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Evaluation of Chemical Composition Limits of GMA Welding Electrode Specifications for HSLA-100 Steel

A Turbo C++ algorithm evaluates chemical composition limits of selected GMAW electrode specifications for potential application to welding HSLA-100 steel

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ABSTRACT. A PC-based Turbo C++ algorithm was developed to quantitatively evaluate chemical composition limits of selected GMAW electrode specifications and two relevant U.S. patents for potential application to HSLA-100 steel. The algorithm chiefly consisted of three parts: the first part defined boundary conditions for obtaining a predominantly low-carbon bainitic weld metal; the second part covered chemical composition ranges for four principal elements — carbon, manganese, nickel, and molybdenum — as specified in AWS A5.28, MIL-E-23765/2E for ER100S- and ER120S-type welding electrodes, or as claimed in U.S. Patents 5,523,540 or 5,744,782; and the third part addressed “mutually inclusive” computational requirements. Results showed both A5.28 and MIL-E-23765/2E specifications did not contain any acceptable ER100S type composition, but contained 177 of ER120S-type compositions, with carbon content ranging from 0.03 to 0.08 wt-%. Both U.S. Patents contained thousands of ER100- and ER120S-type electrode chemical compositions, and appeared quite robust for application to welding HSLA-100 steel. The algorithmic approach clearly demonstrated that a high-strength steel welding electrode specification could not allow simultaneous increases in carbon and nickel contents, or concurrent increases to any three or all four of the principal alloying elements near their respective specified upper limit.

Background

In recent years, high-strength low-alloy (HSLA) type steels with a specified minimum yield strength of 80 or 100 ksi are gaining traction as high-performance structural materials for the construction of ships, aircraft carriers and submarines (Ref. 1), off-shore structures, off-highway vehicles, bridges, pressure vessels, and storage vessels including those for long-term radiation containment of nuclear waste.

U.S. Navy initially developed the HSLA steels in the 1980s as potential alternatives to HY-80 and HY-100 steels, primarily in an effort to reduce preheat-related fabrication costs (Ref. 2). The HSLA-100 steels (Ref. 3) are characterized by a low carbon content (0.06 wt-% maximum in ladle analysis, and 0.07 wt-% maximum in product analysis) and exhibit a bainitic microstructure. The low-carbon bainitic microstructures exhibit little or no susceptibility to hydrogen-assisted cracking (HAC) in the weld heat-affected zone (HAZ). Therefore, HSLA-100 steels require much less preheating controls than HY-80 and HY-100 steel grades, thus offering a tremendous potential for low-cost fabrication of very large structures.

The gas metal arc welding (GMAW) process is commonly the preferred fabrication process for constructing various structures for the above applications. Current fabrication practices primarily use Ar-5%CO_2 as weld shielding gas, although Ar-2%O_2 can also be used. AWS A5.28, *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding* (Ref. 4), specifies ER100S, ER110S, and ER120S wire electrodes as welding consumables suitable for joining HY-80 and HY-100 steels. Currently, these electrodes are used for fabricating HSLA-80 and HSLA-100 steels because electrodes that could recreate or retain the metallurgical characteristics of HSLA steels are not yet commercially available.

Table 1 specifies the chemical composition range and mechanical property requirements for ER100S and ER120S GMAW consumable solid wire electrodes (Ref. 4). These electrodes often exhibit a carbon content in excess of 0.05 wt-%. Consequently, when welding HSLA-100 steel, these welding consumables require significant preheat to eliminate the occurrence of HAC in the weld metal (Ref. 5). Since the currently available ER100S and ER120S solid wire electrodes require preheat and interpass controls, and post soak temperature control for ER120S, their use precludes the full economic benefits of HSLA-100 steel, thus raising an acute need for the commercial availability of advanced high- strength steel welding electrodes.

As the prime user of HSLA-100 steel, the U.S. Navy has identified that candidate advanced GMAW electrodes for HSLA-100 steel should exhibit the following characteristics: 1) eliminate or substantially reduce the need for preheat controls; 2) show adequate resistance to HAC; 3) meet or exceed the mechanical property requirements of the existing ER100S and ER120S electrodes; 4) allow welding over a broad operational envelope in terms of plate thickness, welding position, and weld energy input; and 5)

KEYWORDS

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ER100S-Type Electrode
ER120S-Type Electrode

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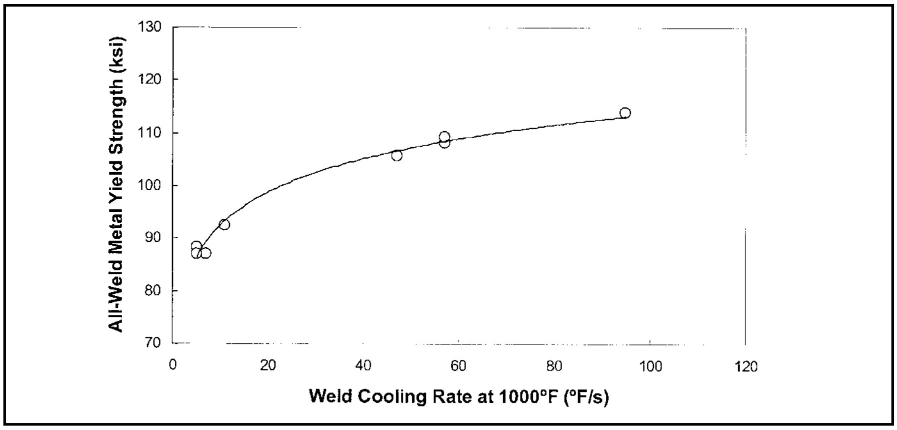

Fig. 1 — Variation of weld metal yield strength with calculated weld cooling rate at 1000°F.

Table 1 — Chemical Composition Ranges and Mechanical Property Requirements

	AWS A5.28	
Element	ER100S	ER120S
Carbon	0.08	0.10
Manganese	1.25–1.80	1.40–1.80
Silicon	0.20–0.55	0.25–0.60
Phosphorous	0.010	0.010
Sulfur	0.010	0.010
Nickel	1.40–2.10	2.0–2.80
Chromium	0.30	0.60
Molybdenum	0.25–0.55	0.30–0.65
Vanadium	0.05	0.03
Titanium	0.10	0.10
Zirconium	0.10	0.10
Aluminum	0.10	0.10
Copper	0.25	0.25
Other Elements, Total	0.50	0.50
Iron	Balance	Balance
Mechanical Property		
Tensile Strength (ksi)	100	120
Yield Strength (ksi)	88	105
Elongation (%)	16	14
Minimum CVN at 0°F (ft.lb)	–	–
Minimum CVN at 60°F (ft.lb)	50	50

Single values for chemical composition are maximum

show minimal variation in weld mechanical properties (especially yield strength) when welded over a broad operational envelope.

Recent Pioneering Research

A recently published research work (Ref. 6) has described the use of an innovative constraints-based modeling approach in successfully specifying the chemical composition range for advanced consumable electrodes based on the Fe-C-Mn-Ni-Mo-Ti system for GMA welding of HSLA-100 steel for critical U.S. Navy applications. This pioneering approach established a set of mathematical tools to describe and support experimental data. Specifically, this approach relied on statistical fit of chemical compositional data to selected parameters. This approach is extremely powerful for use with complex materials systems characterized by a number of critical processing parameters in which conclusions are hard to draw because of the many interrelated effects. In such cases, statistical or mathematical models can be helpful to clarify data and allow ease of interpretation of results.

