rates are attained. Other welding variables, such as voltage and travel speed, must be adjusted to maintain a stable arc and to ensure quality welding. The ESO variable should always be within the range recommended by the manufacturer.

• Electrode diameter is another critical variable. Larger electrodes can carry higher welding currents. For a fixed amperage, however, smaller electrodes result in higher deposition rates. This is because of the effect on current density discussed below.

• Polarity is a definition of the direction of current flow. Positive polarity (reverse) is achieved when the electrode lead is connected to the positive terminal of the direct current (DC) power supply. The work lead is connected to the negative terminal. Negative polarity (straight) occurs when the electrode is connected to the negative terminal and the work lead to the positive terminal. Alternating current (AC) is not a polarity, but a current type. With AC, the electrode is alternately positive and negative. Submerged arc is the only process that commonly uses either electrode positive and electrode negative polarity for the same type of electrode. AC may also be used. For a fixed wire feed speed, a submerged arc electrode will require more amperage on positive polarity than on negative. For a fixed amperage, it is possible to utilize higher wire feed speeds and deposition rates with negative polarity than with positive. AC exhibits a mix of both positive and negative polarity characteristics.

• The magnetic field that surrounds any DC conductor can cause a phenomenon known as arc blow, where the arc is physically deflected by the field. The strength of the magnetic field is proportional to the square of the current value, so this is a more significant potential problem with higher currents. AC is less prone to arc blow, and can sometimes be used to overcome this phenomenon.

• Heat input is proportional to the welding amperage, times the arc voltage, divided by the travel speed. Higher heat inputs relate to larger weld cross sectional areas, and larger heat affected zones, which may negatively affect mechanical properties in that region. Higher heat input generally results in slightly decreased yield and tensile strength in the weld metal, and generally lower notch toughness because of the interaction of bead size and heat input.

• Current density is determined by dividing the welding amperage by the cross sectional area of the electrode. For solid electrodes, the current density is therefore proportional to $I/d^2$. For tubular electrodes where current is conducted by the sheath, the current density is related to the area of the metallic cross section. As the current density increases, there will be an increase in deposition rates, as well as penetration. The latter will increase the amount of admixture for a given joint. Notice that this may be accomplished by either increasing the amperage or decreasing the electrode size. Because the electrode diameter is a squared function, a small decrease in diameter may have a significant effect on deposition rates and plate penetration.

• Preheat and interpass temperature are used to control cracking tendencies, typically in the base materials. Regarding weld metal properties, for most carbon-manganese-silicon systems, a moderate interpass temperature promotes good notch toughness. Preheat and interpass temperatures greater than 550 degrees F may negatively affect notch toughness. When the base metal receives little or no preheat, the resultant rapid cooling may also lead to a deterioration of notch toughness. Therefore, careful control of preheat and interpass temperatures is critical.

## Purpose Of WPSs

The particular values for the variables discussed above have significant affect on weld soundness, mechanical properties, and productivity. It is therefore critical that those procedural values used in the actual fabrication and erection be appropriate for the specific requirements of the applicable code and job specifications. Welds that will be architecturally exposed, for example, should be made with procedures that minimize spatter, encourage exceptional surface finish, and have limited or no undercut. Welds that will be covered with fireproofing, in contrast, would naturally have less restrictive cosmetic requirements.

Many issues must be considered when selecting welding procedure values. While all welds must achieve fusion to ensure their strength, the required level of penetration is a function of the joint design in the weld type. All welds are required to deliver a certain yield and/or tensile strength, although the exact level required is a function of the connection design. Not all welds are required to deliver minimum specified levels of notch toughness. Acceptable levels of undercut and porosity are a function of the type of loading applied to the weld. Determination of the most efficient means by which these conditions can be met cannot be left to the welders, but is determined by knowledgeable welding technicians and engineers who create written welding procedure specifications and communicate those requirements to welders by the means of these documents. The WPS is the primary tool that is used to communicate to the welder, supervisor, and the inspector how a specific weld is to be made. The suitability of a weld made by a skilled welder in conformance with the requirements of a WPS can only be as good as the WPS itself. Procedural variable values must be properly selected in order to have a WPS appropriate for the application.

