JMEPEG (2008) 17:808–819
DOI: 10.1007/s11665-008-9236-2

1059-9495/$19.00

Metallurgical Design of High-Performance GMAW Electrodes for Joining HSLA-65 Steel

V. Sampath, J. Kehl II, C. Vizza, R. Varadan, and K. Sampath

(Submitted June 26, 2007; in revised form February 24, 2008)

A C++ algorithm was used to metallurgically design high-performance GMAW electrodes for joining HSLA-65 steel. The electrode design was based on: (1) a carbon content ≤0.06 wt.% for improved weldability, (2) a 5-15% lower A_{r3} transformation temperature than HSLA-65 steel for enhanced strength and toughness, and (3) a desirable range of carbon equivalent number (CEN) for consistently overmatching the minimum specified tensile strength of HSLA-65 steel. The algorithm utilized a set of boundary conditions that included calculated A_{r3}, B_S, B_F, and M_S transformation temperatures besides CEN. Numerical ranges for boundary conditions were derived from chemical compositions of commercial HSLA-65 steel, substituting thermomechanical effects with weld solidification effects. The boundary conditions were applied in evaluating chemical composition ranges of the following three prospective welding electrode specification groups that offered to provide ≤0.06 wt.% carbon, a minimum transverse-weld tensile strength of 552 MPa (80 ksi), and a minimum CVN impact toughness of 27 J at −29 °C through −51 °C (20 ft lbf at −20 °F through −60 °F) in the as-welded condition: (1) ER80S-Ni1, (2) E90C-K3, and (3) E80C-W2. At ≤0.06 wt.% carbon, the algorithm returned over 3100 results for E90C-K3 that satisfied the boundary conditions, but returned no acceptable results for other two electrode specification groups. Results revealed that welding electrode designs based on an Fe-C-Mn-Ni-Mo system, containing 0.06 wt.% C, 1.6 wt.% Mn, 0.8 wt.% Ni, and 0.3 wt.% Mo that provide weld metals characterized by an A_{r3} of 690 °C, a CEN of 0.29, and a ($B_F - M_S$) of 30 °C are expected to consistently overmatch the minimum specified tensile strength of HSLA-65 steel while offering a minimum CVN impact toughness of 41 J at −40 °C (30 ft lbf at −40 °F).

Keywords C++ algorithm, carbon equivalent number, chemical composition limits, ER 80 type electrodes, ER 90 type electrodes, GMAW process, HSLA-65 Steel, overmatching, transformation temperatures, welding electrode specifications

1. Introduction

1.1 HSLA-65 Steel

In recent years, high-strength, low-alloy (HSLA) steels have gained increased acceptance in automobile manufacturing and shipbuilding, as these low-carbon steels provide improved formability and weldability. One promising high-strength low-alloy steel, HSLA-65, may find extensive use in shipbuilding (Ref 1) and in the construction of off-highway vehicles, bridges, pressure vessels, storage tanks, pipelines, etc. because of its high yield strength, exceptional toughness, and higher strength-to-weight ratio compared to conventional higher-strength steels (HSS) such as DH-36. In regard to the transportation industry in particular, the higher strength-to-weight ratio of HSLA-65 steels offers to raise Corporate Average Fuel Economy (CAFE) while reducing fabrication and life cycle costs.

V. Sampath, J. Kehl II, and **C. Vizza**, Richland Senior High School, Johnstown, PA; **R. Varadan**, Siemens Power Transmission and Distribution Inc., Richland, MS; and **K. Sampath**, Kreative Koncepts, Johnstown, PA. Contact e-mail: rs127@yahoo.com.

Table 1 shows chemical compositional requirements for HSLA-65 steel per ASTM A945 material specification (Ref 2) for "High-Strength Low-Alloy Structural Steel Plate with Low Carbon and Restricted Sulfur for Improved Weldability, Formability, and Toughness," together with the nominal chemical composition of certain commercial HSLA-65 steels. The A945 specification requires that HSLA-65 grade plate steel must have a 448 MPa (65 ksi) minimum yield strength and a 538 MPa (78 ksi) minimum tensile strength. Compared to conventional HSS such as HY-80, thermomechanically processed HSLA-65 plate steels exhibit a low carbon content (nominally at 0.08 wt.%), a low alloy content (total <5 wt.%), a restricted sulfur content, and a refined ferrite grain size that typically ranges between ASTM 10 and 12. These characteristics allow over 448 MPa (65 ksi) yield strength, 538 MPa (78 ksi) tensile strength, and exceptional Charpy V-notch (CVN) impact toughness over 41 J at −40 °C (30 ft lbf at −40 °F), while improving both formability and weldability (Ref 2).

A prior investigation (Ref 3) had evaluated the use of ER70S-series gas metal arc welding (GMAW) electrodes, with a 483 MPa (70 ksi) minimum transverse-weld tensile strength and 27 J at −29 °C (20 ft lbf at −20 °F) minimum CVN impact toughness requirements, for joining HSLA-65 steel plates. However, the resulting weld metals, produced at about 2 kJ/mm (51 kJ/in.) weld energy input, did not consistently meet the required CVN impact toughness in the as-welded condition. Furthermore, while welding HSLA-65 steel plates, these

Table 1 Specification requirements and typical chemical compositions of HSLA-65 and Title III plate steels

	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Nb	V	Al	Others
ASTM A945 requirements	0.10	1.10-1.65	0.025	0.010	0.10-0.50	0.40	0.20	0.08	0.35	0.05	0.10	0.08	
Mittal steel HSLA-65	0.08	1.39	0.006	0.003	0.22	0.35	0.16	0.06	0.25	0.035	0.057	0.003	0.003 Ti
U.S. steel HSLA-65	0.08	1.35	0.008	0.003	0.26	0.35	0.03	0.06	0.35	0.021	0.023		0.012 Ti
U.S. steel Title III Grade 65	0.07	1.55	0.017	0.002	0.27	0.03	0.06	0.06	0.03	0.030			

Note: Single values are maximum. All values are expressed in wt.%

electrodes suffer from a minimal welding operational envelope, thus requiring strict control of welding conditions and weld cooling rate to achieve acceptable mechanical properties. This deficiency adversely affects both welding productivity and fabrication costs. Therefore, alternative high-performance GMAW electrodes must be identified to allow a widespread use of HSLA-65 steels in structural fabrication. Furthermore, when specific advances in constructional steels are matched by appropriate developments in high-performance welding electrodes, one could expect to achieve a higher welding productivity and a highly efficient welded structure.

1.2 Welding Electrode Specifications

AWS A5.28-05 (Ref 4) "*Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*" recommends the following four groups of GMAW electrode specifications for joining HSLA-65 steels when the as-deposited weld metal is expected to provide a 552 MPa (80 ksi) minimum transverse-weld tensile strength, and a desirable CVN impact toughness of 27 J at −29 °C through −51 °C (20 ft lbf at −20 °F through −60 °F):

(1) ER80S-Ni1 (based on Fe-C-Mn-Ni system);
(2) ER80S-D2 (based on Fe-C-Mn-Mo system);
(3) E90C-K3 (based on Fe-C-Mn-Ni-Cr-Mo system); and
(4) E80C-W2 (based on Fe-C-Mn-Ni-Cr system).

As shown in parentheses, these four groups of GMAW electrode specifications are classified on the basis of certain principal alloy elements, but include chemical composition ranges for other elements such as S, P, Si, Cu, Nb, V, Ti, Al, Zr, etc. Control of these other elements is critical to eliminate weld defects and to promote desirable combinations in weld metal microstructure development. Depending on their nominal content and actual effects during welding and/or following postweld heat treatment, these other elements enhance (or impair) weld metal soundness, cleanliness, and mechanical properties, particularly low-temperature impact toughness.

1.3 High-Performance Electrodes

Design of high-performance electrodes for HSLA-65 steel that also belong to one or more of these four electrode specification groups is based on several factors. A recent article (Ref 5) had summarized that the following factors are critical in selecting high-performance electrodes for welding high-strength steel:

(1) chemical compatibility with base metal;
(2) superior weldability to provide crack-free weldments;
(3) ability to "recreate and/or retain" microstructure similar to base metal;
(4) ability to provide a clean and defect-free weld metal;
(5) eliminate or substantially reduce a need for expensive preheat, interpass, and postsoak temperature controls during welding;
(6) perform satisfactorily over a broad welding operational envelope for improving welding productivity and reducing overall fabrication costs; and
(7) provide weld metal with an overmatched tensile strength and acceptable toughness, in as-welded and/or postweld heat-treated condition.