Initially, specific U.S. Navy requirements for advanced consumable electrodes were converted into a set of “mutually inclusive” constraints that related chemical composition of steel electrodes or weld metals with three statistically determined metallurgical characteristics - B_{50} temperature, M_S temperature and Yurioka’s carbon equivalent number (CEN). These three metallurgical characteristics are specified in terms of a set of numerical ranges, one for ER100S-type, and another for ER120S-type. These characteristics of the advanced welding electrodes allow fabricators to meet or exceed various requirements for improved weldability (i.e., reduced preheat controls), strength and low-temperature toughness. The underlying metallurgical relationships among chemical composition, welding conditions (operational envelope or weld cooling rate), microstructure development and mechanical properties enable such high performance.

The above three metallurgical characteristics and their numerical ranges are also useful in identifying carbon, manganese, nickel, and molybdenum as principal elements for compositional control, thus allowing one to specify the compositional ranges for the individual alloy elements. To demonstrate the utility of this novel approach, a 2^3 factorial design of experiments with one low and another high level for manganese (aim 1.5 wt-% and 1.8 wt-%), nickel (aim 2.5 wt-% and 3.8 wt-%), and molybdenum (aim 0.5 wt-% and 1.0 wt-%) was used in developing a batch of eight, low-carbon (aim 0.03 wt-%) bare solid wire electrodes, 1⁄16- in. in diameter. All of the eight electrodes, based on the Fe-C-Mn-Ni-Mo-Ti system, were essentially free from chromium, but contained other elements such as silicon, phosphorus, and sulfur at some nominal values. The electrode chemical compositions also included approximately 0.03 wt-% titanium as a deoxidizer and ‘nitrogen getter.’ Titanium addition is critical to control the amount of oxygen and nitrogen in the weld metal. Additionally, titanium also served to refine weld metal grains.

Evaluating Electrode Performance

Initially, limited GMA welding experiments were carried out to evaluate the performance of the above eight welding electrodes, and to select a candidate electrode with the most potential for additional evaluation. Results showed that two of the eight electrodes consistently met or exceeded ER100S requirements, while one of the eight electrodes consistently met or exceeded ER120S requirements. Additional weld evaluations were performed over a much wider welding operational envelope using 1-in.- thick HSLA-100 or HY-100 steel plates, and one of the eight electrodes that contained chiefly 0.03 wt-% carbon, 1.5 wt-% manganese, 3.8 wt-% nickel, 0.5 wt-% molybdenum, and 0.03 wt-% titanium. Table 2 shows relevant welding conditions and the corresponding weld metal mechanical property test results. All of the weldments showed acceptable weld mechanical properties for ER100S over the entire range of welding conditions. Figure 1 illustrates the above results as variation in weld metal yield strength with calculated weld cooling rate at 1000°F (Ref. 6). The trend line showed the following statistical relationship, at a r^2 value of 0.99:

Yield strength (in ksi) = 75 × (Calculated weld cooling rate at 1000°F)$^{0.09}$

The above test results revealed that a welding electrode containing chiefly 0.03 wt-% carbon, 1.5 wt-% manganese, 3.8 wt-% nickel, 0.5 wt-% molybdenum, and 0.03 wt-% titanium and characterized by a calculated B_{50} temperature of 440°C, M_S temperature of 422°C, and a 0.32 CEN provided weldments with acceptable variation in weld mechanical properties, consistently meeting or exceeding specific U.S. Navy requirements. However, the chemical composition of this high-performance electrode showed a higher nickel content, much wider than the limit specified for either ER100S electrodes in AWS A5.28 specification, or the military equivalent MIL-100S electrodes (Table 3) specified in MIL-E-23765/2E specification (Ref. 7).

Furthermore, two related U.S. patents (Refs. 8, 9) on low-carbon bainitic steel welding electrodes also claim a much wider range for nickel content compared with the above two specifications (Table 3). Both these patents claim chemical composition ranges for welding electrodes that are useful for GMAW of high-strength steels such as HSLA and HY steels used as hull materials for naval ships, aircraft carriers, and submarines. The welding electrodes provided in these two patents are claimed to form weld deposits with a low-carbon bainitic ferrite microstructure that offer yield strength in excess of 80 ksi.

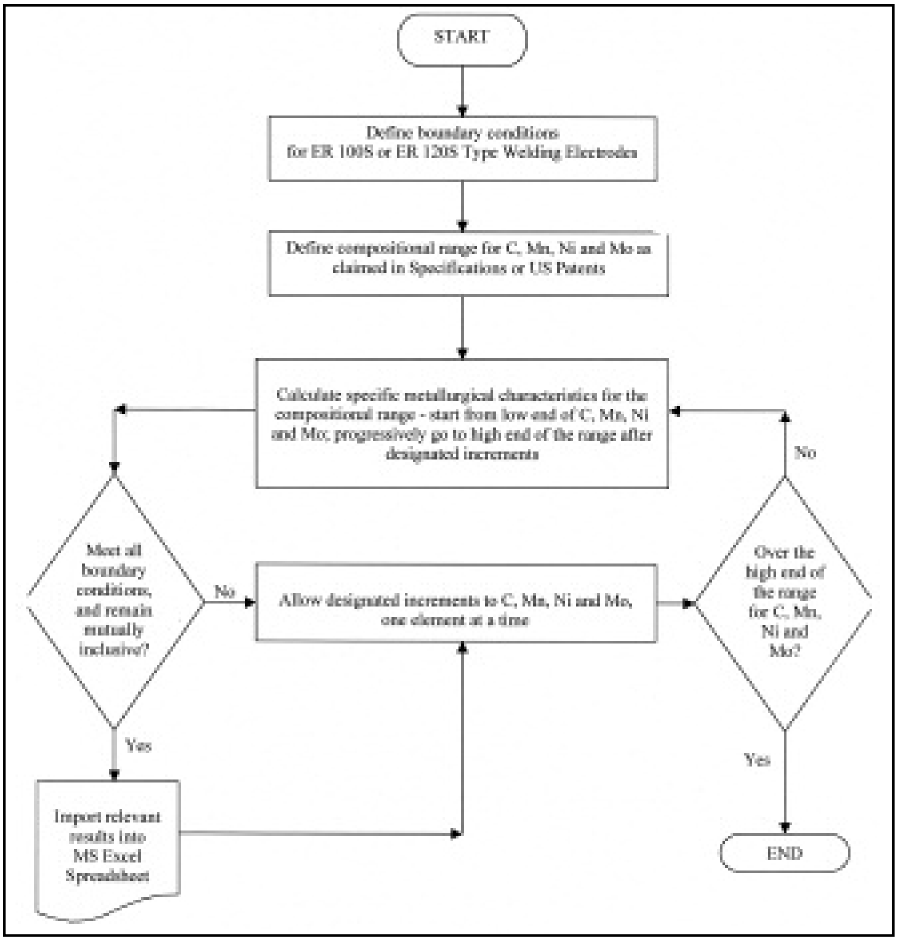

Fig. 2 — Flow chart of the algorithmic approach.

