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Strengthening Materials Specifications

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Continuing efforts to strengthen materials specifications readily recognize that a mere compliance with a materials specification only assures a material meeting or exceeding the minimum expectations explicitly detailed in the specification. Implicitly, such efforts also recognize that additional and specific client needs must be addressed as supplementary requirements and introduced during material procurement to reduce risks and assure enhanced performance. This article describes two U.S. Navy-related case studies that allowed further strengthening of the materials specification process, using newer methods and renewed understanding. The first case demonstrates the use of a constraints-based modeling approach to specify the chemical composition of high-performance welding electrodes for critical U.S. Navy applications. This approach helps to distinguish high-performance welding electrode chemical compositions from rich and lean welding electrode chemical compositions that might limit the operational envelope, reduce performance, or both, while increasing overall cost of fabrication but otherwise meet electrode specification requirements. The second case identifies that the size of an ingot could be an important factor while specifying the aluminum and sulfur contents of very large-size, heavy-gauge plates. Renewed understanding of melt fluidity issues associated with the solidification of very large-size ingots shows that deficiencies in through-thickness ductility of heavy-gauge plates are related to controlling aluminum and sulfur contents of the voluminous melt, notwithstanding explicit compliance with specification requirements.

Keywords aluminum and sulfur contents, constraints-based modeling, electrode specification, heavy-gauge high-strength steel plates, materials specification, procurement specification, welding electrodes

1. Introduction

Materials specifications provide the basis for the high performance of engineered materials. Because materials specifications prescribe chemical composition and properties requirements for various engineering materials, they can also be considered the backbones that support the spread of modern civilization. A materials specification is often a consensus document developed by various stakeholders who contribute their technical and managerial insights to formulating and strengthening different parts of the materials specification. Evidently, the stakeholders have their vested interests, but their contributions are generally necessary to capture vital aspects of the specification. These aspects include relationships among chemical composition, methods of processing, control of processing conditions to avoid defects, development and control of microstructures, and the effects of microstructure on physical and mechanical properties and material performance. However, as a consensus document, a relevant materials specification only serves as a safety net. Safety net essentially means that a mere compliance with the materials specification would result in a material meeting or exceeding the minimum expectations explicitly detailed in the specification.

Commonly, a materials specification has two or more parts. The first part relates to ranges for the chemical composition of specific elements making up the material, and the other parts might relate to specific aspects such as processing, heat treatment, size, finish, methods of nondestructive and destructive testing, range of physical and mechanical properties, and acceptance limits or performance requirements. Occasionally, it is quite possible that a material that explicitly meets a relevant materials specification in terms of chemical composition or physical and mechanical property requirements may fail to live up to certain other implicit expectations. In such special cases, it is a common industry practice to address additional and specific client (user) needs as supplementary requirements and introduce them during material procurement.

Under these circumstances, a reader might wonder, "Could adhering strictly to a materials specification cause adverse events, even occasionally? What are the risks? Why should the materials community remain vigilant in seeking newer methods and renewed understanding to strengthen materials specifications and approval processes?"

In recent years, within the U.S. Navy, the strengthening of materials specification development and approval process assumed center stage after the events associated with the construction of the first Seawolf submarine. These events included extensive hydrogen-assisted cracking (HAC) of weldments in the pressure hull and subsequent technoeconomic analyses, development, qualification, certification, and implementation of appropriate repair procedures that also led to considerable schedule delays and significant cost overruns.

Among other things, HAC of the welded pressure hull was attributed to the high-carbon content of the 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. The 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. A follow-up

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investigation (Ref 1) revealed 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."

The above events showed clearly to the materials community that adhering strictly to a materials specification in terms of chemical composition range alone could expose one to very large risks during subsequent secondary processing, especially so when a material meets the specified chemical composition requirements for various (critical) elements on the high side (i.e., rich in chemical composition) or for that matter on the low side (i.e., lean in chemical composition).

The above issues underscore the various risks and a continuous and critical need for strengthening specification development and approval process to eliminate, mitigate, or manage specific risks.

2. Purpose

The purpose of this article is to describe two U.S. Navy-related case studies that allowed further strengthening of the materials specification process using newer methods and renewed understanding of related technological issues. The U.S. Navy has been in the forefront of supporting research, development, specification, certification, and introduction and sustained use of advanced materials. The U.S. Navy also funds the operation of several national centers of excellence, including one in materials joining technology and another in metalworking technology.

The first case shows how a constraints-based modeling approach (Ref 2) can be used successfully in developing a procurement specification for high-strength steel welding electrodes while complying with chemical composition requirements specified in MIL-E-23765/2E (Ref 3) or its commercial equivalent A5.28 specification (Ref 4) issued by the American Welding Society. This case is a logical follow-up to the events associated with the construction of the first Seawolf submarine.