To this end, a high-performance welding electrode must have about 0.02-0.04 wt.% less carbon and a controlled alloy content that shows a desirable range of Yurioka's carbon equivalent number (CEN), while achieving a 30-50 °C lowering of the relevant transformation temperatures compared to the characteristics of the high-strength steel being welded. Considering high-strength steels, the following on-cooling transformation (austenite decomposition) temperatures are important for controlling microstructural development:

(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.

1.4 Weldability

Yurioka's CEN is calculated from chemical composition of structural steels as shown in Eq 1 (Ref 6).

$$\mathrm{CEN} = \mathrm{C} + A(\mathrm{C}) \times \{\mathrm{Si}/24 + \mathrm{Mn}/6 + \mathrm{Cu}/15 + \mathrm{Ni}/20 + (\mathrm{Cr} + \mathrm{Mo} + \mathrm{V} + \mathrm{Nb})/5 + 5\mathrm{B}\} \quad \text{(Eq 1)}$$

where $A(\mathrm{C}) = 0.75 + 0.25 \times \tanh\ [20 \times (\mathrm{C} - 0.12)]$ and concentrations of all elements are expressed in wt.%. The CEN equation was originally developed to assess hydrogen-assisted cracking (HAC) sensitivity of a wide variety of structural steels, as it offers a viable means to assess relative effects of various alloy elements on weldability. The equation is also relevant to weld metal. Higher the CEN, higher is the susceptibility to HAC. Carbon content has by far the greatest impact on weldability. Therefore, it is essential to select welding electrodes with a lower carbon content than the steel being welded. Yet, weld metal must remain chemically compatible with the base metal, and more or less match the CEN of the base metal.

1.5 Microstructure Development

Secondly, controlled lowering of the relevant transformation temperature allows one to refine grains and microstructural constituents while simultaneously improving both strength and overall toughness. Several constitutive equations allow one to relate chemical composition with transformation temperatures, thus further aiding selection and manipulation of type, size, and volume fraction of various microstructural constituents.

The A_{r3} temperature is approximately related to chemical composition as shown in Eq 2 (Ref 7). Likewise, B_S, B_F, and M_S temperatures are statistically related to chemical composition of low-alloy steels as shown in Eq 3-5 (Ref 8).

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

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

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

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

These statistically determined relationships between chemical composition and transformation temperatures were originally developed for particular types of steels, under specific experimental conditions. Nevertheless, these equations and other similar equations (Ref 9) serve as simple tools to manipulate alloying elements in welding electrodes, thus allowing one to target desirable ranges of transformation temperatures, albeit inherent approximations. Consequently, this research capitalized on this simple and convenient utility, but did not attempt to either estimate associated errors or quantify uncertainty in calculating transformation temperatures from chemical composition data.

1.6 Desirable Features of High-Performance Electrodes

Based on Eq 1-5, Table 2 provides calculated values of CEN and transformation temperatures of commercially available HSLA-65 steels. Due to inherent approximations, calculated values of transformation temperatures do not represent actual transformation temperatures of these steels. Nevertheless, one can infer from Table 2 (columns 6-9) that in the case of HSLA-65 and Title III steels, the various calculated transformation temperatures are related as follows: $A_{r3}(^\circ\mathrm{C}) > B_S(^\circ44\mathrm{C}) > B_F(^\circ\mathrm{C}) > M_S(^\circ\mathrm{C})$.

Based on data on commercial HSLA-65 steels shown in Table 2, it appeared that the following "mutually inclusive" constraints would be desirable in metallurgically designing high-performance GMAW electrodes suitable for joining HSLA-65:

(1) A carbon content of 0.05-0.06 wt.% in the welding electrode;
(2) a 5-15% lowering of the A_{r3} transformation temperature of the welding electrode or weld metal relative to that of HSLA-65 plate steel; and
(3) a CEN value comparable to HSLA-65 plate steel.

In principle, when these three conditions are satisfied simultaneously, one would be able to identify a GMAW electrode chemical composition suitable for joining HSLA-65 steel that would offer high-performance over a broad welding operational envelope.

1.7 Constraints-Based Modeling

A previous research (Ref 10) had pioneered a constraints-based modeling (CBM) methodology for designing high-performance GMAW electrode compositions suitable for joining HSLA-100 steels. This methodology relied on a set of mutually inclusive metallurgical constraints that included CEN and a certain group of calculated transformation temperatures as a basis for designing high-performance GMAW electrode compositions. One of the identified electrodes (with 0.028 wt.% C, 1.54 wt.% Mn, 3.78 wt.% Ni, 0.52 wt.% Mo, 0.34 wt.% Si, and 0.028 wt.% Ti) was used to produce a set of representative test weldment over a broad range of welding conditions. The large welding operational envelope corresponded to calculated weld cooling rates ranging from 3 to 55 °C/s at 538 °C (5-95 °F/s at 1000 °F). Amazingly, the resulting weld metals met or exceeded tensile strength requirements for all-weld metals in the as-welded condition (Fig. 1). A single GMAW electrode composition provided all-weld metals with superior tensile properties that overmatched the specified minimum tensile strength of HSLA-100/HY-100 steel at high weld cooling rates, while undermatching HSLA-100/HY-100 steel at low weld cooling rates.

A subsequent research (Ref 11) had reported using a set of mutually inclusive metallurgical constraints together with a C++ algorithm as a low-cost, low-risk means to evaluate and

Table 2 Typical C, Mn, and Ni contents, CEN and calculated transformation temperatures of HSLA-65 and Title III Grade 65 plate steels

Type	C, wt.%	Mn, wt.%	Ni, wt.%	CEN	A_{r3}, °C	B_S, °C	B_F, °C	M_S, °C
Mittal steel HSLA-65	0.08	1.39	0.35	0.28	743	654	534	467
U.S. steel HSLA-65	0.08	1.35	0.35	0.28	741	654	534	467
U.S. steel Title III Grade 65	0.07	1.55	0.03	0.24	756	661	541	474
Desirable range for electrode	≤0.06	≥1.10	≤1.10	0.25-0.35	650-700	<650	<530	<460
Calculated characteristics of metallurgically designed electrode (a)	0.06	1.6	0.8	0.29	690	608	488	458

(a) The algorithm used the following mean values in the metallurgical design of GMAW electrodes: Si at 0.60 wt.%, Cu at 0.20 wt.%, V at 0.005 wt.%, Nb at 0.005 wt.%, Ti at 0.03 wt.%, and B at 0.0002 wt.%

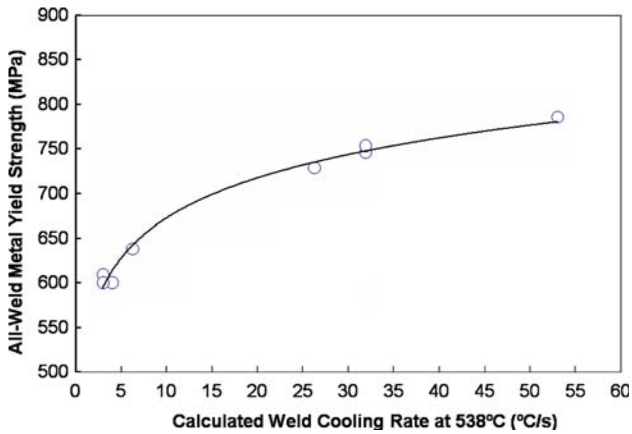

Fig. 1 Variation in all-weld metal yield strength with calculated weld cooling rate at 538 °C (1000 °F). The eight test weldments were produced using a single heat of 1.6 mm (1/16 in.) dia. GMAW electrode and 25 mm (1 in.) thick HSLA-100 or HY-100 type steels (Ref 10)

verify successful design of candidate welding electrodes for HSLA-100 steel.

