How to Choose Electrodes for Joining High-Strength Steels

Technical insight is provided for evaluating the variety of GMAW and FCAW electrodes available for joining high-strength steel

BY K. SAMPATH

All over the world, adoption of gas metal arc welding (GMAW) and flux cored arc welding (FCAW) processes continues to grow for low-cost fabrication of various grades of structural steels, including high-strength steels. The growth of GMAW/FCAW is driven primarily by the increased availability of numerous consumables, including solid, fluxcored, and metalcored wire electrodes. But, how does one select an electrode for joining a particular grade of high-strength steel? Will a simple reliance on relevant AWS/ANSI electrode specifications be adequate? How does one evaluate data from a multitude of electrode manufacturers? This article offers to provide technical insight into those questions.

Factors to Consider

Selection of an electrode for a particular application is based on several factors. Chief among them is a fundamental understanding of the relationships among chemical composition, processing, microstructure, and mechanical properties of the steel being welded. Also, specific design requirements for mechanical properties of the welded component or structure should be known.

The "things to-do" list is long while underlying issues are complex. However, such an understanding is a prerequisite for achieving quality, productivity, and improved performance of welded constructions, while controlling overall fabrication cost.

Basic Principles of Electrode Selection

Electrode selection is based on an electrode's ability to provide weld metal that is chemically compatible with the base metal. Electrodes that offer a similar (not same but matching)

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chemical composition as the base metal minimize potential adverse effects of base metal dilution, which can include localized corrosion.

Welding electrodes are also selected to enhance weldability. A major aspect of weldability is the ability to obtain crack-free weldments. In the case of high-strength steels, the primary concern is achieving resistance to hydrogen-assisted cracking (HAC) in both the weld metal and the heat-affected zone (HAZ). Resistance to solidification cracking is seldom a concern. Most often, solidification cracking in weld metal is attributed to segregation of impurities such as sulfur and phosphorus along the weld centerline. Control of impurities (sulfur and phosphorus, each at 0.01 wt-% maximum) and trace elements in the welding electrode, and control of weld solidification conditions through manipulation of travel speed, most often avoid solidification cracking in weld metal.

Microstructure

Microstructure underpins mechanical properties. The term microstructure includes type, size distribution, morphology, and volume fraction of various microstructural constituents. Microstructure, in turn, is dependent on chemical composition and processing conditions, especially cooling rate. Based on a need to achieve desired mechanical properties, weldability may be looked upon as the ability to "recreate and/or retain" microstructures similar to the base metal.

Various carbon equivalent formulas allow one to relate chemical composition with weldability of steel. In particular, Yurioka's carbon equivalent number (CEN), as shown in Equation 1, offers a viable means to assess relative effects of various alloy elements on weldability.

$$CEN = C + A(C) \times \left\{ \begin{array}{l} \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} \\ + \frac{Cr + Mo + V + Nb}{5} + 5B \end{array} \right\} \qquad (1)$$

where A(C) = 0.75 + 0.25 × tanh [20 ×(C – 0.12)], and concentrations of all elements are expressed in wt-%.

Although the CEN equation was originally developed to assess hydrogen cracking sensitivity of structural steels, the equation is also relevant to weld metal. The higher the CEN, the lower is the resistance to HAC. Carbon has by far the greatest impact on weldability. So, it is essential to select welding electrodes with a carbon content lower than that of the steel being welded. Considering possible carbon pick-up from CO_2 in the weld shielding gas, and base metal dilution, it is prudent to select welding electrodes with about 0.02 to 0.04 wt-% lower carbon than the base metal. Lowering carbon content must be compensated for by using other alloy elements to maintain or further increase CEN. A 0.12 wt-% for carbon is considered an appropriate upper limit in high-strength steel welding electrodes, as twinned martensite, which has an extremely poor resistance to HAC, is likely to form above this limit.

The CEN equation is helpful in selecting various principal alloy elements in the welding electrode. Alloy elements with a lower coefficient (nickel, copper, and manganese) are preferable to those with a higher coefficient (chromium and molybdenum). Yet, weld metal must remain chemically compatible with the base metal. A prior knowledge of the chemical composition of the base metal and the roles of various alloy elements is valuable.

Overmatching Strength and Overall Alloy Content

Welding electrodes must provide weld metals with a minimum required weld tensile strength and acceptable impact toughness properties, either in the as-welded or postweld heat treated condition. Use of a welding consumable that offers a deposited weld metal with higher weld tensile strength than the tensile strength of steel being welded is called overmatching. Overmatching is used primarily to "protect" the weld deposit from the presence of fabrication-related weld flaws. These flaws when subjected to occasional excessive service loads can potentially lead to catastrophic consequences.