The ability of a welder to follow a written WPS is determined by welder qualification tests (D1.1-96, paragraph C4.1.2). The welder may not know how or why each particular variable was selected, although these values must be used in production. The inspector is required to ensure that all welding is done in accordance with the WPS, observing the technique of each welder on a periodic basis (D1.1-96, paragraph 6.5.4). Inspectors do not develop WPSs, but they must ensure the procedures exist and are followed (D1.1-96, paragraph 6.3.1).

The D1.1-96 Structural Welding Code - Steel requires written welding procedures for all fabrication performed (D1.1-96, paragraph 5.5). These WPSs are required to be written, regardless of whether they are prequalified or qualified by test. Each fabricator or erector is responsible for the development of WPSs (D1.1-96, paragraph 4.1.1.1, 4.6). Confusion about this issue apparently still exists since there continue to be reports of fabrication being performed in the absence of written welding procedure specifications. One prevalent misconception is that if the actual parameters under which welding will be performed meet all the conditions for "prequalified" status, written WPSs are not required. This is not true. As has been shown in the cited code references, the requirement is clear.

The WPS is a communication tool, and it is the primary means of communication to all the parties involved regarding how the welding is to be performed. It must therefore be readily available to foremen, inspectors and the welders. The code is not prescriptive in its requirements regarding availability and distribution of WPSs. Some shop fabricators have issued each welder employed in their organization with a set of welding procedures that are typically retained in the welder's locker or tool box. Others have listed WPS parameters on shop drawings. Some company bulletin boards have listings of typical WPSs used in the organization. Regardless of the method used, WPSs must be available to those authorized to use them.

It is in the contractor's best interest to ensure that efficient communication is maintained with all parties involved. Not only can quality be compromised when WPSs are not available, but productivity can suffer as well. Regarding quality, the limits of suitable operation of the particular welding process and electrode for the steel, joint design and position of welding must be understood. Obviously, the particular electrode employed must be operated on the proper polarity, proper shielding gases must be used, and amperage levels must be appropriate for the diameter of electrode, and for the thickness of material on which welding is performed. Other issues may not be as obvious. For example, the required preheat for a particular application is a function of the grade(s) of steel involved, the thickness(es) of material, and the type of electrode employed (whether low hydrogen or non-low hydrogen). All of this can be communicated by means of the written WPS.

Lack of conformance with the parameters outlined in the WPS may result in the deposition of a weld that does not meet the quality requirements imposed by the code or the job specifications. When an unacceptable weld is made, the corrective measures to be taken may necessitate weld removal and replacement, an activity that routinely increases the cost of that particular weld tenfold. Avoiding these types of unnecessary activities by clear communication has obvious quality and economic ramifications.

There are other economic issues to be considered as well. In a most general way, the cost of welding is inversely proportional to the deposition rate. The deposition rate, in turn, is directly tied to the wire feed speed of the semiautomatic welding processes. If it is acceptable, for example, to make a given weld with a wire feed speed of 200 ipm, then a weld made at 160 ipm (which may meet all the quality requirements) would cost approximately 25% more than the weld made at the optimum procedure. Conformance with WPS values can help ensure that construction is performed at rates that are conducive to the required weld quality and are economical as well.

The code imposes minimum requirements for a given project. Additional requirements may be imposed by contract specifications. The same would hold true regarding WPS values. Compliance with the minimum requirements of the code may not be adequate under all circumstances. Additional requirements can be communicated through the WPS. For example, the D1.1-96 code permits the use of an E71T-11 FCAW electrode for multiple pass welding without any restriction on plate thickness. The Lincoln Electric product, Innershield NR211MP, has a maximum thickness restriction imposed by the manufacturer of ½". This additional requirement can be incorporated into the applicable WPS. Other recommendations that may be imposed by the steel producer, electrode manufacturer, or others can and should be documented in the WPS.

### Prequalified Procedures

The AWS D1.1 code provides for the use of prequalified WPSs. Prequalified WPSs are those that the AWS D1 Committee has determined to have a history of acceptable performance, and so does not subject them to the qualification testing imposed on all other welding procedures. The use of prequalified WPSs does not preclude the requirement that they be written. The use of prequalified WPSs still requires that the welders be appropriately qualified. All the workmanship provisions imposed in the fabrication section of the code apply to prequalified WPSs. The only code requirement exempted by prequalification is the nondestructive testing and mechanical testing required for qualification testing of welding procedures.