2. Objectives

The objectives of the current work were to:

(1) design a high-performance GMAW electrode composition belonging to one or more welding electrode classification groups of AWS A 5.28-05 specification; and
(2) leverage CBM methodology (Ref 10) and algorithmic approach (Ref 11) as a low-cost, low-risk means to evaluate, validate, and report on the successful design of candidate welding electrode compositions for overmatching the specified minimum tensile strength of HSLA-65 steel.

3. Methodology

3.1 Model Development

The model development efforts focused on known relationships among chemical composition, transformation temperature, microstructure development, and mechanical properties of HSLA-65 steel (Ref 1), and common rationale for selecting welding electrodes for high-strength steels (Ref 5). To identify all usable electrode compositions for welding HSLA-65 steel, a previously published C++ algorithm for HSLA-100 steel (Ref 11) was adapted for use with HSLA-65 steel. Figure 2 shows a flowchart of the algorithm, while Appendix A provides the algorithm in nonlanguage specific "pseudo-code."

The C++ algorithm consisted of three main sections to:

(1) define a set of boundary conditions along with appropriate numerical ranges;
(2) define a set of electrode chemical composition ranges for evaluation; and
(3) identify electrode compositions that satisfied the boundary conditions, using a series of iterative loops and if-else filters.

3.2 Boundary Conditions and Numerical Ranges

The algorithm used calculated A_{r3}, B_S, B_F, and M_S transformation temperatures and CEN as boundary conditions to aid electrode design. The first section of the algorithm defined the following numerical ranges for the set of boundary conditions:

- CEN between 0.25 and 0.35;
- A_{r3} between 650 and 700 °C;
- B_S between 590 and 650 °C;
- B_F between 470 and 530 °C; and
- M_S between 430 and 460 °C.

As shown in Table 2, these boundary conditions primarily retained the existing relationships among calculated A_{r3}, B_S, B_F, and M_S temperatures in HSLA-65 steel, while meeting the desired numerical ranges for A_{r3}, B_S, B_F, M_S, and CEN.

Thus, selection of specific numerical ranges for boundary conditions is not arbitrary, but is derived from chemical composition, processing, and microstructure relationships observed in commercial HSLA-65 steels. For example, the microstructure of HSLA-65 plate steel is obtained through thermomechanical manipulation of austenite decomposition (Ref 1). To obtain a similar high-performance microstructure in weld metal, the model considered a 5-15% lowering of the A_{r3} transformation temperature by manipulating the contents of selected alloy elements in the welding electrode. This approach offered to simplify, yet effectively substitute for the various effects of thermomechanical operations with those of weld solidification.

In the above context, increasing the alloy content to lower A_{r3} transformation temperature (of the welding electrode and thus the deposited weld metal) will result in a highly refined, predominantly ferritic microstructure in the weld metal, which is expected to overmatch the strength of HSLA-65 steel while offering acceptable toughness. However, an indiscriminate increase in alloy content is likely to adversely affect both chemical compatibility and weldability, and in particular result in an increased susceptibility to galvanic corrosion and HAC.

3.3 Specification Ranges

The second section of the algorithm defined the chemical composition ranges for C, Mn, Cr, Ni, and Mo as specified in the AWS A5.28-05 welding electrode specification for ER80S-Ni1, ER80S-D2, E90C-K3, and E80C-W2 (Table 3). However, within the broader specification range, the chemical composition ranges for C, Mn, and Ni were modified slightly, and the relevant rationale is outlined in the subsection "Usable Electrode Compositions."

In general, GMAW electrodes for high-strength steels contain C, Mn, Cr, Ni, and Mo as principal elements for compositional control. Secondly, these electrodes also contain small amounts of Ti, Al, and/or Zr to control the amounts of dissolved gases, such as oxygen and nitrogen in the weld metal (Ref 12). These "scavenging" elements also contribute to grain size control and microstructure development. Commonly, one may find about 0.03 wt.% Ti in GMAW electrodes (Ref 13-15) suitable for joining high-strength steels. As Ti, Al, and Zr are not part of Eq 1-5 for CEN, A_{r3}, B_S, B_F, and M_S temperatures, the algorithm

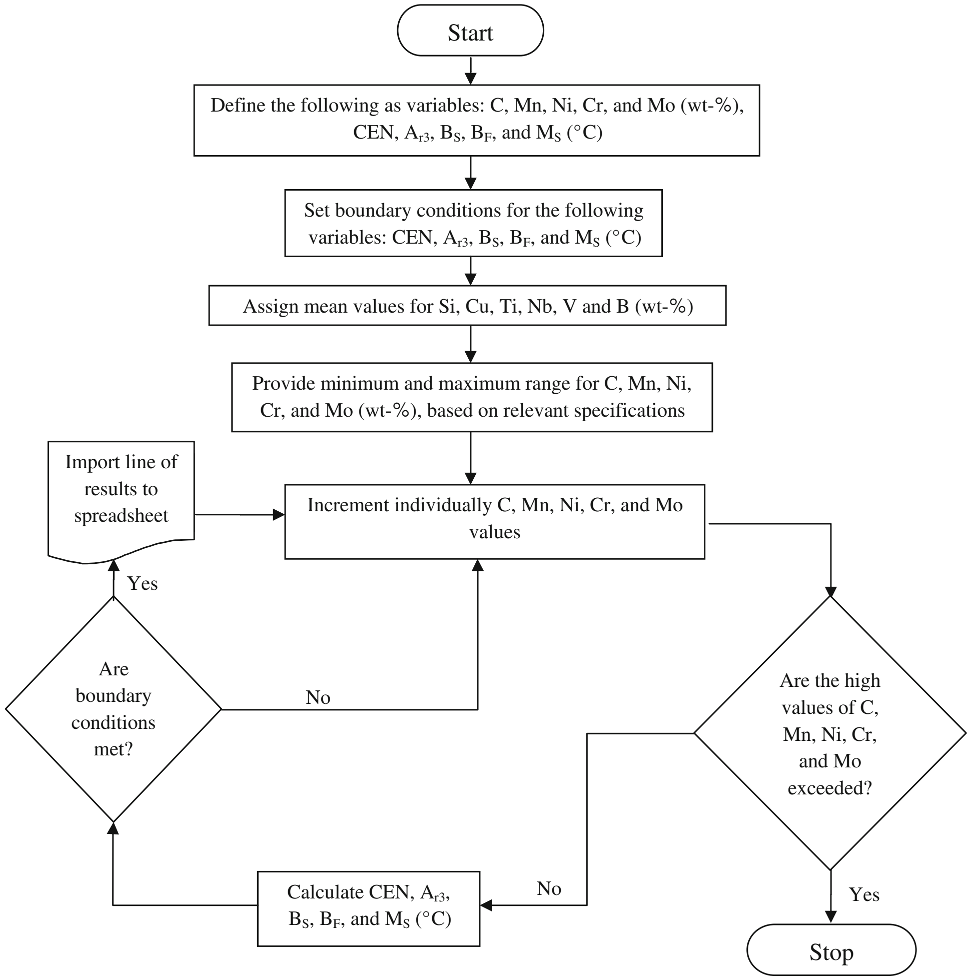

Fig. 2 Flowchart for algorithm

Table 3 Chemical composition ranges of selected GMAW electrode specifications

AWS A5.28-05	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V
ER80S-Ni1	0.12	1.25	0.025	0.025	0.40-0.80	0.80-1.10	0.15	0.35	0.35	0.05
ER80S-D2	0.07-0.12	1.60-2.10	0.025	0.025	0.50-0.80	0.15	…	0.40-0.60	0.50	…
E90C-K3	0.15	0.75-2.25	0.025	0.025	0.80	0.50-2.50	0.15	0.25-0.65	0.35	0.03
E80C-W2	0.12	0.50-1.30	0.025	0.030	0.35-0.80	0.40-0.80	0.45-0.70	…	0.30-0.75	0.03

Note: Single values are maximum. All values are expressed in wt.%

addressed this by evaluating the chemical composition limits of only the five critical elements (C, Mn, Cr, Ni, and Mo) while maintaining all other elements (Si, Cu, Nb, V and B) identified in the electrode specifications at mean values as indicated in Table 2. Within the chemical composition ranges specified, the combined effect of all other elements on the calculated values of CEN, A_{r3}, B_S, B_F, and M_S temperatures is not significant, relative to the set of mean values (Table 2) used in this algorithm for each of these other elements.