The second case involves heavy-gauge (75 mm or 3 in. and over) HY-100 grade steel plates that met the explicit chemical composition and mechanical property requirements of MIL-S-16216K (SH) specification (Ref 5). However, selected plates failed to live up to certain other implicit expectations on required values of through-thickness ductility considered essential for achieving high performance in certain critical ship structures. This second case shows how a renewed understanding of melt fluidity issues associated with the solidification of the very large-size ingot (Ref 6) helped to relate deficiencies in through-thickness ductility of the plate with melt chemical composition control of aluminum and sulfur contents.

3. Case 1: Advanced Welding Electrodes

How does one reduce various risks associated with a welding electrode characterized by a rich or a lean chemical composition while conforming to a specification such as MIL-E-23765/2E? An innovative constraints-based modeling approach offers a solution. The modeling approach specifically allows one to accept a heat based on melt composition when certain metallurgical criteria are met. Alternatively, one could reject a rich or a lean heat even when the melt composition is otherwise well within MIL-E-23765/2E or AWS 5.28 specification. When the metallurgical criteria are not met, a rich or a lean heat is decided as an "out-lier." Such a decision eliminates or substantially reduces further processing costs and associated risks. This level of reliability and risk reduction while specifying an electrode chemical composition is not commonly achieved.

Table 1 MIL-E-23765/2E chemical composition ranges and mechanical property requirements

Element	MIL-E-23765/2E MIL 100S	MIL-E-23765/2E MIL 120S
Carbon	0.08	0.09
Manganese	1.25–1.80	0.90–2.35
Silicon	0.20–0.55	0.60
Phosphorus	0.012	0.012
Sulfur	0.008	0.008
Nickel	1.40–2.10	1.0–3.0
Chromium	0.30	0.80
Molybdenum	0.25–0.55	0.30–1.00
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 in as-welded condition		
Yield strength, MPa, ksi	565–758 (82–110)	703–841 (102–122)
Tensile strength, MPa, ksi	…	…
Elongation, %	16	14
Minimum CVN, J at 18 °C, ft.lb at 0 °F	81 (60)	81 (60)
Minimum CVN, J at −50 °C, ft.lb at −60 °F	48 (35)	61 (45)

The constraints-based modeling approach uses the following two key principles:

- Consolidate prior and perceived knowledge into a coherent set of mutually inclusive constraints that meet end-user requirements.
- Based on the set of constraints, formulate controlled experiments that limit the experimental space while reducing inherent risks, thereby allowing one to reach beyond the consolidated knowledge in developing novel, low-cost, low-risk solutions to overcome persistent materials (processing and fabrication) issues.

Table 1 specifies the chemical composition range and mechanical property requirements for current MIL-100S and MIL-120S consumable electrodes used with the gas metal arc welding (GMAW) process. After the experience with the construction of the first Seawolf submarine, the U.S. Navy had identified that the candidate advanced GMAW electrodes for high-strength steels should exhibit the following additional characteristics (Ref 7):

- Eliminate or substantially reduce the need for preheat controls while joining higher strength steels such as HSLA-100, HY-100, HSLA-80, and HY-80
- Show adequate resistance to HAC
- Meet or exceed the mechanical property requirements of the existing MIL-100S or MIL-120S electrodes
- Allow welding over a broad operational envelope in terms of plate thickness, welding position, and weld energy input

- Show minimal variation in weld mechanical properties (especially yield strength) when used over a broad operational envelope for welding HSLA-100, HY-100, HSLA-80, and HY-80 steels

Under the constraints-based modeling approach, the above U.S. Navy requirements for advanced welding electrodes were converted into a set of mutually inclusive constraints. These constraints related the chemical composition of candidate steel electrodes to appropriate numerical ranges, using a set constitutive equations. Each of these constitutive equations underscores one or more metallurgical characteristics such as strength, toughness, and weldability. The respective numerical ranges for the selected metallurgical characteristics were obtained from an analysis of published literature. Specific numerical ranges were decided based on the possibility to achieve desirable range of mechanical properties (tensile strength, low-temperature toughness) for both MIL-100S and MIL-120S electrodes while improving their weldability in terms of resistance to HAC.

A composition having the features of the constraints-based model is comprised of iron, and specific amounts (in percent by weight) of carbon, manganese, nickel, chromium, molybdenum, silicon, copper, vanadium, niobium, and boron, which concurrently satisfy the following three equations:

$$B_{50}\,(^\circ C) = 770 - (270 \times C) - (90 \times Mn) - (37 \times Ni) - (70 \times Cr) - (83 \times Mo) \quad \text{(Eq 1)}$$

where the calculated value of B_{50} is 400-500 °C;

$$M_S(^\circ C) = 561 - (474 \times C) - (33 \times Mn) - (17 \times Ni) - (17 \times Cr) - (21 \times Mo) \quad \text{(Eq 2)}$$

where the calculated value of M_S is 400-450 °C; and

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

where $A(C) = 0.75 + 0.25 \tanh [20 \times (C - 0.12)]$ and the calculated value of the carbon equivalent number (CEN) is 0.28-0.41.