A host of restrictions and limitations imposed on prequalified welding procedures do not apply to welding procedures that are qualified by test. Prequalified welding procedures must conform with all the prequalified requirements in the code. Failure to comply with a single prequalified condition eliminates the opportunity for the welding procedure to be prequalified (D1.1-96, paragraph 3.1).

In order for a WPS to be prequalified, the following conditions must be met:

- The welding process must be prequalified. Only SMAW, SAW, GMAW (except GMAW-s), and FCAW may be prequalified (D1.1-96, paragraph 3.2.1).
- The base metal/filler metal combination must be prequalified. Prequalified base metals, filler metals, and combinations are shown in D1.1-96, paragraph 3.3, Table 3.1.
- The minimum preheat and interpass temperatures prescribed in D1.1-96, paragraph 3.3, Table 3.2 must be employed (D1.1-96, paragraph 3.5).
- Specific requirements for the various weld types must be maintained. Fillet welds must be in accordance with D1.1-96, paragraph 3.9, plug and slot welds in accordance with D1.1-96, paragraph 3.10, and groove welds in accordance with D1.1-96, paragraph 3.11, 3.12, and 3.13 as applicable. For the groove welds, whether partial joint penetration or complete joint penetration, the required groove preparation dimensions are shown in D1.1-96, Figures 3.3 and 3.4.

Even if prequalified joint details are employed, the welding procedure must be qualified by test if other prequalified conditions are not met. For example, if a prequalified detail is used on an unlisted steel, the welding procedures must be qualified by test.

Prequalified status requires conformance to a variety of procedural parameters. These are largely contained in D1.1-96, Table 3.7, and include maximum electrode diameters, maximum welding current, maximum root pass thickness, maximum fill pass thicknesses, maximum single-pass fillet weld sizes, and maximum single pass weld layers (D1.1-96, Table 3.3). In addition to all the preceding requirements, welding performed with a prequalified WPS must be in conformance with the other code provisions contained in the fabrication section of AWS D1.1-96 Structural Welding Code.

The code does not imply that a WPS that is prequalified will automatically achieve the quality conditions required by the code. The commentary language for paragraph 3.2.1 states the following:

"The use of prequalified joints and procedures does not necessarily guarantee sound welds. Fabrication capability is still required, together with effective and knowledgeable supervision to consistently produce sound welds." (AWS D1.1-96, paragraph C3.2.1)

It is the contractor's responsibility to ensure that the particular parameters selected within the requirements of the prequalified WPS are suitable for the specific application. An extreme example will serve as an illustration. Consider the following example of a hypothetical proposed WPS for making a ¼" fillet weld on ⅜" A36 steel in the flat position. The weld type and steel are prequalified. SAW, a prequalified process, is selected. The filler metal selected is F7A2-EM12K, meeting the requirements of D1.1-96, Table 3.1. No preheat is specified since it would not be required according to D1.1-96, Table 3.2. The electrode diameter selected is 3/32", less than the ¼" maximum specified in D1.1-96, Table 3.7. The maximum single pass fillet weld size in the flat position, according to D1.1-96, Table 3.7, is unlimited, so the ¼" fillet size can be prequalified. The current level selected for making this particular fillet weld is 800 amps, less than the 1000 amp maximum specified in D1.1-96, Table 3.7.

However, the amperage level imposed on the electrode diameter for the thickness of steel on which the weld is being made is inappropriate. It would not meet the requirements of D1.1-96, paragraph 5.3.1.2 in the section entitled Fabrication, which requires that the size of electrode and amperage be suitable for the thickness of material being welded. This illustration demonstrates the fact that compliance with all prequalified conditions does not guarantee that the combination of selected variables will always generate an acceptable weld.

Most contractors will determine preliminary values for a prequalified WPS based upon their experience, recommendations from publications such as Lincoln Electric's Procedure Handbook of Arc Welding, industry publications such as the AWS Welding Handbooks, from AWS Welding Procedure Specifications (AWS B2.1), or other sources. It is the responsibility of the contractor to verify the suitability of the suggested parameters prior to the application of the actual procedure on a project, although the verification test need not be subject to the full range of procedure qualification tests imposed by the code. Typical tests will be made to determine soundness of the weld deposit (e.g., fusion, tie-in of weld beads, freedom from slag inclusions, etc.). The plate could be nondestructively tested or, as is more commonly done, cut, polished, and etched. The latter operations allow for examination of penetration patterns, bead shapes, and tie-in. Welds made with prequalified WPSs that meet the physical dimensional requirements (fillet weld size, maximum reinforcement levels, and surface profile requirements), and are sound (that is, having adequate fusion, tie-in and freedom from excessive slag inclusions and porosity) should meet the strength and ductility requirements imposed by the code for welding procedures qualified by test. Weld soundness, however, cannot be assumed just because the WPS is prequalified.