3.4 Usable Electrode Compositions

Table 1 shows the maximum allowable C content for HSLA-65 as 0.10 wt.%, and the typical C content of selected commercial HSLA-65 and Title III Grade 65 Plate Steels at about 0.08 wt.%. Therefore, to substantially improve weldability while maintaining the ability to meet the 552 MPa (80 ksi) strength level, the model specified that a 0.05-0.06 wt.% C in the welding electrode is desirable. Yet, to identify all usable electrode compositions for welding HSLA-65 steel, the model evaluated the range of 0.05-0.10 wt.% C in the welding electrode. However, as the ER80S-D2 electrode specification required a minimum of 0.07 wt.% C (see Table 3), the algorithmic results for ER80S-D2 are presented in Table 4 primarily to allow ready comparisons, but offer no other additional consideration.

To achieve a minimum of 552 MPa (80 ksi) strength level, the model considered that CEN of the welding electrode could

Table 4 Analysis of algorithm results for three electrode specifications

Boundary conditions	Specified ranges for five critical elements	Evaluation criterion	Number of acceptable electrode chemical compositions						
			0.05 wt.% C	0.06 wt.% C	0.07 wt.% C	0.08 wt.% C	0.09 wt.% C	0.1 wt.% C	Total
A_{r3}: 650-700 °C B_S: 590-650 °C B_F: 470-530 °C M_S: 430-460 °C CEN: 0.25-0.35	*Modified ER80S-Ni1* C: 0.05-0.10; Mn: 1.10-1.25; Cr: 0.15 Ni: 0.80-1.10; Mo: 0.35	$(B_F - M_S) \geq 0$ Lowest possible A_{r3}, °C	… …	… …	9 694	41 690	70 687	79 686	199 …
	Modified E80S-D2 C: 0.07-0.10; Mn: 1.10-2.10; Ni: 0.15; Mo: 0.40-0.60	$(B_F - M_S) \geq 0$ Lowest possible A_{r3}, °C	… …	… …	80 683	58 685	1 698	… …	139
	Modified E90C-K3 C: 0.05-0.10; Mn: 1.10-2.25; Cr: 0.15 Ni: 0.5-1.10; Mo: 0.25-0.65	$(B_F - M_S) \geq 0$ Lowest possible A_{r3}, °C	1023 662	2082 662	3017 660	3280 (a) 661	1695 (a) 666	243 (a) 682	11340 …
	Modified E80C-W2 C: 0.05-0.10; Mn: 1.10-1.3; Cr: 0.45-0.70 Ni: 0.40-0.80; Mo: 0	$(B_F - M_S) \geq 0$ Lowest possible A_{r3}, °C	… …	… …	… …	… …	… …	… …	0 …

(a) At 0.08 wt.% C content, a total of 70 chemical compositions showed $(B_F - M_S) \geq 50$ °C. Similarly, at 0.09 wt.% C content, a total of 266 chemical compositions showed $(B_F - M_S) \geq 50$ °C, and at 0.10 wt.% C content, all 243 chemical compositions showed $(B_F - M_S) \geq 50$ °C

potentially range between 0.25 and 0.35. Within this CEN range, to ensure chemical compatibility with the base metal, the model specified the minimum Mn content of the welding electrode at 1.10 wt.% as in A945 specification for HSLA-65 steel (Ref 2), and the maximum Ni content as not to exceed 1.10 wt.%. Implicitly, imposition of this additional constraint meant that the welding electrode would have a higher Mn content than Ni content, as in HSLA-65 steel; yet the model would allow evaluation of much wider ranges for both Mn and Ni contents as in the electrode specifications.

3.5 Iterative Loops

The third section of the algorithm addressed identifying electrode compositions that satisfied the boundary conditions. This section used five iterative loops for computing CEN and A_{r3}, B_S, B_F, M_S temperatures based on chemical composition data. Each loop pertained to one critical element (C, Mn, Cr, Ni, or Mo), and allowed small incremental increases to their wt.% values starting from their respective lower limit to their respective upper limit (except for the above limits specified for C, Mn, and Ni) of the ranges specified for these elements in ER80S-Ni1, ER80S-D2, E90C-K3, or E80C-W2 welding electrode specifications. The incremental values used in this computation are consistent with typical accuracy values commonly reported for the respective elements when performing quantitative chemical analysis of low-carbon HSLA steels.

3.6 Additional Constraint

The third section of the algorithm imposed yet another metallurgical constraint—the difference between the calculated values of B_F and M_S temperatures, as another desirable characteristic. The value of $(B_F - M_S)$ is important, as it is critical to determining the relative amounts of ferrite, bainite, and martensite in the weld metal. This is derived from the observation that in HSLA-65 steel, $A_{r3} > B_S > B_F > M_S$. This relationship is important in understanding the effects of weld cooling rate on the decomposition of austenite in weld metal into various types of microstructural constituents, their size distribution, and morphological features. For example, a large difference between B_F and M_S transformation temperatures can indicate that all available austenite would transform to ferrite, pearlite, and/or bainite at the higher temperature. Thus, no austenite would be available to transform to martensite at the lower transformation temperature.

For the condition, higher the difference between B_F and M_S, there remains virtually no austenite, despite a possibility for some retained austenite from localized elemental segregation, that could transform to martensite, as most, if not all of the austenite had already transformed into ferrite, pearlite, and/or bainite. Within the range of 0-50 °C, higher the value of $(B_F - M_S)$, higher is the likelihood that the weld metal will be virtually free from martensite, despite any localized elemental segregation. Thus, the weld metal can be expected to show exceptional resistance to HAC. Use of $(B_F - M_S)$ value as an additional metallurgical constraint in the model allowed one to further organize and discern the algorithmic results.

Localized chemical segregation could be expected to alter the general sequence of austenite decomposition products. However, the scale of regions with such microstructural "aberrations" should not unduly concern a perspective to achieve minimum mechanical property requirements. In other words, the model surmised that such "aberrations" might only promote additional variations in weld metal mechanical properties "above and beyond" the minimum mechanical property requirements.

3.7 Simplification

The algorithm did not account for the effects of shielding gas composition and the related effects of "delta quantities" on deposited weld metal (Ref 16). Similarly, the algorithm did not account for Al, Ti, or Zr used for "scavenging" and grain refining. Furthermore, as minimal changes in the contents of individual alloy elements from the welding electrode to the weld metal would not significantly affect CEN and calculated transformation temperatures, chemical compositions of the welding electrode and weld metal are referred to interchangeably. Such a simplification is not expected to affect unduly an objective to achieving minimum mechanical property requirements.

3.8 Data Organization

The results of the algorithm were directly imported into a .CSV (comma-separated value)-type spreadsheet. This allowed further manipulation and organization of the results. Based on the total number of chemical compositions that showed desirable ranges for CEN, A_{r3}, B_S, B_F, and M_S, and a desirable value for $(B_F - M_S)$, the electrode specifications were considered robust and suitable for application to joining HSLA-65 steel.

4. Results and Discussion

For the specified boundary conditions, the algorithm did not return acceptable results for ER80S-Ni1 and E80C-W2 electrode specification groups, particularly for $C \leq 0.06$ wt.% (Table 4). While these null results for ER80S-Ni1 and E80C-W2 further served to validate the algorithm and relevancy of the boundary conditions, readers might expect such a result as both ER80S-Ni1 and E80C-W2 specifications were not designed to meet the particular requirements of HSLA-65 steel.

However, the above null results do not mean that ER80S-Ni1 and E80C-W2 electrode specification groups do not offer scope for joining HSLA-65 steel. Rather, these electrode specification groups would be suitable for welding HSLA-65 steel, but might offer acceptable properties only when the electrodes are used over a limited operational envelope, thus adversely affecting productivity and fabrication cost. These specific results indicate that a simple reliance on relevant AWS electrode specifications will not be adequate to identify high-performance welding electrodes. Readers might recognize that such a discriminating feature is especially important to saving time, materials, and effort during weld procedure qualification.