The first equation relates the chemical composition to the B_{50} temperature, i.e., the temperature at which 50% bainite transformation occurs (Ref 8). Bainite is a transformation product of austenite, and it refers to a crystalline structure of considerable toughness, combining high strength with high ductility. Bainitic steels exhibit high-tensile strength (in the 931-1172 MPa or 135-170 ksi range) and good impact toughness at low temperature. Lowering the transformation temperature allows one to refine the grain size of the transformation product, leading to simultaneous increases in both tensile strength and ductility. The higher strength bainitic steels exhibit a B_{50} temperature in the range of 420-550 °C, and in this range, the strength of these steels increases linearly with a decrease in B_{50} temperature (Ref 9, 10). Therefore, a range of 400-500 °C for B_{50} temperature allowed one to match the tensile strength range for MIL-100S and MIL-120S electrodes.

The second equation relates the chemical composition to the M_S temperature, i.e., the temperature at which martensite transformation starts (Ref 8). Martensite is also a transformation product of austenite, but it has a higher susceptibility to HAC. In other words, both bainite and martensite form only from austenite. The M_S temperature of high strength bainitic steels is often well below their corresponding B_{50} temperature. One could manipulate this characteristic to design the chemical composition of high-performance steel. For example, a careful lowering of the M_S temperature below the B_{50} temperature of a candidate steel allowed one to achieve a larger volume fraction of bainite than martensite in the resultant microstructure and thereby substantially reduced the susceptibility to HAC.

Based on the ranges for tensile strength, low-temperature toughness, and resistance to HAC of MIL-100S and MIL-120S electrodes, the desired range for M_S temperature is approximately 400-450 °C.

The third equation relates the chemical composition to the CEN, which is often used to distinguish high-strength structural steels that may require preheating during weld fabrication (Ref 11). One could also use the CEN equation to assess the relative effects of different alloy elements on the need for preheat. Evidently, carbon content has the greatest effect on the CEN. When considering weld metal, a substantial reduction in the carbon content of the welding consumable is necessary to obtain significant reduction in preheat levels. To reduce further the CEN and the sensitivity of weld metals to preheat controls, it is desirable to limit the levels of elements with the highest coefficients in the CEN equation (e.g., boron, chromium, molybdenum, vanadium, and niobium) and increase the levels of elements with the lowest coefficients in the CEN equation (e.g., silicon, nickel, copper, and manganese). The desired value for CEN of structural steels, which may eliminate or substantially reduce the need for preheat and interpass temperature controls, ranges between 0.28 and 0.41.

Besides compositional control to achieve mechanical property goals, the constraints-based model also limited the combined oxygen and nitrogen content of the electrodes to preferably below 550 ppm (Ref 12), consistent with dissolved gas content commonly obtainable with gas-shielded welding processes.

In the constraints-based modeling approach, the above metallurgical characteristics and their numerical ranges, in turn, were used to identify carbon, manganese, nickel, and molybdenum as critical elements for compositional control and to specify the compositional ranges for these individual alloy elements. Subsequently, a 2^3 factorial design of experiments was used to develop a batch of eight low-carbon (at about 0.03 wt.%) welding electrodes, with one low and another high level for manganese (1.5 and 1.8 wt.% as aim composition), nickel (2.5 and 3.8 wt.% as aim composition), and molybdenum (0.5 and 1.0 wt.% as aim composition). The eight electrodes also contained other elements such as silicon, phosphorus, and sulfur at some nominal values. The compositions also included approximately 0.03 wt.% titanium as a deoxidizer, grain refiner, and "nitrogen getter" and thus attempted to control the amount of oxygen and nitrogen in the weld metal. The addition of titanium also served to refine the weld metal grains. Table 2 shows the melt chemical composition of the solid wire electrodes. Table 3 shows the calculated metallurgical characteristics of the solid wire electrodes based primarily on melt composition.