### GUIDELINES

When developing prequalified WPSs, the starting point is a set of welding parameters appropriate for the general application being considered. Parameters for overhead welding will naturally vary from those required for down-hand welding. The thickness of material involved will dictate electrode sizes and corresponding current levels. The specific filler metals selected will reflect the strength requirements of the connection. Many other issues must be considered.

Depending on the level of familiarity and comfort the contractor has with the particular values selected, welding a mock-up may be appropriate. Once the parameters that are desired for use in production are established, it is essential to check each of the applicable parameters for compliance with the D1.1-96 code.

To assist in this effort, Annex H has been provided in the D1.1-96 code. This contains a check list that identifies prequalified requirements. If any single parameter deviates from these requirements, the contractor is left with two options: (1) the preliminary procedure can be adjusted to conform with the prequalified constraints; or, (2) the WPS can be qualified by test. If the preliminary procedure is adjusted, it may be appropriate to reexamine its viability by another mock-up.

The next step is to document, in writing, the prequalified WPS values. A sample form is included in Annex E of the code. The fabricator may utilize any convenient format (D1.1-96, paragraph 3.6). Also contained in Annex E are a series of examples of completed WPSs that may be used as a pattern.

### Qualifying By Test

Conducting qualification tests — There are two primary reasons why welding procedures may be qualified by test. First, it may be a contractual requirement. Secondly, one or more of the specific conditions encountered in production may deviate from the prequalified requirements. In either case, a test weld must be made prior to the establishment of the final WPS. The first step in qualifying a welding procedure by test is to determine the procedure one wants to qualify. The same sources cited for the prequalified WPS starting points could be used for WPSs qualified by test. These will typically be the parameters used for fabrication of the test plate, although this is not always the case, as will be discussed later. In the simplest case, the exact conditions that will be encountered in production will be replicated in the procedure qualification test. This would include the welding process, filler metal, grade of steel, joint details, thicknesses of material, preheat values, minimum interpass temperature level, and the various welding parameters of amperage, voltage, and travel speed. The initial parameters used to make the procedure qualification test plate beg for a name to define them, although there is no standard industry term. It has been suggested that "TWPS" be used where the "T" could alternately stand for temporary, test, or trial. In any case, it would define the parameters to be used for making the test plate since the validity of the particular parameters cannot be verified until they have successfully passed the required test. The parameters for the test weld are recorded on a Procedure Qualification Record (PQR). The actual values used should be recorded on this document. The target voltage, for example, may be 30 volts but, in actual fact, only 29 volts were used for making the test plate. The 29 volts would be recorded.

After the test plate has been welded, it is allowed to cool and the plate is subjected to the visual and nondestructive testing as prescribed by the code. The specific tests required are a function of the type of weld being made and the particular welding consumables. The types of qualification tests are described in D1.1-96, paragraph 4.4.

In order to be acceptable, the test plates must first pass visual inspection followed by nondestructive testing (NDT) (D1.1-96, paragraphs 4.8.1, 4.8.2). At the contractor's option, either RT or UT can be used for NDT. The mechanical tests required involve bend tests (for soundness), macro etch tests (for soundness), and reduced section tensile tests (for strength). For qualification of procedures on steels with significantly different mechanical properties, a longitudinal bend specimen is possible (D1.1-96, paragraph 4.8.3.2). All weld metal tensile tests are required for unlisted filler metals. The nature of the bend specimens, whether side, face, or root, is a function of the thickness of the steel involved. The number and type of tests required are defined in D1.1-96, Table 4.2 for complete joint penetration groove welds, D1.1-96, Table 4.3 for partial joint penetration groove welds, and D1.1-96, Table 4.4 for fillet welds.