Secondly, in the case of E90C-K3, the algorithm returned 11340 acceptable results meeting the specified boundary conditions (Table 4). The C content varied from 0.05 to 0.10 wt.%, Mn from 1.10 to 2.05 wt.%, Ni from 0.5 to 1.10 wt.%, Cr from 0 to 0.15 wt.%, and Mo from 0.25 to 0.65 wt.%. The calculated values for A_{r3} ranged from 660 to 700 °C, while that for B_S from 590 to 634 °C, B_F from 470 to 514 °C, M_S from 440 to 460 °C, and CEN ranged from 0.27 to 0.35. The $(B_F - M_S)$ value ranged from 10 to 64 °C indicating that the weld metal could be potentially free from martensite, and thus show exceptional resistance to HAC. The total alloy content ranged from 3.33 to 4.10 wt.%, consistent with the normal range specified for HSLA-65 steels.

Interestingly, when C content was limited to 0.05 and 0.06 wt.%, the algorithm returned only 3105 acceptable results for E90C-K3 electrode specification. Nearly a four-fold decrease in the total number of acceptable results underscored the importance of C content in formulating electrode chemical composition for HSLA-65 steel. This finding is particularly instructive to electrode manufacturers desirous of catering to the HSLA-65 market, as they must focus their attention on a very narrow range of C content. Analysis of these results showed that $(B_F - M_S)$ ranged from 14 to less than 40 °C when the C content was held at 0.06 wt.%.

Tables 5-8 present additional analyses of the algorithm results for E90C-K3 electrode specification as Cases 1 through 4, when $(B_F - M_S)$ is greater than 10, 20, 30, and 40 °C, respectively. These analyses offered significant insights with quantifiable and usable knowledge. For example, Table 6 shows that the maximum number of acceptable E90C-K3 type electrode chemical compositions corresponding to 0.06 wt.% C occurred for Case 2, when $(B_F - M_S)$ is ≥20 °C but <30 °C. Furthermore, an examination of Tables 5-7 shows that at 0.06 wt.% C, it is prudent to control Mn content much below 1.85 wt.% because of the availability of a very larger number of acceptable compositions. If one were to control C at 0.06 wt.% and Mn content at about 1.6 wt.%, then one would have improved flexibility to vary Ni and Mo content, at about 0.8 and 0.3 wt.%, respectively.

The above results clearly showed that welding electrode compositions containing about 0.06 wt.% C, 1.6 wt.% Mn,

Table 5 Analysis of algorithm results for E90C-K3 electrode specification (case 1)

Boundary conditions	Specified ranges for five critical elements	Evaluation criterion	Number of acceptable E90C-K3 type electrode chemical compositions: 0.05 wt.% C	0.06 wt.% C	0.07 wt.% C	0.08 wt.% C	0.09 wt.% C	0.10 wt.% C	Total
A_{r3}: 650-700 °C B_S: 590-650 °C B_F: 470-530 °C M_S: 430-460 °C CEN: 0.25-0.35	C: 0.05-0.10; Mn: 1.10-2.25; Cr: 0.15 Ni: 0.5-1.10; Mo: 0.25-0.65	$(B_F - M_S)$ ≥10 °C <20 °C	727	364	20	…	…	…	1111
		Upper limit for manganese	2.05 wt.%	2.05 wt.%	1.70 wt.%	…	…	…	…
		Corresponding upper limit for nickel	0.55 wt.%	0.50 wt.%	0.50 wt.%	…	…	…	…
		Corresponding upper limit for molybdenum	0.25 wt.%	0.25 wt.%	0.55 wt.%	…	…	…	…

Table 6 Analysis of algorithm results for E90C-K3 electrode specification (case 2)

Boundary conditions	Specified ranges for five critical elements	Evaluation criterion	Number of acceptable E90C-K3 type electrode chemical compositions: 0.05 wt.% C	0.06 wt.% C	0.07 wt.% C	0.08 wt.% C	0.09 wt.% C	0.10 wt.% C	Total
A_{r3}: 650-700 °C	C: 0.05-0.10;	$(B_F - M_S)$	296	1400	1358	695	…	…	3749
B_S: 590-650 °C	Mn: 1.10-2.25;	≥20 °C							
B_F: 470-530 °C	Cr: 0.15	<30 °C							
M_S: 430-460 °C	Ni: 0.5-1.10;	Upper limit for manganese	1.95 wt.%	2.00 wt.%	2.0 wt.%	1.95 wt.%	…	…	…
CEN: 0.25-0.35	Mo: 0.25-0.65	Corresponding upper limit for nickel	0.60 wt.%	0.60 wt.%	0.55 wt.%	0.55 wt.%	…	…	…
		Corresponding upper limit for molybdenum	0.25 wt.%	0.25 wt.%	0.25 wt.%	0.25 wt.%	…	…	…

Table 7 Analysis of algorithm results for E90C-K3 electrode specification (case 3)

Boundary conditions	Specified ranges for five critical elements	Evaluation criterion	Number of acceptable E90C-K3 type electrode chemical compositions: 0.05 wt.% C	0.06 wt.% C	0.07 wt.% C	0.08 wt.% C	0.09 wt.% C	0.10 wt.% C	Total
A_{r3}: 650-700 °C	C: 0.05-0.10;	$(B_F - M_S)$	…	318	1371	1616	170	…	3475
B_S: 590-650 °C	Mn: 1.10-2.25;	≥30 °C							
B_F: 470-530 °C	Cr: 0.15	<40 °C							
M_S: 430-460 °C	Ni: 0.5-1.10;	Upper limit for manganese	…	1.85 wt.%	1.90 wt.%	1.90 wt.%	1.80 wt.%	…	…
CEN: 0.25-0.35	Mo: 0.25-0.65	Corresponding upper limit for nickel	…	0.50 wt.%	0.50 wt.%	0.55 wt.%	0.55 wt.%	…	…
		Corresponding upper limit for molybdenum	…	0.25 wt.%	0.25 wt.%	0.25 wt.%	0.25 wt.%	…	…

Table 8 Analysis of algorithm results for E90C-K3 electrode specification (case 4)

Boundary conditions	Specified ranges for five critical elements	Evaluation criterion	Number of acceptable E90C-K3 type electrode chemical compositions: 0.05 wt.% C	0.06 wt.% C	0.07 wt.% C	0.08 wt.% C	0.09 wt.% C	0.10 wt.% C	Total
A_{r3}: 650-700 °C	C: 0.05-0.10;	$(B_F - M_S)$	…	…	268	899	1259	…	2426
B_S: 590-650 °C	Mn: 1.10-2.25;	≥40 °C							
B_F: 470-530 °C	Cr: 0.15;	<50 °C							
M_S: 430-460 °C	Ni: 0.5-1.10;	Upper limit for manganese	…	…	1.70 wt.%	1.75 wt.%	1.75 wt.%	…	…
CEN: 0.25-0.35	Mo: 0.25-0.65	Corresponding upper limit for nickel	…	…	0.55 wt.%	0.50 wt.%	0.60 wt.%	…	…
		Corresponding upper limit for molybdenum	…	…	0.25 wt.%	0.25 wt.%	0.25 wt.%	…	…

0.8 wt.% Ni, and 0.3 wt.% Mo, and characterized by 690 °C A_{r3}, 0.29 CEN, and $(B_F - M_S)$ of 30 °C are likely to provide weld metal potentially exceeding 552 MPa (80 ksi) tensile strength, and a CVN impact toughness of 41 J at –40 °C (30 ft lbf at –40 °F), thus surpassing the specified minimum properties for HSLA-65 steel. Welding electrode manufacturers targeting the above chemical composition as their "aim" composition would indeed benefit, particularly from a quality assurance perspective.