However, overmatching of high-strength steels using welding electrodes with high-carbon content requires expensive preheat, interpass, and occasionally post-soak temperature controls during welding to ensure against HAC, thus hurting productivity and overall economics of fabrication. Therefore, overmatching is an option only when the overmatched weld metal offers adequate toughness, particularly acceptable low-temperature impact toughness, and overmatching allows cost-effective fabrication.

Other aspects of strength consideration are heat input and cooling rates. It is well known that high weld energy input and associated slow weld cooling rates produce a lower strength weld metal, and vice versa. Depending on the electrode diameter, the weld energy input commonly ranges between 20 and 80 kJ/in. A high-performance welding electrode is expected to overmatch at the highest usable weld energy input while meeting or exceeding weld metal toughness requirements. This invariably means that at the lowest usable weld energy input, the same welding electrode may overmatch the minimum specified tensile strength of the base metal, possibly in excess of 10%. In other words, an electrode that provides marginal overmatching at the highest usable energy input is likely to offer excessive overmatching at the lowest usable weld energy input. Fortuitously, the high-strength weld metal simultaneously offers higher toughness, primarily due to the presence of refined grains and microstructural constituents. Expectedly, CEN of the corresponding welding electrode would be higher than the base metal, in excess of 10%.

The strength and other mechanical properties of a clean, defect-free weld metal depend primarily on chemical composition, and secondarily on weld cooling rate. As shown in Equation 1, a higher alloy content results in a higher CEN, and thus a higher tensile strength. As a higher CEN progressively impairs weldability, control of alloy content of the selected electrode to a desirable range of CEN is crucial. The inherent conflict requires "balancing" or optimization of competing criteria. When there is an inability to resolve this underlying conflict, as in the case of certain very high-strength steels such as HY-130, overmatching may no longer be a viable option.

Toughness and Transformation Temperature

How does one select a welding electrode to improve weld metal toughness? Besides chemical composition, welding conditions (particularly weld cooling rate) contribute to microstructure development.

The following on-cooling transformation temperatures are important with regard to microstructural development in high-strength steels: 1) austenite-to-ferrite (A_{r3}), 2) austenite-to-pearlite (i.e., eutectoid transformation), 3) austenite-to-bainite (i.e., B_S, bainite-start and B_F, bainite-finish), and 4) austenite-to-martensite (i.e., M_S, martensite-start and M_F, martensite-finish) temperatures.

Controlled lowering of the relevant transformation temperatures allows one to refine grains and microstructural constituents in weld metal, and thus simultaneously improve both strength and overall toughness. Here again, several constitutive equations allow one to relate chemical composition with transformation temperatures, thus further allowing selection and manipulation of various microstructural constituents.

The A_{r3} temperature is approximately related to chemical composition as shown in Equation 2. Likewise, B_S, B_F, and M_S temperatures are statistically related to chemical composition of low-alloy steels as shown in Equations 3–5.

$$A_{r3}\ (^\circ C) \sim 910 - (310 \times C) \\ -(80 \times Mn) - (80 \times Mo) \\ -(55 \times Ni) - (20 \times Cu) - (15 \times Cr) \quad (2)$$

$$B_S\ (^\circ C) = 830 - (270 \times C) \\ -(90 \times Mn) - (37 \times Ni) \\ -(70 \times Cr) - (83 \times Mo) \quad (3)$$

$$B_F\ (^\circ C) = 710 - (270 \times C) \\ -(90 \times Mn) - (37 \times Ni) \\ -(70 \times Cr) - (83 \times Mo) \quad (4)$$

$$M_S\ (^\circ C) = 561 - (474 \times C) \\ -(33 \times Mn) - (17 \times Ni) \\ -(17 \times Cr) - (21 \times Mo) \quad (5)$$

The above statistically valid relationships between chemical composition and transformation temperatures were originally developed for particular types of steels, under specific experimental conditions. Nevertheless, these equations are useful for manipulating alloying elements in welding electrodes, thus targeting desirable ranges of transformation temperatures.

The objective is to select a welding electrode or control its alloy content within a desirable range of CEN, while achieving a 30° to 50°C lowering of the relevant transformation temperatures compared to the characteristics of the high-strength steel being welded. Thus, a complete understanding of chemical composition and microstructures of the base metal is a prerequisite to selecting a high-performance welding electrode.