Once the number of tests has been determined, the test plate is sectioned and the specimens machined for testing. The results of the tests are recorded on the PQR. According to D1.1-96, if the test results meet all the prescribed requirements, the testing is successful and welding procedures can be established based upon the successful PQR. If the test results are unsuccessful, the PQR cannot be used to establish the WPS. If any one specimen of those tested fails to meet the test requirements, two retests of that particular type of test may be performed with specimens extracted from the same test plate. If both of the supplemental specimens meet the requirements, the D1.1-96 allows the tests to be deemed successful. If the test plate is over 1½" thick, failure of a specimen necessitates retesting of all the specimens at the same time from two additional locations in the test material (D1.1-96, paragraph 4.8.5).

It is wise to retain the PQRs from unsuccessful tests as they may be valuable in the future when another similar welding procedure is contemplated for testing.

The acceptance criteria for the various tests are prescribed in the code. The reduced section tensile tests are required to exceed the minimum specified tensile strength of the steel being joined (D1.1-96, paragraph 4.8.3.5). Specific limits on the size, location, distribution, and type of indication on bend specimens is prescribed in D1.1-96, paragraph 4.8.3.3.

Writing WPSs from successful PQRs— When a PQR records the successful completion of the required tests, welding procedures may be written from that PQR. At a minimum, the values used for the test weld will constitute a valid WPS. The values recorded on the PQR are simply transcribed to a separate form, now known as a WPS rather than a PQR.

It is possible to write more than one WPS from a successful PQR. Welding procedures that are sufficiently similar to those tested can be

supported by the same PQR. Significant deviations from those conditions, however, require additional qualification testing. Changes that are significant enough to warrant additional testing are considered essential variables, and these are listed in D1.1-96, Tables 4.5, 4.6, and 4.7. For example, consider an SMAW welding procedure that is qualified by test using an E8018-C3 electrode. From that test, it would be possible to write a WPS that utilizes E7018 (since this is a decrease in electrode strength) but it would not be permissible to write a WPS that utilizes E9018-G electrode (because Table 4.5 lists an increase in filler metal classification strength as an essential variable). It is important to carefully review the essential variables in order to determine whether a previously conducted test may be used to substantiate the new procedure being contemplated.

D1.1-96, Table 4.1 defines the range of weld types and positions qualified by various tests. This table is best used, not as an after-the-fact evaluation of the applicability of the test already conducted, but rather for planning qualification tests. For example, a test plate conducted in the 2G position qualifies the WPS for use in either the 1G or 2G position. Even though the first anticipated use of the WPS may be for the 1G position, it may be advisable to qualify in the 2G position so that additional usage can be obtained from this test plate.

In a similar way, D1.1-96, Table 4.7 defines what changes can be made in the base metals used in production vs. qualification testing. An alternate steel may be selected for the qualification testing simply because it affords additional flexibility for future applications.

If WPS qualification is performed on a non-prequalified joint geometry, and acceptable test results are obtained, WPSs may be written from that PQR utilizing any of the prequalified joint geometries (D1.1-96, Table 4.5, Item 32).

## EXAMPLES

To provide some insight into the thought process that a welding engineer may follow to develop a WPS, two examples will be given. In both cases, the weld is the same, namely, a 5⁄16" fillet weld. The specific application conditions, however, will necessitate that a separate WPS be developed for each situation. A sample WPS is included for each situation.

Situation One: The weld to be made is a 5⁄16" fillet weld that connects the shear tab to the column. This weld will be made in the fabrication shop with a column in the horizontal position. The fillet weld is applied to either side of a ½" shear tab. It is welded to a W14x311 column with a flange thickness of 2¼". The shear tab is made of A36 steel, while the column is of A572 Gr 50.

The welding engineer recognizes that for the grades of steel involved, and for the type of weld specified, a prequalified WPS could be written. The process of choice for this particular shop fabricator is gas shielded flux cored arc welding, a prequalified welding process. From Table 3.1 of the D1.1-96 code, a list of prequalified filler metals is given. Outershield 70, an E70T-1 electrode is selected because, for semiautomatic welding, it is likely to be the most economical process considering deposition rate and cleanup time. The electrode operates on DC+ polarity. From experience, the engineer knows that 3⁄32" diameter is appropriate for the application, and specifies that the shielding gas should be CO2 based upon the electrode manufacturer's recommendation and its low cost characteristics. From Table 3.2 of the D1.1-96 code, the preheat is selected. It is controlled by the thicker steel, that is, the column flange, and required to be a minimum of 150 degree F since the column flange thickness is 2¼". From recommendations supplied by the electrode manufacturer, the welding engineer selects a welding current of 460 amps, 31 volts, and specifies that the welding speed should be 15-17 ipm. The final variable is determined based upon experience. If any doubts still exist, a simple fillet weld test could be made to verify the travel speed for the given amperage.