Intuitively it is well known that "rich" (wherein all principal alloying elements are near their specified upper limits) and "lean" (wherein all principal alloying elements are near their specified lower limits) welding electrode compositions offer limited operational envelope as they are "less forgiving." Additional analyses of the algorithmic results allowed one to distinguish high-performance welding electrode compositions from rich and lean welding electrode compositions. For example, Fig. 3-6 show the trends in the corresponding upper limits for Mn, Ni, and Mo as a function of C content when $(B_F - M_S)$ is greater than 10, 20, 30, and 40 °C, respectively. These trends clearly demonstrated that at many C contents, when Mn content is at the allowable maximum, Mo content is at its allowable minimum. Furthermore, as shown in Fig. 5 and 6, larger differences in $(B_F - M_S)$ occurred at C contents in excess of 0.08 wt.%. For example, at 0.08 wt.% C content, 70 compositions showed $(B_F - M_S) \geq 50$ °C. Similarly,

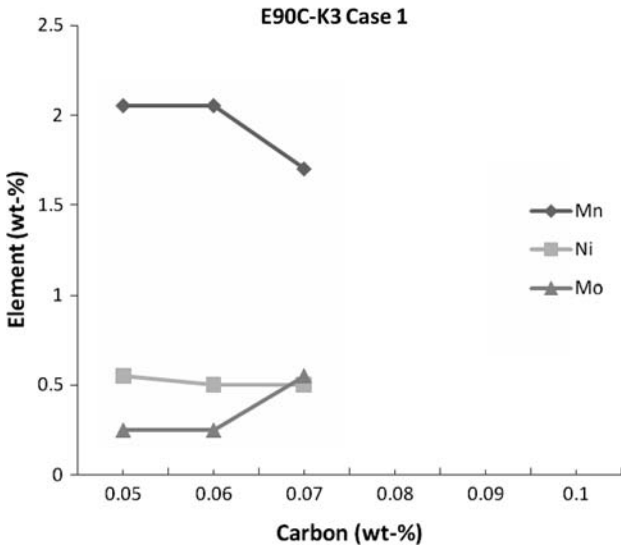

Fig. 3 Case 1: variation of maximum allowable alloy content with carbon content in weld metal

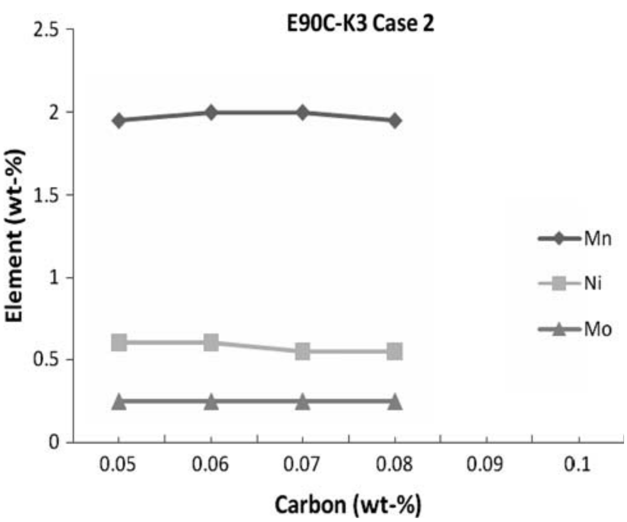

Fig. 4 Case 2: variation of maximum allowable alloy content with carbon content in weld metal

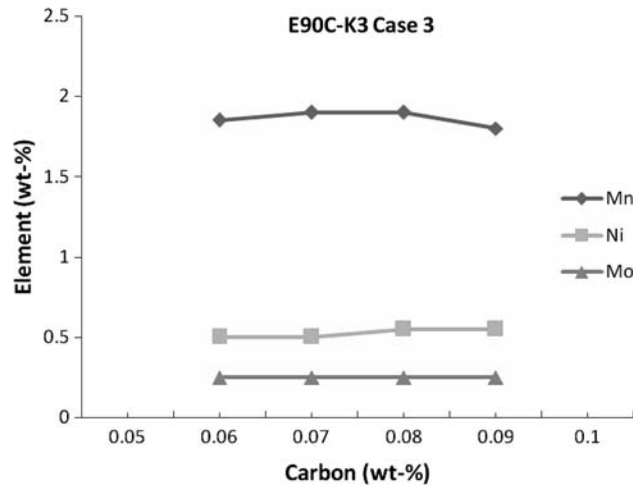

Fig. 5 Case 3: variation of maximum allowable alloy content with carbon content in weld metal

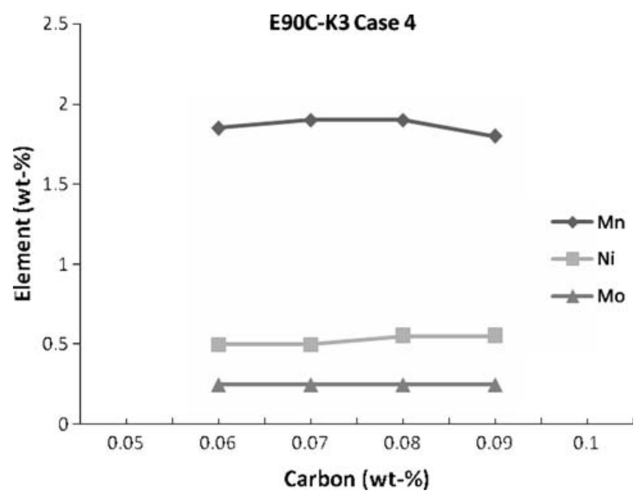

Fig. 6 Case 4: variation of maximum allowable alloy content with carbon content in weld metal

at 0.09 wt.% C content, 266 compositions showed $(B_F - M_S) \geq 50$ °C. At these relatively high C contents, one had to decrease the Mn content and increase the Ni content to realize larger differences in $(B_F - M_S)$ while reining in CEN. In other words, these trends showed that in high-strength steel welding electrode specifications, one could achieve larger differences in $(B_F - M_S)$ only at the expense of higher C content and its potential adverse consequence to weldability. Also, Fig. 3-6 show that one could not allow simultaneous increases in Mn and Mo contents at a higher C content, or concurrent increases to all principal alloying elements near their respective specified upper limit. These quantitative trends provide usable knowledge for controlling the relative amounts of Mn, Ni, and Mo in a high-C weld metal.

In fact, these interpretations provide quantifiable value additions offered by the CBM methodology and the algorithmic approach compared to a mere compliance with a welding electrode specification. Indeed, the ability to design high-performance welding electrode compositions, thereby clearly distinguishing them from "rich" and "lean" welding electrode compositions, and an acute awareness of the adverse effects of concurrent increases/decreases to all principal alloying elements near their respective specified upper/lower limit on weld metal microstructure development, mechanical properties, and weldability confer tremendous value to the CBM methodology and the algorithmic approach.

Results of future experimental runs can be expected to both validate and offer additional insights into this powerful methodology, and confirm its robustness and utility in advancing materials research.

4.1 Model Validation

A comparison of algorithmic results to currently available commercial welding electrode chemical compositions indicated that Kobelco (Ref 17) had offered a GMAW electrode

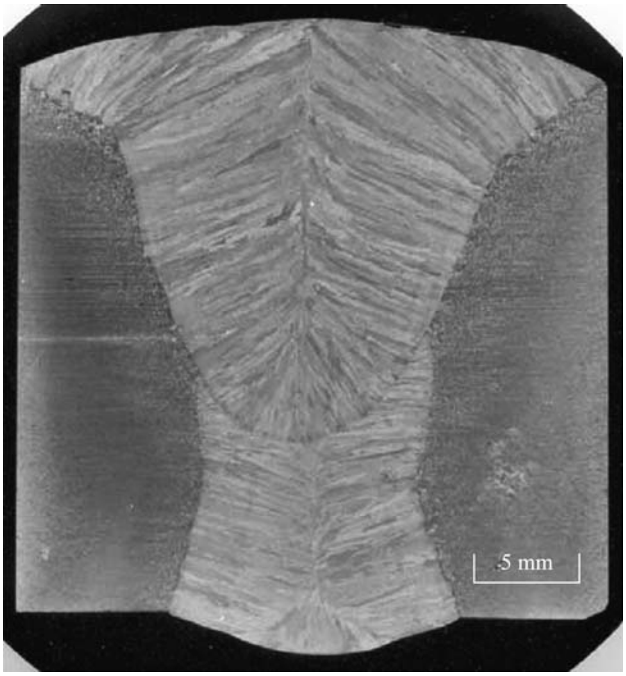

Fig. 7 Macrostructure of a one-sided butt weld produced using SAW process with 25-mm-thick HSLA-65 steel plates, Lincoln MIL-800H flux, and a Hobart experimental metal-cored wire combination (Ref 19)