Readers might recognize that while the two U.S. patents address chemical composition limits of low-carbon bainitic steel welding electrodes, AWS A5.28 and MIL-E-23765/2E specifications primarily address chemical composition limits of conventional medium-carbon high-strength steel electrodes that provide a tempered martensitic weld metal. This may explain the observed variation in nickel content between these two classes of welding electrodes. However, what should be the specification limits of individual alloy elements of welding electrodes that are based on the low-carbon bainitic steel system, if the electrodes were to consistently meet or exceed U.S. Navy requirements? The present work was carried out primarily to answer this vital question.

Obtaining an appropriate answer to this question is also critically important particularly to standards-setting organizations such as the American Welding Society and various end users. In recent years, within the

Table 2 — GMA Welding Conditions and Weld Mechanical Property Test Results

						Room-Temperature All-Weld Tensile Test				CVN Impact Test	
Weld No.	Base Plate	Energy Input (kJ/in.)	Welding Position	Metal Transfer	Calculated Weld Cooling Rate at 1000˚F (˚F/s)	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Reduction in Area (%)	At –60˚F	At 0˚F
ER 100S	HY-100/HY-80	—	—		—	—	100.0 min	—	—	50 min	—
1	HSLA-100	30	Flat	Spray	95	114.0	119.2	19.2	63	86	124
2	HSLA-100	45	Flat	Spray	57	108.2	114.8	21.3	68	74	90
3	HY-100	45	Flat	Spray	57	109.2	116.2	22.3	67	76	96
4	HSLA-100	55	Flat	Spray	47	105.7	114.6	22.0	69	75	102
5	HSLA-100	110	Flat	Spray	11	92.6	105.1	23.5	71	73	112
6	HSLA-100	110	Uphill	Pulsed	7	87.0	109.0	24.3	72	125	146
7	HSLA-100	110	Flat	Spray	5	88.3	102.8	24.3	71	49	95
8	HY-100	110	Flat	Spray	5	87.0	102.8	25.8	72	99	129

Tensile test results represent an average of 2 tests; CVN impact test results represent an average of 5 tests.

Table 3 — Chemical Composition Ranges of AWS A5.28, MIL-E-23765/2E, U.S. Patent 5,523,540 and U.S. Patent 5,744,782

Element	A5.28-05		MIL-E-23765/2E		U.S. Patent 5,523,540			U.S. Patent 5,744,782		
					Experimental Range		Range Claimed	Experimental Range		Range Claimed
	ER 100S	ER 120S	MIL-100S	MIL-120S	Minimum	Maximum		Minimum	Maximum	
Carbon	0.08	0.10	0.08	0.10	0.012	0.035	0.01–0.05	0.026	0.030	0.06
Manganese	1.25–1.80	1.40–1.80	1.25–1.80	1.40–1.80	0.89	1.69	0.70–1.80	1.49	1.82	1–2
Phosphorus	0.010	0.010			0.008	0.012		0.001	0.001	0.01
Sulfur	0.010	0.010			0.003	0.012		0.0018	0.023	0.01
Silicon	0.20–0.55	0.25–0.60	0.20–0.55	0.25–0.60	0.27	0.36	0.20 –0.40	0.33	0.37	0.2–0.5
Chromium	0.30	0.60	0.3	0.6	0.01	0.60	0.80	0.01	0.02	
Nickel	1.40–2.10	2.0–2.80	1.40–2.10	2.0–2.80	2.46	5.92	2.0–9.0	2.38	3.78	2–4
Molybdenum	0.25–0.55	0.30–0.65	0.25–0.55	0.30–0.65	0.44	0.96	0.40–1.50	0.51	0.99	0.3–1
Vanadium	0.05	0.03			0.004	0.01	0.01	0.001	0.003	
Copper	0.25	0.25	0.25	0.25	0	0	1.0	0.001	0.20	0.5
Titanium	0.10	0.10	0.10	0.10	0.003	0.045	0.03	0.0025	0.0033	0.05
Aluminum	0.10	0.10	0.10	0.10	0.001	0.038	0.035			
Boron								0.0003	0.0057	0.01
Oxygen								47 ppm	82 ppm	300 ppm
Nitrogen								4 ppm	10 ppm	50 ppm
Hydrogen								1.15 mL/100 g	2.35 mL/100 g	5 mL/100 g

Single values are maximum.

Table 4 — Analysis of Algorithm Results for ER100S-Type Electrode Chemical Compositions

Boundary Conditions	Specified Ranges for Four Critical Elements	Evaluation Criterion	Number of Acceptable ER100S-Type Electrode Chemical Compositions 0.01 wt-% C	0.02 wt-% C	0.03 wt-% C	0.04 wt-% C	0.05 wt-% C	0.06 wt-% C	Total
	AWS A5.28/ MIL-E-23765/2E C, 0.01 to 0.08; Mn, 1.25 to 1.8; Ni, 1.40 to 2.10; Mo, 0.25 to 0.55	$(B_{50}–M_S) \geq 0$	0	0	0	0	0	0	0
B_{50}: 417°–461°C M_S: 410°–451°C CEN: 0.29–0.38	U.S. Patent 5,523,540	$(B_{50}–M_S) \geq 0$	1029	1228	1313	1253	893	—	5716
	C, 0.01 to 0.05; Mn, 0.70 to 1.8; Ni, 2.0 to 9.0; Mo, 0.40 to 1.50	Upper Limit for Nickel	6.6 wt-%	6.3 wt-%	6.0 wt-%	5.8 wt-%	5.5 wt-%	— —	— —
	U.S. Patent 5,744,782	$(B_{50} - M_S) \geq 0$	495	588	652	668	556	346	3305
	C, 0.01 to 0.06; Mn, 1.0 to 2.0; Ni, 2.0 to 4.0; Mo, 0.30 to 1.0	Upper Limit for Nickel	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	—

U.S. Navy, the strengthening of materials specification development and approval process assumed center stage following the events associated with the construction of the first Seawolf submarine. These events included extensive HAC of weldments in the HY-100 pressure hull, subsequent techno-economic analyses, development, qualification, certification, and implementation of appropriate repair procedures that also led to considerable schedule delays, significant cost overruns, etc.

Among other things, HAC of the welded pressure hull was attributed to the high carbon content of the MIL-120S high-strength steel welding electrode, even though the welding electrode explicitly met the MIL-E-23765 specification requirements for carbon content, but on the high side, and despite the use of previously certified welding procedures. Contents of other critical elements that adversely affect weldability were also found to be at a higher level in the electrode, very near their respective maximum allowed in the electrode specification.

In a follow-up investigation, a U.S. Government Accountability Office report that examined the lessons learned from the manufacturing experience of the first Seawolf submarine (Ref. 10) has quoted that "only 39% of (U.S. Government) specification parameters were supported by historical data and less than 5% of the parameters were supported by test data," thereby, strongly underscoring a need for further strengthening of the specification development and approval process.

To this end, the present work describes the development of a PC-based Turbo C++ algorithm for quantitatively evaluating the chemical composition limits of selected GMAW electrode specifications for potential application to the welding of HSLA-100 steel.