As a quick check, the engineer reviews Annex H to ensure that all the prequalified conditions have been achieved. Finally, these are tabulated on the WPS.

Situation Two: The second weld to be made is also a 5⁄16" fillet weld, but in this case, the weld will be made in the field. The weld will be made between the shear tab described above, and the beam web. In this situation, the beam is a W36x150, specified to be of A36 steel. Under field conditions, the weld must be made in the vertical position.

The welding engineer again recognizes that the WPS for this application could be prequalified if all the applicable conditions are met. Self shielded flux cored arc welding is selected in order to ensure high quality welds under windy conditions. This is a prequalified process. In D1.1-96, Table 3.1, the engineer locates suitable filler metals and selects Innershield NR232, an E71T-8 self-shielded flux cored electrode which operates on DC negative polarity. Because the welding will be made in the vertical position, a 0.068 in. diameter electrode is specified. From technical literature supplied by Lincoln Electric, a middle-of-the-range procedure suitable for vertical position welding is selected. The engineer specifies the current to be 250 amps, 19-21 volts, with a travel speed of 5.5-6.5 ipm. The controlling variable is the thickness of the beam web, which is ⅝". In this situation, Table 3.2 of the D1.1-96 code does not require any minimum preheat.

The two welds to be made are remarkably similar, and yet the WPS values specified are significantly different. In order to ensure that quality welds are delivered at economical rates, it is imperative that a knowledgeable individual establish WPS values. These values must be adhered to during fabrication and erection in order to ensure quality welds in the final structure.

## REVIEW AND APPROVAL

After a WPS is developed by a fabricator or erector, it is required to be reviewed by the inspector (AWS D1.1-96, paragraph 6.3.1). This applies whether the WPS has been qualified by test, or whether it is prequalified. The code requires WPSs that are qualified by test to be submitted to the engineer for approval (D1.1-96, paragraph 4.1.1).

Prequalified WPSs are required to be reviewed by the inspector who is required to "make certain that the procedures conform to the requirements of this code" (D1.1-96, paragraph 6.3.1). The D1.1-96 code does not require prequalified WPSs to be submitted to the engineer for approval. Welding procedures that have been qualified by test are required to be reviewed by the engineer (D1.1-96, paragraph 4.1.1). However, the use of a "prequalified joint" does not exempt the engineer from using engineering judgment in determining the suitability of application for these joints (D1.1-96, paragraph 3.1). The code is not explicit with respect to engineering responsibility for the other aspects of a prequalified WPS.

The code is clear that the inspector is required to review all WPSs. For a prequalified WPS, Annex H, "Contents of a Prequalified WPS", is particularly helpful. This Annex provides a list of the various elements of a prequalified WPS, and has a reference to the code paragraph where these restrictions are listed. In the reorganized D1.1-96 code format, user-friendly tables and figures summarize many of the prequalified requirements. These include:

- Table 3.1 - Prequalified Base Metal - Filler Metal Combinations for Matching Strength
- Table 3.2 - Prequalified Minimum Preheat and Interpass Temperatures
- Table 3.3 - Filler Metal Requirements for Exposed Bare Applications of A588 Steel
- Table 3.7 - Prequalified WPS Requirements
- Figure 3.3 - Prequalified Groove Weld Joint Details
- Figure 3.4 - Prequalified CJP Groove Weld Details

In addition to the above tables, Table 4.5 lists the essential variable changes required for WPS requalification. The limitation of variables prescribed in Table 4.5 also apply to prequalified WPSs (D1.1-96, paragraph 3.6). Through the use of these tables, the majority of the prequalified conditions can be easily checked by the inspector as part of the required review.

The fundamental premise on which the suitability of prequalified procedures stands is stated in the commentary as follows:

> "Certain shielded metal arc, submerged arc, gas metal arc (excluding the short circuiting mode of metal transfer across the arc), and flux cored arc WPSs in conjunction with certain related types of joints have been thoroughly tested and have a long record of proven satisfactory performance." (D1.1-96, paragraph C3.2.1).