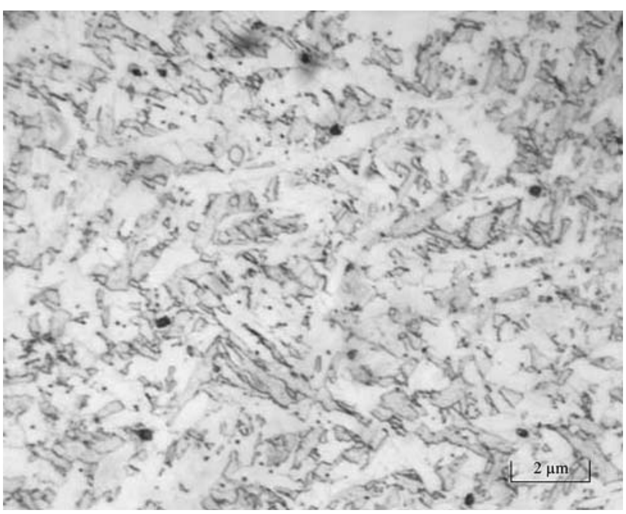

Fig. 8 Microstructure of as-deposited weld metal produced using SAW process with 25-mm-thick HSLA-65 steel plates, Lincoln MIL-800H flux, and a Hobart experimental metal-cored wire combination (Ref 19)

(MGS-63S) belonging to ER90S-G classification that provided weld metal with about 0.06 wt.% C, 1.34 wt.% Mn, 0.93 wt.% Ni, 0.47 wt.% Mo. Interestingly, this typical weld metal composition, obtained with Ar-15% CO_2 as shielding gas, is one of the 318 chemical compositions identified in Table 7, corresponding to 0.06 wt.% C. While using only the values for these principal alloy elements, the MGS-63S weld metal yielded a calculated A_{r3} of 695 °C, a CEN of 0.26, and a $(B_F - M_S)$ of 37 °C. However, when calculated using nominal values for other alloy elements (at 0.6 wt.% Si, 0.2 wt.% Cu, 0.005 wt.% Nb, 0.005 wt.% V, and 0.0002 wt.% B), the MGS-63S weld metal yielded a calculated A_{r3} of 691 °C, a CEN of 0.28, and a $(B_F - M_S)$ of 37 °C, thus fully aligning with the boundary conditions set by the algorithmic approach.

The MGS-63S GMA weld metal, following a postweld heat treatment (PWHT) at 635 °C (1170 °F) for 27 h, offered over 621 MPa (90 ksi) tensile strength and over 135 J (100 ft lbf) CVN impact toughness at −12 °C (10 °F), thereby indicating tremendous potential for consistently meeting the minimum requirements of HSLA-65 steel. As this welding electrode is traditionally used with heat-resistant low-alloy steels, which often require PWHT, the tensile and CVN impact toughness properties of the weld metal in the as-welded condition could not be readily ascertained.

Hobart (Ref 18) currently offers Metalloy 90, a metal-cored wire belonging to E90C-K3 specification for welding HSLA steels, particularly for applications that require high toughness at subzero temperatures. With Ar-2% O_2 as shielding gas, the Metalloy 90 yielded an undiluted weld metal with the following chemical composition: 0.05 wt.% C, 1.31 wt.% Mn, 1.89 wt.% Ni, and 0.37 wt.% Mo that corresponds to a calculated A_{r3} of 655 °C, a CEN of 0.26, and a $(B_F - M_S)$ of 23 °C, based only on the values for these principal alloy elements. Notice that the algorithm results did not identify this electrode composition as Ni content of the weld metal is over 1.10 wt.% and is also much higher than Mn content unlike in HSLA-65 steel. When calculated using nominal values for other alloy elements (at 0.6 wt.% Si, 0.2 wt.% Cu, 0.005 wt.% Nb, 0.005 wt.% V, and 0.0002 wt.% B), the Metalloy 90 weld metal yielded a calculated A_{r3} of 651 °C, a CEN of 0.28, and a $(B_F - M_S)$ of 23 °C, thus showing compliance with the boundary conditions set by the algorithmic approach.

In the as-welded condition, the Metalloy 90 weld metal offered over 621 MPa (90 ksi) tensile strength and over 34 J (25 ft lbf) CVN impact toughness at −51 °C (−60 °F). Interestingly, a low CEN and a low A_{r3} can be directly correlated with a relatively lower Mn content and a higher Ni content compared to the chemical composition of the welding electrode identified by the algorithmic approach.

Readers might readily recognize that despite a wide variation in Ni-content and Mn-to-Ni ratio, both MGS-63S and Metalloy 90 electrodes show compliance with the boundary conditions set by the algorithmic approach. The above chemical composition and mechanical property test results of MGS-63S and Metalloy 90 electrodes offer industrially hardened experimental data that validate the modeling approach.

Furthermore, in the case of slag-metal reactions involving selected flux-wire combinations as in the submerged arc welding (SAW) process, one may benefit from additional latitude in selecting flux-wire combinations. Such a selection can lead to weld metal with a desirable combination of chemical composition and microstructure, under high-productive welding conditions. A recent research effort (Ref 19) performed under the auspices of the National Shipbuilding Research Program (NSRP) has demonstrated the use of a Variable Balance AC SAW process for one-side welding of a butt-joint (Fig. 7) in 25 mm (1 in.) thick HSLA-65 steel plates. This demonstration used a Lincoln MIL-800H flux and a Hobart experimental metal-cored wire combination, under extremely high (over 200 kJ/mm) weld energy input condition that was necessary to support high-productive shipyard welding practices. The resulting weld metal showed the following chemical composition: 0.07 wt.% C, 1.62 wt.% Mn, 0.92 wt.%

Ni, 0.18 wt.% Mo, 0.35 wt.% Si, 0.025 wt.% Al, and 0.011 wt.% Ti corresponding to a calculated A_{r3} of 690 °C, 0.30 CEN, and 37 °C ($B_F - M_S$). The microstructure of the as-deposited weld metal (Fig. 8) consisted of submicroscopic carbide particles nearly uniformly distributed in a coarse-grained ferritic matrix. This weld metal provided acceptable combination of tensile strength and CVN impact toughness properties that exceeded the minimum mechanical property requirements for HSLA-65 steel.

4.2 Significance

Thus, the algorithmic approach substantially reduces uncertainty and risk inherent to electrode design, development, and certification efforts. Electrode manufacturers desirous of offering "new and improved" solid wire GMAW electrodes suitable for joining HSLA-65 may undeniably benefit from this research effort. In addition, depending on weld energy input, the identified welding electrode composition containing about 0.06 wt.% C, 1.6 wt.% Mn, 0.8 wt.% Ni, 0.3 wt.% Mo may also be suitable for undermatching or matching the minimum specified tensile strength of HSLA-80 steel, further enabling "market penetration" and "economies of scale" for these advanced electrodes.

Furthermore, chemical composition ranges identified by this algorithmic approach may also be suitable for producing high-strength steel powder metal parts and weldable castings and forgings that could be expected to show exceptional resistance to HAC. In a strategic sense, the algorithmic approach also provides a viable means for quantitatively substituting one alloy element for another—should the price of one alloy element increase dramatically for a variety of reasons—while remaining in compliance with electrode specification requirements. Thus, electrode and material manufacturers may further benefit from the added flexibility inherent to the algorithmic approach. The algorithmic approach derives its utility from an ability to:

(1) develop an appropriate set of mutually inclusive metallurgical constraints;
(2) use statistical relationships among chemical composition, transformation temperatures, and properties; and
(3) use a C++ algorithm in evaluating the set of mutually inclusive metallurgical constraints together with chemical composition limits of materials specifications.

This approach provides a quantitative basis for including the latest advances in the understanding of the statistical relationships among chemical composition and transformation temperatures, microstructure development, strength, and weldability. Design of GMAW electrode compositions using this innovative approach provides an additional means to strengthen electrode specification development efforts and approval processes (Ref 20, 21). Consequently, Standard Development Organizations such as the American Welding Society (AWS) and the American National Standards Institute (ANSI) may like to recognize the power of this algorithmic approach and utilize this innovative approach in their standards setting activities.