Table 5 — Analysis of Algorithm Results for ER100S-Type Electrode Chemical Compositions with Microstructure Control

Boundary Conditions	Source and Specified Ranges for Four Critical Elements	Evaluation Criterion (B_{50}–M_S)	Number of Acceptable ER100S Type Electrode Chemical Compositions						
			0.01 wt-% C	0.02 wt-% C	0.03 wt-% C	0.04 wt-% C	0.05 wt-% C	0.06 wt-% C	Total
B_{50}: 417°–461°C M_S: 410°–451°C CEN: 0.29–0.38	U.S. Patent	> 20°C	41	207	377	532	634	—	1791
	5,523,540	Upper Limit for Nickel	4.3 wt-%	6.1 wt-%	5.8 wt-%	5.8 wt-%	5.3 wt-%	—	—
	C, 0.01 to 0.05;	> 30°C	—	1	49	126	231	—	407
	Mn, 0.70 to 1.8;	Upper Limit for Nickel	—	4.5 wt-%	5.7 wt-%	5.3 wt-%	5.4 wt-%	—	—
	Ni, 2.0 to 9.0;	> 40°C	—	—	—	1	15	—	16
	Mo, 0.40 to 1.50	Upper Limit for Nickel	—	—	—	5.3 wt-%	5.1 wt-%	—	—
	U.S. Patent	20°C	31	113	210	305	397	346	1402
	5,744,782	Upper Limit for Nickel	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	—
	C, 0.01 to 0.06;	> 30°C	—	—	14	57	141	231	443
	Mn, 1.0 to 2.0;	Upper Limit for Nickel	—	—	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	—
	Ni, 2.0 to 4.0;	> 40°C	—	—	—	—	2	23	25
	Mo, 0.30 to 1.0	Upper Limit for Nickel	—	—	—	—	4.0 wt-%	4.0 wt-%	—

Table 6 — Analysis of Algorithm Results for ER120S-Type Electrode Chemical Compositions

Boundary Conditions	Source and Specified Ranges for Four Critical Elements	Evaluation Criterion (B_{50}–M_S)	Number of Acceptable ER120S-Type Electrode Chemical Compositions								
			0.01 wt-% C	0.02 wt-% C	0.03 wt-% C	0.04 wt-% C	0.05 wt-% C	0.06 wt-% C	0.07 wt-% C	0.08 wt-% C	Total
	AWS A5.28/ MIL-E-23765/2E	(B_{50}–M_S) > 0	—	—	6	22	31	38	45	35	177
	C, 0.01 to 0.10; Mn, 1.4 to 1.8; Ni, 2.0 to 2.80; Mo, 0.30 to 0.65	Upper Limit for Nickel	—	—	2.8 wt-%	2.8 wt-%	2.8 wt-%	2.8 wt-%	2.8 wt-%	2.8 wt-%	—
	U.S. Patent 5523540	(B_{50}–M_S) > 0	57	434	910	1320	1501	—	—	—	4222
B_{50}: 404°C to 461° M_S: 403°C to 430° CEN: 0.32 – 0.41	C, 0.01 to 0.05; C Mn, 0.70 to 1.8; C Ni, 2.0 to 9.0; Mo, 0.40 to 1.50	Upper Limit for Nickel	5.5 wt-%	6.5 wt-%	6.3 wt-%	6.2 wt-%	5.9 wt-%	—	—	—	—
	U.S. Patent 5,744,782	(B_{50}–M_S) > 0	39	211	461	698	800	725	—	—	2934
	C, 0.01 to 0.06; Mn, 1.0 to 2.0; Ni, 2.0 to 4.0; Mo, 0.30 to 1.0	Upper Limit for Nickel	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	4.0 wt-%	— —	— —	— —

Objectives

The specific objectives of this work were to develop a PC-based Turbo C++ algorithm that would prove a useful tool in 1) quantitatively evaluating chemical composition limits of current AWS A5.28, MIL-E-23765/2E welding electrode specifications for potential application to the welding of HSLA-100 steel; and 2) comparing the results with similar quantitative evaluations performed on the chemical composition ranges claimed in two related U.S. patents.

Algorithm Development

The primary emphasis of the algorithm development effort was to capture current knowledge into a definitive baseline for reliably assuring the quality of high-strength steel welding electrodes while allowing flexibility in quantitatively evaluating relevant electrode specifications and patented claims. Figure 2 provides a flowchart of the algorithmic approach. Appendix A shows the developed Turbo C++ algorithm for evaluating the chemical composition ranges claimed in U.S. Patent 5,744,782 for ER100S-type electrode chemical composition. Selected parts of this algorithm were modified to allow the evaluation of electrode chemical compositions for both ER100S and ER120 types specified in AWS A5.28 and MIL-E-23765/2E and chemical composition ranges claimed in U.S. Patent 5,523,540.

For the purpose of this work, the Turbo C++ algorithm consisted of three main parts. The first part defined a set of baseline ranges or boundary conditions, one each for ER100S- and ER120S-type welding electrodes, for calculated B_{50} temperature, calculated M_S temperature, and Yurioka's CEN. Prior research on a new metallurgical model to speed the development of consumable electrodes (Ref. 11) has identified specific or desirable baseline ranges for both ER100S- and ER120S-type electrodes following an analysis of the chemical compositions of solid, flux-cored, and metal-cored wire electrodes or weld metals obtained thereof. This approach to identifying desirable or acceptable baseline ranges as boundary conditions is also comprehensive as it included all three types of GMAW electrodes. Furthermore, this approach likely removed any inherent bias

Table 7 — Analysis of Algorithm Results for ER120S-Type Electrode Chemical Compositions with Microstructure Control

Boundary Conditions	Source and Specified Ranges for Four Critical Elements	Evaluation Criterion ($B_{50} - M_S$)	Number of Acceptable ER120S Type Electrode Chemical Compositions 0.01 wt-% C	0.02 wt-% C	0.03 wt-% C	0.04 wt-% C	0.05 wt-% C	0.06 wt-% C	0.07 wt-% C	0.08 wt-% C	Total
	AWS A5.28/MIL-E-23765/2E	> 20°C	—	—	2	20	30	38	45	35	170
		Upper Limit for Nickel	—	—	2.8	2.8	2.8	2.8	2.8	2.8	-—
	C, 0.01 to 0.10;				wt-%	wt-%	wt-%	wt-%	wt-%	wt-%	
	Mn, 1.4 to 1.8;	> 30°C	—	—	—	3	16	28	38	35	120
	Ni, 2.0 to 2.80;	Upper Limit for Nickel	—	—	—	2.7	2.8	2.8	2.8	2.8	-—
	Mo, 0.30 to 0.65					wt-%	wt-%	wt-%	wt-%	wt-%	
		> 40°C	—	—	—	—	—	2	11	28	41
		Upper Limit for Nickel	—	—	—	—	—	2.7	2.8	2.8	-—
								wt-%	wt-%	wt-%	
B_{50}: 404°–461°C	U.S. Patent 5,523,540	> 20°C	—	—	71	393	668	—	—	—	1132
M_S: 403°–430°C	C, 0.01 to 0.05;	Upper Limit for Nickel	—	—	5.0	6.2	5.9	—	—	—	—
CEN: 0.32–0.41	Mn, 0.70 to 1.8;		—	—	wt-%	wt-%	wt-%	—	—	—	—
	Ni, 2.0 to 9.0;	>30°C	—	—	—	57	240	—	—	—	297
	Mo, 0.40 to 1.50	Upper Limit for Nickel	—	—	—	4.9	5.9	—	—	—	—
			—	—	—	wt-%	wt-%	—	—	—	—
		> 40°C	—	—	—	—	9	—	—	—	9
		Upper Limit for Nickel	—	—	—	—	5.1	—	—	—	—
							wt-%	—	—	—	—
	U.S. Patent 5,744,782	> 20°C	—	—	58	252	401	497	—	—	1208
	C, 0.01 to 0.06;	Upper Limit for Nickel	—	—	4.0	4.0	4.0	4.0			
	Mn, 1.0 to 2.0;				wt-%	wt-%	wt-%	wt-%	—	—	—
	Ni, 2.0 to 4.0;	>30°C	—	—	—	45	141	239	—	—	425
	Mo, 0.30 to 1.0	Upper Limit for Nickel	—	—	—	4.0	4.0	4.0	—	—	—
						wt-%	wt-%	wt-%	—	—	—
		> 40°C	—	—	—	—	2	23	—	—	25
		Upper Limit for Nickel	—	—	—	—	4.0	4.0	—	—	—
							wt-%	wt-%			

toward either type of welding electrodes or specific welding conditions. Electrode chemical compositions that met the baseline ranges for calculated B_{50} temperature, calculated M_S temperature, and CEN for either ER100S- or ER120S-type electrodes have already been shown to consistently meet or exceed U.S. Navy requirements when welding HSLA-100 steel over a broad operational envelope (Ref. 6), thereby providing validity to this approach.