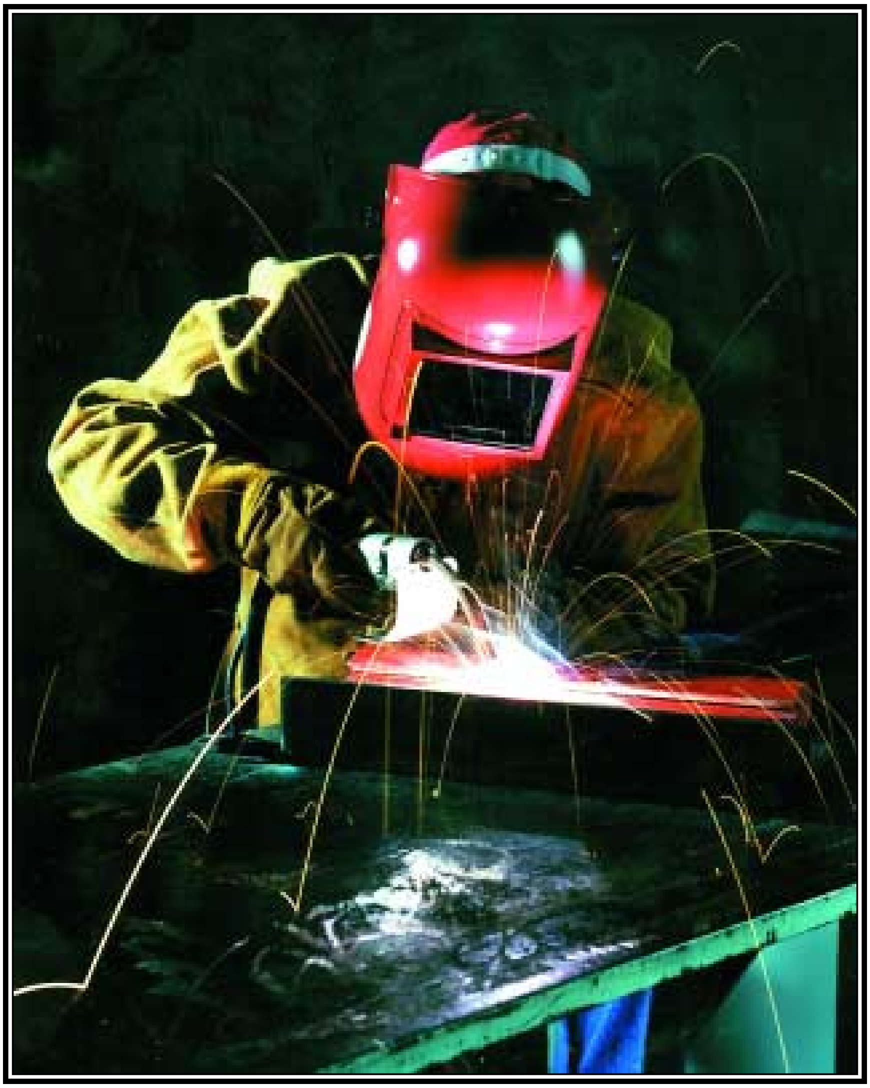
The review required by the inspector in D1.1-96, paragraph 6.3.1 does not specifically require a determination regarding the suitability of the procedure for the particular application, but rather requires that the procedure conform to the requirements of the code. As previously stated, the engineer is not exempted from exercising engineering judgment when prequalified joint details are used.

The previously described responsibility of the inspector to review all WPSs applies equally to those qualified by test. However, D1.1-96, paragraph 4.1.1 additionally requires the following:

> "Except for prequalified WPSs in conformance with Section 3, a WPS for use in production welding shall be qualified in conformance with Section 4, Part B, and shall be approved by the engineer."

The apparent logic behind the differences in approval approaches is that while prequalified WPSs are based upon well established, time proven, and documented welding practices (see D1.1-96, paragraph C3.2.1), WPSs that have been qualified by test may utilize new, unproven and sometimes controversial concepts. WPSs that are qualified by test are not automatically subject to the same restrictions that would apply to prequalified WPSs. Even though the required qualification tests have demonstrated the adequacy of the particular WPS under test conditions, further scrutiny by the engineer is justified to ensure that it is applicable for the particular situation that will be encountered in production.