5. Conclusions

(1) A C++ algorithm with a set of boundary conditions and chemical composition limits for C, Mn, and Ni was used in evaluating three groups of GMAW electrode specifications for potential application to welding HSLA-65 steel.
(2) For the chemical composition ranges cited for C, Mn, Ni, Cr, and Mo in ER80S-Ni1 and E80C-W2 electrode specifications, and particularly for $C \leq 0.06$ wt.%, the algorithm did not return acceptable results.
(3) For the chemical composition ranges cited for C, Mn, Ni, Cr, and Mo in E90C-K3 electrode specification, the algorithm returned 11340 acceptable chemical compositions. Of these, 3105 electrode compositions contained 0.05 or 0.06 wt.% C, much less than the nominal level of 0.08 wt.% C in HSLA-65 steel, making them ideally suitable for joining HSLA-65 steel.
(4) Results of the algorithm showed that welding electrode compositions containing about 0.06 wt.% C, 1.6 wt.% Mn, 0.8 wt.% Ni, 0.3 wt.% Mo are likely to provide high-performance weld metals characterized by an A_{r3} transformation temperature of about 690 °C, 0.29 CEN, and a ($B_F - M_S$) value of 30 °C that are suitable for joining HSLA-65 steel.
(5) Results clearly demonstrated that a high-strength steel welding electrode specification could not allow simultaneous increases in Mn, Ni, and Mo contents especially at higher C content, or concurrent increases to all principal elements near their respective specified upper limit, without aggravating weldability concerns.
(6) This algorithmic approach is quite helpful in distinguishing high-performance welding electrode chemical compositions from "rich" and "lean" welding electrode chemical compositions for joining HSLA-65 steels, and may serve a vital need in strengthening electrode specification development efforts and approval processes.

Appendix A: An Algorithm for Evaluating Chemical Composition Limits of Welding Electrode Specifications Suitable for HSLA-65 Steel in Nonlanguage Specific "Pseudo Code"

1) Define new variables as real numbers for Carbon, Manganese, Nickel, Chromium, and Molybdenum content in wt.% as well as maximum and minimum values.
2) Define new variables as real numbers representing mean values of Silicon, Copper, Titanium, Vanadium, Niobium, and Boron content in wt.%.
3) Define new variables as real numbers for CEN, A_{r3}, B_S, B_F, M_S, and B_F-M_S maximum values, minimum values, and calculated values.
4) Assign values for variables based on relevant electrode and base metal specifications.
5) Display on screen: "Welding Electrode Composition Evaluation".
6) Display on screen: "Enter integer difference in temperature between calculated B_F & calculated M_S".
7) Receive value for B_F-M_S.
8) **If** B_F-M_S is less than 0 or greater than 50 display on screen "Range incorrect. Enter value between 0 & 50".
9) **Else** display on screen "filename name to store weld metal chemical compositions. Filename with .csv (comma separated values) would be best for viewing").

10) User enters file name.
11) **If** Filename is NULL display "Error! The file could not be opened"
12) **Else** filename is OK then continue calculations

   a) Print Carbon, Manganese, Nickel, Chromium, and Molybdenum minimum and maximum wt-%, CEN, A_{r3}, B_S, B_F, M_S, and B_F-M_S values to spreadsheet (.csv)
   b) **For** loop: Increment C wt-% until it hits the maximum defined.

   i) **For** loop: Increment Mn wt-% until it hits the maximum defined.
      (1) **For** loop: Increment Ni wt-% until it hits the maximum defined.
         (a) **For** loop: Increment Cr wt-% until it hits the maximum defined.
            (i) **For** loop: Increment Mo wt-% until it hits the max defined.
               1. Calculate CEN.
               2. **If** CEN is between max and min values
                  a. Calculate A_{r3}
                  b. **If** A_{r3} is between max and min values
                     i. Calculate B_S
                     ii. **If** B_S is between max and min values
                        1. Calculate B_F
                        2. **If** B_F is between max and min values
                           (a) Calculate M_S
                           (b) **If** M_S is between max and min values
                              (i) **If** M_S + B_F-M_S is less than B_F
                                 (1) Print C, Mn, Ni, Cr, Mo, Cu, Si, Ti, Nb, B, V, CEN, A_{r3}, B_S, B_F, M_S values to spreadsheet

13) Close all statements

References

1. K. Sampath, An Understanding of HSLA-65 Plate Steels, *J. Mater. Eng. Perform.*, 2006, **15**(1), p 32–40
2. ASTM A945/A945M-00, 2000. "Standard Specification for High-Strength Low-Alloy Structural Steel Plate with Low Carbon and Restricted Sulfur for Improved Weldability, Formability, and Toughness," American Society for Testing & Materials, Philadelphia, PA
3. P.J. Konkol, J.L. Warren, and P.A. Hebert, Weldability of HSLA-65 Steel for Ship Structures, *Weld. J.*, 1998, **77**(9), p 361s–371s
4. A5.28–05, 2005. "Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding," American Welding Society, Miami, FL
5. K. Sampath, How to Choose Electrodes for Joining High-Strength Steels, *Weld. J.*, 2007, **86**(7), p 26–28
6. N. Yurioka, H. Suzuki, S. Ohshita, and S. Saito, Determination of Necessary Preheating Temperature in Steel Welding, *Weld. J.*, 1983, **62**(6), p 147s–153s
7. C. Ouchi, T. Sampei, and I. Kozasu, The Effect of Hot Rolling Condition and Chemical Composition on the Onset Temperature of Austenite-to-Ferrite Transformation After Hot Rolling, *Trans. Iron Steel Inst. Jpn.*, 1982, **22**, p 214–222
8. W. Steven and A.G. Haynes, The Temperature of Formation of Martensite and Bainite in Low-Alloy Steels, *J. Iron Steel Inst.*, 1956, **183**(8), p 349–359
9. K.W. Andrews, Empirical Formulae for the Calculation of Some Transformation Temperatures, *J. Iron Steel Inst.*, 1965, **203**(7), p 721–727
10. K. Sampath, Constraints Based Modeling Enables Successful Development of a Welding Electrode Specification for Critical Navy Applications, *Weld. J.*, 2005, **84**(8), p 131s–138s
11. K. Sampath and R. Varadan, Evaluation of Chemical Composition Limits of GMA Welding Electrode Specifications for HSLA-100 Steel, *Weld. J.*, 2006, **85**(8), p 163s–173s
12. D.P. Fairchild, J. Koo, N.V. Bangaru, M.L. Macia, D.L. Beeson, and A. Ozekcin, Weld Metals with Superior Low Temperature Toughness for Joining High Strength, Low Alloy Steels, US Patent 6,565,678, May 2003
13. K.E. Dorschu and A. Lesnewich, Development of a Filler Metal for a High-Toughness Alloy Plate Steel with a Minimum Yield Strength of 140 ksi, *Weld. J.*, 1964, **43**(12), p 564s–576s
14. J.E. Lyttle , K.E. Dorschu, and W.A. Fragetta, Some Metallurgical Characteristics of Tough, High-Strength Welds, *Weld. J.*, 1969, **48**(11), p 493s–498s
15. R.J. Wong and M.D. Hayes, *The Metallurgy, Welding & Qualification of Microalloyed (HSLA) Steel Weldments, 450–489*. American Welding Society, Miami, FL, 1990
16. P.T. Oldland, C.W. Ramsay, D.K. Matlock, and D.L. Olsen, Significant Features of High-Strength Steel Weld Metal Microstructures, *Weld. J.*, 1989, **68**(4), p 158s–168s
17. *Welding Handbook*, 1989. Kobe Steel, Ltd. Welding Division, Chiyoda-Ku, Tokyo, Japan, p 160–161
18. http://www.hobartbrothers.com/pdf/datasheets/Metalloy90.pdf, Hobart Brothers Company, Troy, OH
19. D. Begg, Evaluation of Variable Balance AC Submerged Arc Welding and Metal-cored Electrode Technology for Panel Welding, BMT Fleet Technology Limited, Kanata, ON, Canada, K2K 1Z8, 2006
20. Navy Ships: Lessons of Prior Programs May Reduce New Attack Submarine Cost Increases and Delays, GAO/NSIAD-95-4, United States General Accounting Office GAO Report to Congressional Requesters, p 7, October 1994
21. K. Sampath, Strengthening Materials Specifications, *J. Mater. Eng. Perform.*, 2005, **14**(5), p 596–603