Initially, limited experiments were carried out to evaluate the performance of the welding electrodes. Results showed that three of the eight electrodes (electrodes 3, 4, and 7) met or exceeded MIL-100S requirements, whereas two of the eight electrodes (electrodes 4 and 8) met or exceeded MIL-120S requirements (Ref 13). Microstructural and fractographic

Table 2 Chemical composition of bare wire gas metal arc welding electrodes

No.	C	Mn	P	S	Si	Cr	Ni	Mo	V	Cu	Ti	B	O	N	H
1	0.027	1.51	0.001	0.0019	0.34	0.02	2.52	0.52	0.001	0.001	0.033	0.001	69	6	2.11
2	0.028	1.49	0.001	0.0018	0.37	0.01	2.38	0.99	0.001	0.001	0.031	0.001	47	9	1.51
3	0.028	1.54	0.001	0.0018	0.34	0.01	3.78	0.52	0.001	0.001	0.028	0.001	52	10	2.13
4	0.029	1.5	0.001	0.0018	0.35	0.01	3.73	0.98	0.002	0.001	0.03	0.001	78	6	1.46
5	0.03	1.82	0.001	0.0020	0.34	0.01	2.37	0.52	0.003	0.001	0.029	0.001	76	6	1.63
6	0.029	1.82	0.001	0.0021	0.35	0.01	2.38	0.98	0.003	0.001	0.029	0.001	66	7	1.15
7	0.026	1.82	0.001	0.0022	0.35	0.01	3.77	0.51	0.002	0.001	0.027	0.001	64	6	1.79
8	0.03	1.8	0.001	0.0019	0.33	0.01	3.72	0.99	0.003	0.001	0.025	0.0003	82	4	1.23

Note: The chemical composition (No. 1 through 8) is expressed in wt.%. Balance is essentially Fe. The chemical composition was determined from vacuum induction melt (VIM) billets. N, O, and H contents were determined from bare solid wire electrodes. N and O contents are expressed in parts/million. The H content is expressed in mL/100 g of Fe. The bare wire size is 1.6 mm (0.0625 in.) diameter.
Source: Ref 2

Table 3 Calculated metallurgical characteristics of bare wire welding electrodes

No.	B_{50} temperature, °C	M_s temperature, °C	Carbon equivalent number (CEN)	Combined (O+N) content, ppm
1	489	444	0.29	75
2	457	437	0.33	56
3	440	422	0.32	62
4	407	414	0.36	84
5	467	435	0.31	82
6	428	426	0.36	73
7	417	414	0.34	70
8	379	403	0.39	86

Source: Ref 2

analyses of the weldments showed that these advanced electrodes provided a predominantly bainitic microstructure in the weld metal. Based on the encouraging results, additional weld evaluations were performed over a much wider welding operational envelope (Table 4) using electrode 3. These weldments provided acceptable weld mechanical properties for MIL-100S over the entire range of welding conditions. Table 5 shows weld metal mechanical property test results.

Figure 1 shows the variation of the all-weld metal yield strength with a calculated weld cooling rate at 538 °C or 1000 °F. (Ref 14). The trend line showed the following statistical relationship, at an r^2 value of 0.99:

All-weld metal yield strength (in MPa) = 524 + [65 × Ln(Calculated weld cooling rate at 538 °C in °C/s)] (Eq 4)

Thus, use of the above constraints-based modeling approach greatly reduced various risks inherent in specifying electrode chemical composition while complying with MIL-E-23765/2E and helped to identify advanced electrode chemical compositions that met weld mechanical properties over a wide welding operational envelope.

In the above instance, a procurement specification that is also in compliance with MIL-E-23765/2E, albeit a wider range for nickel content, has been developed. As shown above, the actual strengthening of the specification was achieved using statistical experimental techniques to gain an improved understanding of the effects of weld metal chemical composition on processing (welding operational envelope), microstructure development, and mechanical properties, including room-temperature and low-temperature fracture behavior.

4. Case 2: Heavy-Gauge, High-Strength Steel Plates

Manufacturers of U.S. Navy submarines and aircraft carriers use heavy-gauge HY-100 grade steel plates produced to MIL-S-16216K (SH) specification (Ref 5), for fabricating certain critical structures. These steel plates are characterized by a tempered martensitic microstructure, with an average prior-austenite grain size of about 15 μm. Through-thickness ductility of the rolled plate is an important property for these structures because they are required to resist shock, blast, and ballistic loading. When the through-thickness ductility of the heavy-gauge plate does not meet a certain value required of critical ship structures, the alternative is to use forgings, at a significant cost penalty.

The MIL-S-16216K (SH) specification for HY-100 requires a fully killed, vacuum-degassed steel plate produced to a fine-grain practice. Even though aluminum is essential for fully killing a steel melt of dissolved oxygen and for achieving a refined grain size in the final plate product, neither MIL-S-16216K (SH) nor its predecessor MIL-S-16216J (SH) specification requires a minimum aluminum content (Table 6). Second, the specification allows up to 100% loss of back-reflection, continuously in one plane, over a 2581 mm^2 (4 $in.^2$) area of the plate during ultrasonic testing (UT). Intuitively, the above UT requirement is inconsistent with any through-thickness ductility requirement.