Two examples will be cited to illustrate the philosophical differences a welding engineer may take when evaluating a WPS qualified by test. In Situation One, the contractor wishes to use a WPS that would otherwise be prequalified, except for one change in the joint detail. Based upon experience and some informal tests, the contractor has determined that a modified groove detail will reduce the required volume of weld



metal without affecting quality. The joint detail is similar to a B-U2a-GF, except that the root opening and groove angles deviate from the prequalified requirements shown in D1.1-96. Specifically, the combination of a 1/8" root opening with a 45 degree included angle when applied to plate 1/2" thick provides a near optimum configuration for this contractor's procedures that utilize FCAW-g. Since these dimensional changes are beyond the limits permitted by the as-detailed tolerances for the specific joint, they must be qualified by test. If there were to be a problem associated with this approach, it would no doubt evidence itself as a fusion-type problem. The required qualification test as outlined in Table 4.2 require two Reduce Section Tension Tests, and four Side Bend Tests. Both of these tests, and the Side Bend Test in particular, will quickly reveal any problem with fusion problems associated with this technique. A successful PQR should satisfy the engineer who is required to approve this procedure.

In Situation Two, the issue is more complex. A new steel is being contemplated for construction, and the claim of the steel producer is that it can be welded with reduced preheat levels. It cannot be prequalified because (a) the steel is not prequalified; and, (b) the preheat levels are below the prequalified limits. In order to qualify the procedure for unlimited thickness qualification, D1.1-96, Table 4.2 requires the test plate be 1 in. or thicker. The contractor qualifies the welding procedure on 1 in. steel, although the actual application will utilize 4 in. thick steel. The actual joint configuration used for qualification testing is a double V groove butt joint, welded from two sides. The test plate is not preheated prior to fabrication (although the air temperature inside the shop where the qualification testing is being performed is at 70 degree F). After the first weld pass is applied, the steel temperature rises well above ambient due to the thermal energy added by the welding process. A second weld pass is applied to the first side. Next, the plate is inverted and the root pass made from the opposite side is gouged out. While the interpass temperature is still well above ambient, the second side of the joint is welded. Finally, the plate is flipped one more time, and the first side of the joint is welded out to completion.

The test plate is subject to all of the code-mandated tests, and successfully meets the code requirements. With this information in hand, the contractor submits the procedure to the engineer for approval, claiming that these tests have proven the weldability of the new steel, and that no preheat is required. While it is true that the code-mandated requirements have been fulfilled, the suitability of this welding procedure for actual fabrication has not been established. The relatively small sizes associated with the test plate (1" thick x 14" minimum wide x 30" minimum long, according to D1.1-96, Figure 4.10) is not sufficient to duplicate the restraint or cooling rates that will be seen in actual structures. These issues will affect the resultant heat affected zone microstructure, hydrogen diffusion rates, and residual stress levels - all elements that affect the possibility of weld cracking. In addition, except for the root pass, all of the weld passes had the benefit of the higher interpass temperature. Furthermore, the root pass that was made without preheat was gouged out when the second side was welded. Although no preheat was applied, the steel was at shop ambient temperature, qualifying a 70 degrees F preheat temperature, not "no preheat" temperature.

The engineer ought to view the second WPS with a greater degree of scrutiny than first. It would be reasonable, for example, to require weldability tests (such as: G-BOP, TEKKEN, or CTS tests) in order to better understand the likely behavior of this proposed welding procedure. Larger scale, restrained mockups would be necessary to evaluate actual restraint and cooling conditions.

When WPSs that have been qualified by test are reviewed, there are three distinct elements of that review: First, the procedure qualification record should be evaluated to ensure that all the required tests have been performed, verifying that the proper thicknesses of material, positions of welding, and number of required tests have all been performed. Secondly, the results of the testing must be examined to be certain that the code requirements have been met. The final aspect of the review is to compare the WPS to the PQR. This will consist of a comparison of the requirements of AWS D1.1-96, Table 4.5, as it relates to any differences between the PQR and the WPS. Requirements regarding the steels used in testing versus those listed on the WPS are addressed in D1.1-96, Table 4.7.

*The opinions and explanations expressed above are the author's alone and do not necessarily reflect the opinions of the AWS or of the AWS D1 Committee. Official interpretations of the D1.1 code can only be made by the D1 Committee. D1.1-96, Annex F, provides information detailing how an official interpretation can be obtained.*

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