An electrode chemical composition having the desirable features specific to this algorithm is based on the Fe-C-Mn-Ni-Mo-Ti system. Specific amounts (in wt-%) of carbon, manganese, nickel, chromium, molybdenum, silicon, copper, vanadium, niobium, and boron concurrently satisfy the following three equations:

$$B_{50}\,(°C) = 770 - (270 \times C) - (90 \times Mn) - (37 \times Ni) - (70 \times Cr) - (83 \times Mo) \qquad (1)$$

where the calculated value of B_{50} is 417° to 461°C for ER100S-type electrodes, or 404° to 461°C for ER120S-type electrodes.

$$M_S\,(°C) = 561 - (474°C) - (33 \times Mn) - (17 \times Ni) - (17 \times Cr) - (21 \times Mo) \qquad (2)$$

where the calculated value of M_S is 410° to 451°C for ER100S-type electrodes, or 403° to 430°C for ER120S-type electrodes.

$$CEN = C + A(C) \times \{Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr + Mo + V + Nb)/5 + 5B\} \qquad (3)$$

where $A(C) = 0.75 + 0.25 \tanh [20 \times (C - 0.12)]$, and where the calculated value of CEN is 0.29 to 0.38 for ER100S-type electrodes, or 0.39 to 0.41 for ER120S-type electrodes.

The second part of the algorithm consisted of chemical composition ranges for carbon, manganese, nickel, and molybdenum either as specified in AWS 5.28, MIL-E-23765/2E, or as claimed in the two U.S. Patents. As outlined in a previous section, prior research (Ref. 6) has clearly established that carbon, manganese, nickel, and molybdenum are critical elements for compositional control of these high-performance welding electrodes. Secondly, these electrodes might also contain about 0.03 wt-% titanium for controlling the amount of dissolved oxygen and nitrogen in the weld metal (Ref. 12). As titanium is not a part of the above equations for B_{50} temperature, M_S temperature, and CEN, the algorithm development focused on evaluating the chemical composition limits of the above four elements while maintaining all other elements identified in the electrode specifications at some nominal value. Within the chemical composition ranges specified, the combined effect of all these other elements (silicon, chromium, copper, niobium, boron and vanadium) on the calculated values of B_{50} temperature, M_S temperature and CEN is not significant, relative to that of a set of nominal (or mean) values used in this algorithm for each of these elements. Nominal (or mean) values used in the algorithm for silicon, chromium, copper, niobium, boron, and vanadium are shown in Appendix A.

The third part of the algorithm addressed "mutually inclusive" computational requirements. This part of the algorithm used four "FOR-NEXT" or "DO" loops to allow computation of B_{50} temperature, M_S temperature, and CEN based on chemical composition data. These four loops pertained one each for carbon, manganese, nickel, and molybdenum, and allowed small incremental variation to their values starting from the respective lower limit to the upper limit of the ranges specified for these elements for ER100S and ER120S in AWS A5.28 specification, for MIL-100S or MIL-120S in

Table 8 — A Comparison of U.S. Patents 5,523,540 and 5,744,782

Evaluation Criterion		Number of Acceptable Electrode Chemical Compositions		
($B_{50} - M_S$)		U.S. Patent 5,523,540		U.S. Patent 5,744,782
		C, 0.01 to 0.05; Mn, 0.70 to 1.8; Ni, 2.0 to 9.0; Mo, 0.40 to 1.50		C, 0.01 to 0.06; Mn, 1.0 to 2.0; Ni, 2.0 to 4.0; Mo, 0.30 to 1.0
	Total	Over 4.0 wt-% Nickel	At or below 4.0 wt-% Nickel	At or below 4.0 wt-% Nickel
		ER100S Type		
> 0°C	5716	1923	3793	3305
> 20°C	1791	709	1082	1404
> 30°C	407	233	174	444
> 40°C	16	15	1	25
		ER120S Type		
> 0°C	4222	1739	2483	2934
> 20°C	1132	460	672	1208
> 30°C	297	138	159	425
> 40°C	9	8	1	25

Table 9 — Proposed Revisions to AWS A5.28 Specification for Application to HSLA-100 Steel

Chemical Composition

Element	ER100S		ER 120S	
	Current	Proposed	Current	Proposed
Carbon	0.08	0.06	0.10	0.06
Manganese	1.25–1.80	1.0–2.0	1.40–1.80	1.0–2.0
Phosphorus	0.010	0.010	0.010	0.010
Silicon	0.20–0.55	0.20–0.55	0.25–0.60	0.20–0.60
Sulfur	0.010	0.010	0.010	0.010
Nickel	1.40–2.10	2.0–4.0	2.0–2.80	2.0–4.0
Chromium	0.30	0.30	0.60	0.30
Molybdenum	0.25–0.55	0.30–1.0	0.30–0.65	0.50–1.0
Vanadium	0.05	0.05	0.03	0.05
Titanium	0.10	0.10	0.10	0.10
Zirconium	0.10	0.10	0.10	0.10
Aluminum	0.10	0.10	0.10	0.10
Copper	0.25	0.25	0.25	0.25
Other Elements, Total	0.50	0.50	0.50	0.50
Iron	Balance	Balance	Balance	Balance

Mechanical Property

Tensile/Impact Property	ER100S		ER120S	
	Current	Proposed	Current	Proposed
Yield Strength (ksi)	—	82–120	—	105–122
Minimum Tensile Strength (ksi)	100	100	120	120
Minimum Tensile Elongation (%)	—	16	—	15
Minimum CVN at 0°F (ft.lb)	—	80	—	80
Minimum CVN at –60°F (ft.lb)	50	50	50	50

Single values for chemical composition are maximum.

MIL-E-23765/2E specification, and the specific ranges claimed in the U.S. Patents 5,523,540 and 5,744,782. The lower limit for carbon was held at 0.01 wt-% to allow ease of computation and comparative evaluation. The incremental values used in the computation are also consistent with typical accuracy values commonly reported for the respective elements when performing quantitative chemical analysis of low-carbon, high-strength steels.

This part of the algorithm also allowed one to introduce the difference between calculated values of B_{50} temperature and M_S temperature as another desirable characteristic. This feature allowed further discrimination of the acceptable electrode chemical compositions. The purpose of this feature is primarily to identify chemical compositions that would allow adequate control of the relative amounts of bainite and martensite in weld metal based on known relationships among chemical composition, B_{50} temperature, and M_S temperature of bainitic steels. It is quite well known that B_{50} temperature indicates the temperature at which 50% bainite forms from austenite, and M_S temperature indicates the temperature at which martensite begins to form from austenite. Furthermore, it is also widely known that in bainitic steels, the B_{50} temperature is often higher than the M_S temperature.