Perhaps in recognition of the above issues, the First Article qualification test procedures developed in 1983 used a minimum requirement of 20% reduction in area (%RA) in through-thickness tensile test of specimens obtained from selected plate locations, top, middle, and bottom (length dimension) as well as from plate edges and center (width dimension) positions. Table 6 shows HY-100 chemical composition of the six 1983 First Article test heats and also their average chemical composition. The First Article qualification test practice involved six HY-100 plates that were produced from bottom-poured, big end down (BED) ingots. The plate thickness varied from 28 to 152 mm (1.10 to 6 in.). The sulfur content of the First Article HY-100 heats ranged between 0.004 and 0.019 wt.% and averaged 0.011 wt.%. The ladle aluminum content of the First

Table 4 GMA welding schedules for evaluation of electrode 3

Weld No.	Base plate	Energy input, kJ/mm (kJ/in.)	Welding position	Metal transfer	Preheat temperature, °C (°F)	Interpass temperature, °C (°F)	Calculated weld cooling rate at 538 °C (1000 °F) in °C/s (°F/s)
1	HSLA-100	1.18 (30)	Flat	Spray	52 (125)	52 (125)	53 (95)
2	HSLA-100	1.77 (45)	Flat	Spray	66 (150)	66 (150)	32 (57)
3	HY-100	1.77 (45)	Flat	Spray	66 (150)	66 (150)	32 (57)
4	HSLA-100	2.17 (55)	Flat	Spray	16 (60)	52 (125)	26 (47)
5	HSLA-100	4.33 (110)	Flat	Spray	16 (60)	52 (125)	6 (11)
6	HSLA-100	4.33 (110)	Vertical-up	Pulsed	149 (300)	149 (300)	4 (7)
7	HSLA-100	4.33 (110)	Flat	Spray	135 (275)	149 (300)	3 (5)
8	HY-100	4.33 (110)	Flat	Spray	149 (300)	149 (300)	3 (5)

Source: Adapted from Ref 2

Table 5 Mechanical property test results of additional GMA welds

			Room temperature all-weld tensile test				CVN impact test, J (ft.lb)	
Weld No.	Base plate	Calculated weld cooling rate at 538 °C (1000 °F) in °C/s (°F/s)	Yield strength, MPa (ksi)	Ultimate tensile strength, MPa (ksi)	Elongation, %	Reduction in area, %	At −50 °C (−60 °F)	At −18 °C (0 °F)
MIL-100S	HY-100/HY-80	…	565–758 (82–110)	…	16 min	…	48 min (35 min)	81 min (60 min)
1	HSLA-100	53 (95)	786 (114.0)	822 (119.2)	19.2	63	117 (86)	168 (124)
2	HSLA-100	32 (57)	746 (108.2)	792 (114.8)	21.3	68	100 (74)	122 (90)
3	HY-100	32 (57)	753 (109.2)	801 (116.2)	22.3	67	103 (76)	130 (96)
4	HSLA-100	26 (47)	729 (105.7)	790 (114.6)	22.0	69	102 (75)	138 (102)
5	HSLA-100	6 (11)	638 (92.6)	725 (105.1)	23.5	71	99 (73)	152 (112)
6	HSLA-100	4 (7)	600 (87.0)	752 (109.0)	24.3	72	170 (125)	198 (146)
7	HSLA-100	3 (5)	609 (88.3)	709 (102.8)	24.3	71	66 (49)	129 (95)
8	HY-100	3 (5)	600 (87.0)	709 (102.8)	25.8	72	134 (99)	175 (129)

Note: Tensile test results represent an average of two tests; CVN impact test results represent an average of five tests.
Source: Adapted from Ref 2

Article HY-100 melts ranged between 0.017 and 0.026 wt.% and averaged at 0.023 wt.%. The First Article qualification test specimens obtained from the above selected locations of HY-100 heavy-gauge plates consistently met the minimum requirement for through-thickness ductility (Ref 15).

In early 1998, a U.S. Navy contractor discovered that some regions in remnant pieces of a 152 mm (6 in.) thick HY-100 plate did not meet the 20%RA requirement. The original steel plate (dimensions, 152 by 2286 by 6096 mm (6 by 90 by 240 in.) was produced from a very large ingot. Table 6 shows the ladle chemical composition corresponding to this plate (heat U4246), that demonstrates compliance with the MIL-S-16216K (SH) specification. Subsequent findings showed that the interior plate regions had through-thickness ductility values significantly below measured values at the plate edges.

The above findings raised concern about the acceptability of heavy-gauge plate made using current production practices. This also underscored the need for evaluating and improving current plate manufacturing practices and reinforcing relevant aspects of the materials specification to ensure that the U.S. Navy had access to the highest quality materials produced cost effectively.