Besides alloy content, increasing (weld) cooling rate is known to suppress (undercool) transformation temperatures. The welding operational envelope controls weld cooling rate. As mentioned previously, increasing the weld cooling rate contributes to a further refining of both grain size and various microstructural constituents, thus strengthening the weld metal while simultaneously increasing its toughness.

Despite this potential, it must be recognized that in fusion welding situations, because of epitaxial growth considerations, the level of undercooling achieved is often minimal, not exceeding a few degrees.

Dissolved Gases and Toughness

Weld metal toughness can be severely impaired by the presence of dissolved gases such as oxygen and nitrogen (in excess of 500 ppm, total), and too many inclusions that contribute to "a dirty weld." Proper control of shielding gas during welding, and the presence of controlled amounts of aluminum, titanium, and zirconium (each at 0.03 wt-% maximum) in the welding electrode are necessary to minimize air ingress, and effectively deoxidize, fix nitrogen in weld metal, allow "scavenging and grain refining," and thus enhance weld metal toughness.

Specifications

Standard setting organizations such as the American Welding Society (AWS) codify the above rationale and knowledge for welding electrode selection into appropriate welding electrode specifications, such as AWS A5.28/A5.28M:2005, *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*, and A5.29-05, *Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding*. Underlying parameters in a specification are supported by both historical data and test data developed by electrode manufacturers and researchers, among others. The specification parameters allow users to select one or more electrode classification(s), and corresponding electrodes offered by one or more welding electrode manufacturer(s).

Welding electrode specifications simplify the above complex electrode selection criteria, and present the recommendations, as clearly and concisely as possible. To maintain neutrality or eliminate bias, the recommendations are classified into groups of welding electrodes based on chemical composition of the electrode or the as-deposited weld metal (as in the case of cored electrodes), and appropriate and acceptable mechanical property (commonly strength and toughness) test results of undiluted, buttered, or diluted weld metal. The relevant electrode classification system also recognizes the fact that electrode manufacturers often produce one type of electrode that can be used to join a broad range of high-strength steels.

It is instructive to recognize that despite a strong attention to detail in reducing various risks inherent to welding electrodes while enhancing reliability of welded structures, welding electrode specifications do not offer an ability to distinguish the combined effects of critical elements in electrodes and weld metals. All the same, as shown by the effects of CEN and calculated transformation temperatures on weldability, microstructure development, and weld mechanical properties, such an ability is essential to achieving desirable combinations of high productivity and superior performance.

Current welding electrode specifications do not distinguish a high-performance welding electrode composition from either a rich or a lean welding electrode composition, although all of them meet electrode specification requirements. Compared to either a rich or a lean welding electrode composition, a high-performance welding electrode composition is flexible or "more forgiving" when it allows welding over a wide welding operational envelope while providing weld metals meeting minimum mechanical property requirements.

Current welding electrode specifications also do not highlight to a potential user various fabrication-related cost risks in selecting either a rich or a lean welding electrode composition that otherwise meets electrode specification requirements. Such limitations could adversely impact weld procedure qualification efforts, particularly in terms of meeting schedules and cost estimates.

Summary

Selection and use of GMAW/FCAW electrodes that eliminate a need for expensive preheat, interpass, and post-soak temperature controls during welding of high-strength steels, yet perform satisfactorily over a broad welding operational envelope, while providing weld metal with an overmatched tensile strength and acceptable toughness, offer exceptional value to both electrode manufacturers and weld fabricators.

To find such high-performance GMAW/FCAW electrodes, first, know the chemical composition, microstructure, and mechanical properties (strength and toughness) of the steel being welded. Know the actual carbon content, and calculate CEN. Based on microstructures of the high-strength steel, identify and calculate relevant transformation temperatures.

Second, know the minimum acceptable structural design requirements for strength and toughness.

Third, refer to AWS A5.28/A5.28M:205, *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding,* and A5.29/A5.29M:205, *Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding,* and identify appropriate electrode classifications based on minimum acceptable requirements for transverse-weld tensile strength and toughness.

Fourth, obtain electrode manufacturers' data sheets for the relevant electrode classification. Identify an electrode that has 0.02 to 0.04 wt-% less carbon, is chemically compatible, and shows a desirable CEN and 30° to 50°C lower calculated transformation temperatures than the steel being welded.

Lastly, evaluate the candidate welding electrode using previously certified welding procedures, and determine that minimum acceptable requirements for weld metal strength and toughness can be consistently achieved.◆