As both bainite and martensite form only from austenite, one could manipulate this characteristic to further evaluate the chemical composition of a high-performance welding electrode and ascertain its ability to form low-carbon bainitic weld metal. In other words, the difference in temperature between the calculated B_{50} temperature and the calculated M_S temperature could be used in microstructural selection or control. As used in this algorithm, when the difference in temperature between the calculated B_{50} temperature and the calculated M_S temperature increases from 0° to 60°C, the bainitic steel will have progressively higher amounts of bainite, starting at about 50% bainite. When the difference in temperature between the calculated B_{50} temperature and the calculated M_S temperature exceeds 60°C, one could expect the microstructure to be entirely or about 100% bainitic.

The algorithm did not explicitly consider the effect of "delta quantities" (Ref. 13) to compensate for the loss or gain of alloying elements across the arc column from the welding electrode to weld metal. In GMA welding, delta quantities of alloy elements vary with alloy element, shielding gas type, flow rate, and weld energy input. For example, when Ar-5% CO_2 is used as a shielding gas, the delta quantity for carbon is +0.01 wt-%, i.e., one would commonly observe a 0.01 wt-% pickup in the carbon content of the weld metal relative to that of the welding electrode. Likewise, under similar welding conditions, the delta quantity for manganese is –0.2 wt-%, i.e., one would commonly observe a 0.2 wt-% decrease in the manganese content of the weld metal relative to that of the welding electrode. The effect of "delta quantities" may be addressed in a more elaborate future effort that could also consider various shielding gases, flow rate, and weld energy input.

Following appropriate computations, the algorithm allowed the output to be directly imported into a Microsoft Excel spreadsheet that also allowed further manipulation of results, and printing of desirable ranges for B_{50} temperature, M_S temperature and CEN, along with the specific individual chemical compositions that offered valid B_{50} temperature, M_S temperature, and CEN values in the above range.

Based on the number of valid chemical compositions that showed desirable ranges for B_{50} temperature, M_S temperature, and CEN, or an appropriate minimum difference between the calculated values of B_{50} temperature and M_S temperature, the individual electrode specification or patented claim was considered robust and suitable for application to welding HSLA-100 steel.

Results and Discussion

ER100S-Type Electrode Composition

AWS A5.28/MIL-E-23765/2E Specification

For the chemical composition ranges cited for carbon, manganese, nickel, and molybdenum for ER100S in AWS A5.28 specification and MIL-100S in MIL-E-23765/2E specification, the algorithm did not return any acceptable electrode chemical composition. Readers might recognize that this result is rather expected as both AWS A5.28 and MIL-E-23765/2E specifications primarily address chemical composition limits of conventional medium-carbon high-strength steel electrodes that provide a predominantly tempered martensitic weld metal with a specified minimum yield strength in the 80 to 100 ksi range. This null result does not mean the current ER100S or MIL-100S electrodes are not suitable for welding HSLA-100 steel. Rather, the null result means that the above electrodes are suitable for welding HSLA-100 steel when appropriate preheat controls and limits on welding operational envelope are strictly in force. Indirectly, the above null result also served to validate the utility of this algorithmic approach.

U.S. Patent 5,523,540

For the chemical composition ranges claimed for carbon, manganese, nickel, and molybdenum contents in U.S. Patent 5,523,540 and with calculated value of B_{50} temperature equal to or greater than the calculated value of M_S temperature, the algorithm returned over 5700 acceptable ER100S-type electrode chemical compositions (Table 4) indicating the robustness of the patented claims. Admittedly, a wider range for nickel content (2.0 to 9.0 wt-%) as claimed in U.S. Patent 5,523,540 is likely responsible for the above overwhelming number of results. Of these, over 1900 electrode compositions contained nickel in excess of 4.0 wt-%. Classification of the results based on carbon content showed a maximum number of 1313 acceptable electrode chemical compositions at the 0.03 wt-% carbon level. This indicated that electrodes (or weld metals) with 0.03 wt-% carbon may tolerate a wide variation in chemical composition, thus would be more "forgiving" while meeting performance requirements. Coincidentally, electrode manufacturers might benefit when formulating their quality control measures for these types of electrodes if they focus their electrode manufacturing and quality assurance efforts on the 0.03 wt-% carbon level.

Table 4 also provides a classification of the results based on the maximum possible or upper limit for nickel content at each of these carbon levels. The upper limit for nickel content did not exceed 6.6 wt-%, and this likely represents a possible specification upper limit. Interestingly, the maximum possible (or allowable) nickel content at each of these carbon levels progressively decreased with increasing carbon levels, thus clearly indicating that a specification for a high-performance welding electrode could not allow simultaneous increases in both carbon and nickel contents, or for that matter increases to any three or all four of the principal alloying elements near their respective specified upper limit.

Furthermore, it is common knowledge that a higher nickel content (together with other austenite stabilizers such as carbon, manganese, or copper) may promote a primary austenitic type of weld solidification that may lead to unacceptable toughness behavior of weld metal, especially at low temperatures. In fact, a previous investigation (Ref. 14) that studied the effect of manganese and nickel on the variation in microstructure and mechanical properties of low-carbon (0.02 wt-%) Fe-C-Mn-Ni system of weld metals suitable for HSLA-100 steel had shown that in a low-manganese (less than 1.0 wt-%) composition, nickel additions increased hardness without sacrificing impact toughness whereas in a high-manganese (over 1.5 wt-%) composition, nickel additions deteriorated the impact toughness quite seriously as it promoted intergranular fracture. The intergranular fracture path appeared to follow columnar grain boundaries that were identical to prior austenite grain boundaries since no δ-ferrite phase formed during solidification. Accordingly, these boundaries without having primary δ-ferrite phase were susceptible to cracking under dynamic loading. Based on hardness and impact resistance reported in this investigation, the optimum levels for manganese and nickel have been suggested to be 0.5–1 wt-% and 4–5 wt-%, respectively. Evidently, and as shown in Table 4, one would expect the specified upper limit for nickel content to decrease further from the 5 wt-% level with a higher carbon and manganese content in a Fe-C-Mn-Ni-Mo-Ti weld metal system.

U.S. Patent 5,744,782

For the chemical composition ranges claimed for carbon, manganese, nickel, and molybdenum contents in U.S. Patent 5,744,782 and with calculated value of B_{50} temperature equal to or greater than the calculated value of M_S temperature, the algorithm returned over 3300 acceptable electrode chemical compositions (Table 4). These results are less robust compared to those obtained with U.S. Patent 5,523,540. Despite claims for a slightly wider range for carbon content (up to 0.06 wt-%), the lower range claimed for nickel content (2.0 to 4.0 wt-%) in U.S. Patent 5,744,782 is mostly responsible for the above reduction in the number of acceptable electrode chemical composition results. Furthermore, a classification of the results based on the maximum possible or upper limit for nickel content returned a value of 4.0 wt-% at each of these carbon levels. This indicated that the upper limit for nickel content claimed in U.S. Patent 5,744,782 is somewhat conservative as it clearly discounted for the adverse effect of higher nickel content on microstructure development and low-temperature impact toughness of weld metal.