In recent years, steel producers have used a variety of advanced manufacturing techniques to achieve significant improvements in strength, toughness, formability, and weldability of high-strength steel plates. For example, these advanced steel manufacturing technologies include a simultaneous reduction in both aluminum and sulfur contents of melts to obtain reduced inclusion count and to achieve inclusion shape control in the resulting plate products. To the latter end, steel manufacturers often control sulfur at 0.008 wt.% maximum for regular grades and further reduce sulfur to 0.002 wt.% maximum for high-performance grades.

In an effort to strengthen the current manufacturing practices, a recent U.S. Navy manufacturing technology program effort (Ref 16) evaluated several approaches for producing 95 and 152 mm (3¾ and 6 in thick) HY-100 plates with the required through-thickness ductility at specified plate locations. These approaches included an evaluation of data from current and modified plate production practices and a comparison with the 1983 First Article qualification records.

Under the above manufacturing technology program effort, a set of four heats of HY-100 was produced at two sulfur levels (regular at 0.008 wt.% maximum and low at 0.002 wt.% maximum). Table 6 shows the chemical composition of these four heats (experimental heats 1-4), which were bottom-poured to either BED or big end up (BEU) ingots and processed to 10 plates, six were 152 mm (6 in.) thick, and four were 95 mm (3¾ in.) thick. BEU or BED ingots weighing 16,672 kg (36,755 lb) were used to produce the 152 mm (6 in.) thick

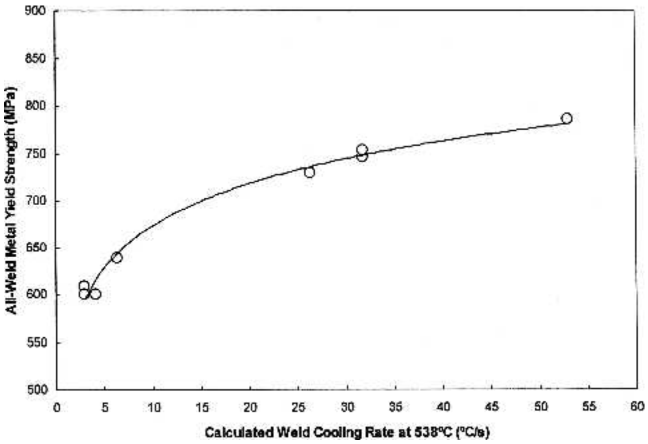

Fig. 1 Variation of weld metal yield strength with calculated weld cooling rate. Source: adapted from Ref 2

plates, whereas BED ingots weighing 34,386 kg (75,806 lb) and 38,554 kg (84,995 lb) were used for producing four very large-size 95 mm (3¾ in.) thick plates.

After the final rolling into plates, through-thickness tensile test specimens were obtained from selected locations of each plate: one from the top, one from the bottom, duplicate specimens from six edge locations (four corresponding to each corner of the plate and the other two corresponding to the mid-section of the plate) and duplicate specimens from 10 locations along the plate centerline. In the 152 mm (6 in.) thick plates, the 10 centerline locations spread from the top to the bottom of each plate (Fig. 2A). However, in the 95 mm (3¾ in.) thick plates, because of their enormous size, the 10 centerline locations were in the top one-third section of the plates (Fig. 2B). Additionally, duplicate through-thickness tensile test specimens were obtained from four locations (W, X, Y, and Z) in the top section of each plate, which UT revealed to be poorly consolidated regions that might contain large-sized shrinkage cavities. These locations varied from one plate to another.

Table 7 shows individual through-thickness ductility (%RA) values or ranges obtained from different locations of each plate. The 10 plates met the 20%RA requirements for all top, bottom, and edge locations, except for one edge location in plate 8. The top and bottom locations showed a low of 58 and a high of 69. This range of values indicated a possible range of through-thickness ductility levels that can be readily obtained from a fully consolidated material. The low values were occasional at these locations in plates processed from either BED or BEU ingot. The %RA values at the edge locations ranged from a low of 19 to a high of 73. Plate 8 (152 mm or 6 in. thick) produced from a 2057 by 1016 mm (81 by 40 in.) BEU ingot showed a 19%RA value in one edge location but acceptable %RA values in the 10 center locations. This ingot contained 0.017 wt.% Al, 0.0018 wt.% S, and was forged prior to rolling. The combination of small BEU ingot, low aluminum, low sulfur, and preforging provided a plate material with improved through-thickness ductility.