Microstructural Control

The above algorithm was subsequently used in additional evaluations that provided more insight on the ability of electrode chemical compositions in offering microstructural selection or control. The chemical composition ranges claimed in U.S. Patents 5,523,540 and 5,744,782 were further evaluated using the difference in temperature between the calculated B_{50} temperature and the calculated M_S temperature as an additional criterion for evaluation. Results were obtained for more than 20, 30, and 40°C difference in temperatures. Table 5 provides the algorithm results as total number of acceptable electrode chemical compositions, and these results are classified on the basis of carbon content, and the corresponding upper limit for nickel content at each carbon level.

In general, the results reported in Table 5 are similar to those reported in Table 4, except the acceptable upper limit for nickel content in U.S. Patent 5,523,540 dropped further to 6.1 wt-%. Furthermore, when a predominantly (over 75%) bainitic microstructure is desired, the total number of acceptable electrode compositions dropped down dramatically, and these compositions required a minimum of 0.04 wt-% carbon. Additionally, when considering a temperature difference of over 30°C, the claimed ranges for the four critical elements in U.S. Patent 5,744,782 appeared to provide somewhat more flexibility in designing acceptable electrode chemical compositions compared to those in U.S. Patent 5,523,540. This flexibility is further reinforced when the upper limit for nickel in U.S. Patent 5,523,540 is limited to 4 wt-%, and the numerical advantage shifts decidedly in favor of U.S. Patent 5,744,782, presumably because of the marginally higher limit for carbon.

ER120S-Type Electrode

Composition

Tables 6 and 7 provide results of similar quantitative evaluations performed on electrode chemical composition ranges in AWS A5.26 and MIL-E-23765/2E specifications, and chemical composition ranges claimed in U.S. Patents 5,523,540 and 5,744,782 with the following boundary conditions that are appropriate for ER120S-type welding electrodes — B_{50}: 404° to 461°C; M_S: 403° to 430°C; and CEN: 0.32 to 0.41. Interestingly, both AWS A5.28 and MIL-E-23765/2E specifications returned 177 chemical compositions, ranging from 0.03 to 0.08 wt-% carbon. Classification of the results based on carbon content showed that 80 of these 177 compositions contained 0.07 or 0.08 wt-% C, a level that was also higher than the specified upper limit for carbon content in (ladle or product analysis of) HSLA-100 steel. Additionally, these 80 compositions are likely to provide weld metals that may exhibit unacceptable variations in yield strength relative to weld cooling rate. In comparison, chemical composition ranges claimed in U.S. Patents 5,523,540 and 5,744,782 contained thousands of ER120S-type electrode composition, and appeared quite robust for application to welding HSLA-100 steel. U.S. Patent 5,523,540 returned 4222 chemical compositions, of which 1739 contained over 4.0 wt-% nickel. U.S. Patent 5,744,782 returned 2934 chemical compositions, all of which contained 4.0 wt-% or less nickel.

Table 8 provides a comparative evaluation of the two U.S. Patents when 4 wt-% nickel is considered the upper limit for either ER100S- or ER120S-type welding electrodes. This comparison is based on the premise that at over 4 wt-% nickel content, one might witness primary austenitic type of weld solidification and the attendant loss of impact toughness in weld metal, especially at low temperatures. As shown in Table 8, when using microstructural control as an evaluation criterion, the available number of acceptable ER 100S and ER 120S electrode compositions clearly indicates that the claimed ranges in U.S. Patent 5,744,782 provide additional flexibility over the claimed ranges in U.S. Patent 5,523,540.

Benefits

The chief advantage of this algorithmic approach to evaluating electrode chemical composition is that this offers a powerful tool in distinguishing high-performance welding electrode chemical compositions from “rich” and “lean” welding electrode chemical compositions. It is well known that the use of rich and lean welding electrode chemical compositions often limits the operational envelope, shows unacceptable sensitivity of yield strength to weld cooling rate and, reduces performance, while increasing overall cost of weld fabrication. Secondly, the algorithmic approach is quite useful in readily identifying an acceptable electrode heat which has a melt composition that meets the desired metallurgical criteria. Alternatively, the algorithmic approach allows one to reject a rich or a lean electrode heat even when the ladle (melt) composition is well within AWS 5.28, MIL-E-23765/2E specifications, or the cited U.S. patents. When the metallurgical criteria are not met, a rich or a lean heat becomes an “out-lier.” This ability to distinguish at an early stage of electrode processing eliminates or substantially reduces subsequent processing costs and associated risks. Readers may recognize that this level of reliability and risk reduction while specifying an electrode chemical composition is not commonly achieved.

Thus, use of the above algorithmic approach greatly reduces various risks inherent in specifying electrode chemical composition, and is powerful in identifying high-performance electrode chemical compositions that have a higher reliability in meeting or exceeding mechanical property requirements when welding HSLA-100 steel, over a wide welding operational envelope.

In strengthening the electrode specification development efforts and approval processes, the algorithmic approach provides a quantitative basis for including the latest advances in the understanding of the relationships among chemical composition, welding conditions, weld microstructure development and resultant weld mechanical properties, and fracture characteristics of high-strength, low-carbon bainitic steel weld metals.

Conclusions

1) A Turbo C++ algorithm has been developed to quantitatively evaluate the chemical composition limits of selected GMAW electrode specifications and two relevant U.S. Patents for potential application to welding HSLA-100 steel.

2) For the chemical composition ranges cited for carbon, manganese, nickel, and molybdenum for ER 100S in AWS A5.28 specification and MIL-100S in MIL-E-23765/2E specification, the algorithm did not return any acceptable electrode chemical composition.

3) For the chemical composition ranges cited for carbon, manganese, nickel, and molybdenum for ER120S in AWS A5.28 specification and MIL-120S in MIL-E-23765/2E specification, the algorithm returned 177 acceptable electrode chemical compositions. Of these, 80 compositions contained 0.07 or 0.08 wt-% C, more than the specified upper limit for carbon in HSLA-100 steel, thus making them unsuitable for welding HSLA-100 steel.

4) For the chemical composition ranges claimed for carbon, manganese, nickel and molybdenum contents in U.S. Patent 5,523,540, the algorithm returned thousands of acceptable ER100S- and ER120S-type electrode chemical compositions indi-

cating the robustness of the patented claims.

5) For the chemical composition ranges claimed for carbon, manganese, nickel, and molybdenum contents in U.S. Patent 5,744,782, the algorithm returned a lesser number of acceptable ER100S- and ER120S - type electrode chemical compositions, but seemed to rightly discount for the adverse effects of nickel content over 4 wt-% in drastically reducing low-temperature impact toughness of weld metal.

6) This algorithmic approach is quite helpful in distinguishing high-performance welding electrode chemical compositions from rich and lean welding electrode chemical compositions, and may serve a vital need in strengthening electrode specification development efforts and approval processes.

Future Work

One could expect that populating this algorithmic approach with test results from other experimental welding electrode development work based on the Fe-C-Mn-Ni-Mo-Ti system would provide a powerful tool in further strengthening welding electrode standards development and certification efforts. Based on the above work, and the results of other recent work performed under the auspices of U.S. Navy and commercial electrode manufacturers, the AWS A5 Committee on Filler Metals and Allied Materials may consider introducing a subset of ER100S and ER120S electrodes suitable for welding HSLA-100 steel. The chemical composition ranges specified in A5.28 ,*Specification for Low-Alloy Steel Electrodes for Gas Shielded Arc Welding,* may be revised as shown in Table 9 for both ER100S- and ER120S-type welding electrodes suitable for HSLA-100 steel that are based on the Fe-C-Mn-Ni-Mo-Ti system.