In comparison, plate 9 (95 mm or 3¾ in. thick) produced from a very large, 2794 by 1016 mm (110 by 40 in.), BED ingot showed high %RA values at edge locations. This ingot contained 0.023 wt.% Al, 0.0011 wt.% S, and was not forged prior to rolling. In three center locations and one UT location, one of the duplicate through-thickness test specimens showed less than 20%RA. In another UT location, both of the duplicate

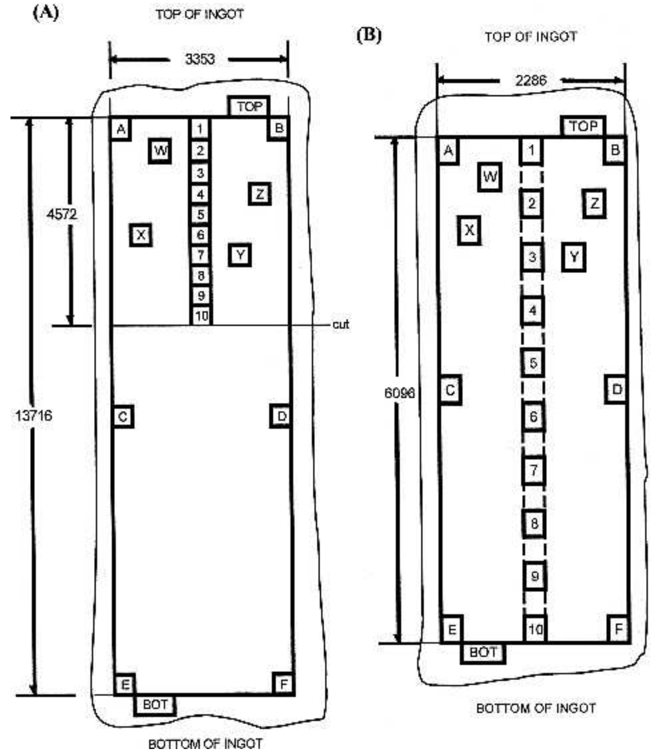

Fig. 2 Schematic diagram showing locations of through-thickness ductility test specimens: (A) 95 mm (3¾ in.) thick plate; (B) 152 mm (6 in.) thick plate. Locations W, X, Y, and Z are chosen at the worst areas after ultrasonic testing. These four locations varied from one plate to another. Source: Ref 6

through-thickness test specimens showed less than 20%RA values. The combination of large BED ingot, high aluminum, low sulfur, and no forging prior to rolling appeared to provide very high ductility values at plate edges but low ductility values at the plate center. Preforging of the small or large BED ingot with either high or low sulfur provided low %RA values in the center locations.

Comparatively, plates obtained from BEU ingots appeared to show a somewhat lower hardenability than plates obtained from BED ingots. This apparent difference in hardenability may be contributing to a relatively better consolidation response of BEU ingots to preforging than BED ingots.

Overall, the two sulfur levels (regular at 0.008 and low at 0.002 wt.%), ingot type, ingot size, or preforging of either BEU or BED ingots did not provide an overwhelming improvement in through-thickness ductility of either 152 mm (6 in.) or 95 mm (3¾ in.) thick plates. These results also showed that UT was by and large effective in identifying plate locations that contained low-consolidation regions. The test results did not identify any other trend. Despite several changes to plate manufacturing practices, the low through-thickness tensile ductility occurred at center locations, thereby demonstrating that low ductility perhaps originated in one or more of the prior stages: during melting, vacuum degassing, or teeming. This warranted a closer comparison of the chemical composition of the heats and their teeming practice with those of the 1983 First Article qualification test heats.

A closer examination of the First Article test data revealed that the plate aluminum content was almost the same as the ladle aluminum content, irrespective of plate thickness or lo-

Table 6 HY-100 steel-ladle chemical composition of First Article test heats, prior heat, and four experimental heats

	Type	C	Mn	P	S	Si	Cr	Ni	Mo	V	Cu	Ti	Al
MIL-S-16216J (SH)	**Min.**	**0.12**	**0.10**			**0.15**	**1.50**	**2.75**	**0.30**				**NS**
heavy-gauge HY-100	**Max.**	**0.20**	**0.40**	**0.02**	**0.02**	**0.35**	**1.90**	**3.50**	**0.65**	**0.03**	**0.25**	**0.003**	**NS**
Heat No.	**Type**	**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Mo**	**V**	**Cu**	**Ti**	**Al**
D0733-1D (28 mm or 1.10 in.)	IC	0.15	0.28	0.005	0.0019	0.22	1.46	2.73	0.38	0.008	0.15	0.003	0.017
B8686-5 (40 mm or 1.59 in.)	IC	0.16	0.25	0.007	0.011	0.27	1.45	2.73	0.39	0.010	0.18	0.003	0.021
D3974-1B (70 mm or 2.75 in.)	IC	0.15	0.31	0.013	0.017	0.22	1.49	3.10	0.40	0.010	0.13	0.003	0.026
B8817-1 (95 mm or 3.75 in.)	IC	0.16	0.28	0.010	0.004	0.23	1.60	3.17	0.50	0.007	0.16	0.003	0.026
D4030-4A (102 mm or 4.00 in.)	IC	0.16	0.26	0.013	0.006	0.25	1.64	3.29	0.54	0.009	0.13	0.004	0.026
B8756-1 (152 mm or 6.00 in.)	IC	0.16	0.25	0.012	0.010	0.23	1.54	3.22	0.52	0.01	0.13	0.003	0.024
Average of the above six HY-100 First Article test heats	Nominal	0.16	0.27	0.01	0.011	0.24	1.53	3.04	0.46	0.009	0.14	0.003	0.023
U4246	IC	0.16	0.31	0.007	0.008	0.20	1.56	3.19	0.54	0.003	0.15	0.003	0.011
Experimental heat 1	IC	0.16	0.31	0.005	0.0024	0.23	1.56	3.14	0.54	0.004	0.12	0.002	0.015
Experimental heat 2	IC	0.16	0.32	0.005	0.0082	0.21	1.59	3.15	0.54	0.004	0.07	0.002	0.011
Experimental heat 3	IC	0.16	0.31	0.005	0.0018	0.23	1.63	3.18	0.54	0.003	0.05	0.002	0.017
Experimental heat 4	IC	0.16	0.31	0.005	0.0011	0.24	1.56	3.15	0.54	0.004	0.14	0.002	0.023