The revisions in Table 9 chiefly address carbon, manganese, nickel, and molybdenum contents of ER100S- and ER120S-type welding electrodes. Further, the chemical compositions of these electrodes are essentially free from chromium addition, except that the chromium content is limited to 0.3 wt-%, a representative value commonly obtainable from re -melting of scrap steel. Additionally, titanium addition is critical to the performance behavior of these welding electrodes. Furthermore, titanium addition is preferred over aluminum for achieving desired levels of deoxidation, and adequate control over nitrogen content and weld metal grain size. Prior research (Refs. 15–18) has shown that a titanium content of 0.01 to 0.03 wt-% in the welding electrode is desirable for achieving exceptional low-temperature impact toughness. Although not revised in Table 9, titanium and aluminum in excess of 0.03 wt-% have been shown to impair low-temperature toughness of high-strength steel weld metal. Consequently, there also exists a need to reconsider allowing titanium and aluminum concentrations as high as 0.10 wt-% in ER100S- and ER120S-type high-strength steel welding electrode specifications. Some of the mechanical property ranges proposed in Table 9 are derived from MIL-E 23765/2E(SH) specification (Ref. 7).

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Appendix A

A Turbo C++ Algorithm for Evaluating Chemical Composition Limits of GMAW Electrode Specifications

```
//5744782 _USP.CPP
#include <stdio.h>
#include <string.h>
#include <complex.h>
#include <math.h>
#include <conio.h> main()
{FILE      *flp;
float CarMax, CarMin, MnMax, MnMin, NiMax,
NiMin, MoMax, MoMin;
// Carbon, Manganese, Nickel & Molybdenum
float SiMean, CrMean, TiMean, CuMean,
NbMean, BMean, VMean;
//Silicon, Chronium, Titanium, Copper, Nio-
bium, Boron, Vanadium
float cenMax, cenMin, tanvar, addvar, cencalc, i,
j, k, l, difcen, b50calc, b50dif;

float msdif, mscalc;

int b50Max, b50Min, count, msMax, msMin;

signed int b50_mscalc_diff = 0;

char         compfile[20],tmpname[20],ch;
clrscr();
cenMin = 0.29;
cenMax = 0.38;
b50Min = 417;
b50Max = 461;
msMin = 410;
msMax = 451;

CarMin = 0.01;
CarMax = 0.06;
MnMin = 1.0;
MnMax = 2.0;
NiMin = 2.0;
```

```
NiMax = 4.0;
MoMin = 0.30;
MoMax = 1.0;
SiMean = 0.30;
CrMean = 0.10;
TiMean = 0.03;
CuMean = 0.10;
NbMean = 0.005;
BMean = 0.0002;
VMean = 0.005;

//Display
printf("\n\n\t\t\tWelding Electrode Composition
Evaluation\n");

//Receive input value for b50_mscalc_diff from
user
printf("\n\n\tEnter integer difference in temper-
ature between calculated B50 & calculated ms:");
scanf("%d",&b50_mscalc_diff);

if((b50_mscalc_diff < 0) || (b50_mscalc_diff >
50)){
printf("\n\n\tRange incorrect enter value be-
tween 0 & 50(included)");
printf("\n\n\tPress Enter & Run Program again to
re-enter value");
getch();
}
else{
//Receive File name from user.
printf("\n\n\tEnter filename to store weld metal
chemical compositions");
printf("\n\n\tFilename with .csv (comma sepa-
rated values) would be best for viewing");
printf("\n\n\t<filename>.csv:");
scanf("%s",compfile);
strcpy(tmpname,compfile);
count = 0;
}
//--------------------------------------------------------------
//If Filename is NULL display Error
if((flp=fopen(tmpname,"wr"))==NULL)
{
    printf("Error! The file %s could not be
opened",compfile);
}
//--------------------------------------------------------------
--
//-----If filename is OK then continue calcs--------
-------------
else
{fprintf(flp,"CENMin,CENMax,B50Min,B50M
ax,MsMin,MsMax\n");
fprintf(flp,"%4.2f,%4.2f,%4d,%4d,%4d,%4d\n",
cenMin,cenMax,b50Min,b50Max,msMin,msMa
x);
fprintf(flp," ,  , \n");

fprintf(flp,"CarMin,CarMax,MnMin,MnMax,Ni
Min,NiMax,MoMin,MoMax\n");
fprintf(flp,"%4.2f,%4.2f,%4.1f,%4.1f,%4.1f,%4.
1f,%4.1f,%4.1f\n",CarMin,CarMax,MnMin,Mn
Max,NiMin,NiMax,MoMin,MoMax);
fprintf(flp," , , \n");

fprintf(flp,"C,Mn,Si,Ni,Cr,Mo,Ti,Cu,Nb,B,V,CE
N,B50,Ms\n");
for(i=CarMin;i<(CarMax+0.001);i+=.01)
{
tanvar = 20*(i-0.12);
fprintf(flp,",  , \n");
for(j=MnMin;j<(MnMax+.01);j+=.1)
{
for(k=NiMin;k<(NiMax+.01);k+=.1)
{
for(l=MoMin;l<(MoMax+.01);l+=.1)
{
addvar
=((SiMean/24)+(j/6)+(CuMean/15)+(k/20)+(
(CrMean+l+VMean+NbMean)/5)+(5*BMea
n)) ;
cencalc =i+((.75+.25*tanh(tanvar))*addvar);

if(cencalc < cenMax && cencalc > cenMin){
b50calc=(770-(270*i)-(90*j)-(37*k)-
(70*CrMean)-(83*l));

if(b50calc < b50Max && b50calc > b50Min){
mscalc=561-(474*i)-(33*j)-(17*k)-
(17*CrMean)-(21*l);

if(mscalc < msMax && mscalc > msMin){
if((mscalc + b50_mscalc_diff)<b50calc){
fprintf(flp,"%5.3f,%4.2f,%4.2f,%4.2f,%4.2f,%4.
2f,%5.3f,%5.3f,%5.3f,%6.4f,%5.3f,%4.2f,%4.0f,
%4.0f\n",i,j,SiMean,k,CrMean,l,
TiMean,CuMean,NbMean,BMean,VMean,cen-
calc,b50calc,mscalc);
}
}
}
}
}
}
}
}
}
return 0;
```

Errata

Three equations that appeared in the welding research supplement titled "Investigating the Bifurcation Phenomenon in Plate Welding" by C. L. Tsai, M. S. Han, and G. H. Jung on page 160-s in the July 2006 *Welding Journal* were incorrect. Below are the corrections.

The *Welding Journal* apologizes for the errors.

$$\varepsilon_{xx}^{ie} = -\alpha^{T_{\max}}(T_{\max} - T_h) \qquad (3)$$

$$\varepsilon_{xx}^{ie} = -\alpha^{T_{\max}}(T_h - T_o)\left[1 + R_H \frac{T_{\max} - T_c}{MMT - T_c}\right] \qquad (4)$$

$$\varepsilon_{xx}^{ie} = -\alpha^{MMT}(1 + R_H)(T_h - T_o) \qquad (5)$$