Note: Single values reported in MIL-S-16216J (SH) for P, S, V, Cu, and Ti represent maximum values. NS, not specified; IC, ingot cast. Plate thickness of the respective First Article test heat is provided in parentheses.
Source: Adapted from Ref 6

Table 7 Details of experimental HY-100 steel plates and through-thickness %RA values

									Through-thickness(a), %RA				
											Range of values obtained from duplicate testing at each location		
Plate No.	**Heat No.**	**Ingot type**	**Ingot size, mm × mm (in. × in.)**	**Plate size, mm × mm × mm (in. × in. × in.)**	**Plate weight, kg (lb.)**	**Al, wt.%**	**S, wt.%**	**Forging before rolling**	**Top**	**Bottom**	**6 Edge**	**10 Center**	**4 UT**
1	1	BED	2083 × 864 (82 × 34)	152 × 2,286 × 6,096 (6 × 90 × 240)	16,672 (36,755)	0.015	0.0024	No	64	60	56–68	3–57	6–27
2	…	BEU	2057 × 1016 (81 × 40)	152 × 2,286 × 6,096 (6 × 90 × 240)	16,672 (36,755)	…	…	No	64	66	37–63	1–35	9–27
3	…	BEU	2057 × 1016 (81 × 40)	152 × 2,286 × 6,096 (6 × 90 × 240)	16,672 (36,755)	…	…	Yes	58	68	47–66	13–34	23–34
4	2	BED	2794 × 1016 (110 × 40)	95 × 3,353 × 13,716 (3.75 × 132 × 540)	34,386 (75,806)	0.011	0.0082	No	59	60	46–55	0–34	7–34
5	…	BED	2794 × 1016 (110 × 40)	95 × 3,353 × 13,716 (3.75 × 132 × 540)	34,386 (75,806)	…	…	Yes	60	61	33–46	3–25	4–10
6	3	BED	2083 × 864 (82 × 34)	152 × 2,286 × 6,096 (6 × 90 × 240)	16,672 (36,755)	0.017	0.0018	No	62	64	53–68	6–37	4–25
7	…	BEU	2057 × 1016 (81 × 40)	152 × 2,286 × 6,096 (6 × 90 × 240)	16,672 (36,755)	…	…	No	64	65	57–65	10–47	20–35
8	…	BEU	2057 × 1016 (81 × 40)	152 × 2,286 × 6,096 (6 × 90 × 240)	16,672 (36,755)	…	…	Yes	68	59	19–63	21–47	23–59
9	4	BED	2794 × 1016 (110 × 40)	95 × 4,699 × 10,973 (3.75 × 185 × 432)	38,554 (84,995)	0.023	0.0011	No	68	69	64–73	3–64	10–60
10	…	BED	2794 × 1016 (110 × 40)	95 × 4,699 × 10,973 (3.75 × 185 × 432)	38,554 (84,995)	…	…	Yes	68	60	57–67	7–45	0–10

(a) Achieving a minimum through-thickness ductility (%RA) is not a requirement in either MIL-S-16216K (SH) or its predecessor MIL-S-16216J (SH) specification.
Source: Adapted from Ref 6

cation of test blocks (Ref 15). Second, thicker plates generally had higher aluminum content in both ladle and plate. It appeared that the steel producer had consciously controlled the aluminum content of the ladle at a higher value when the heat was later processed to a heavy-gauge plate. In particular, heavy-gauge plates (95 mm or 3¾ in. and over) showed a minimum of 0.024 wt.% Al.

Recent changes to steel manufacturing practices, which simultaneously reduced both aluminum and sulfur contents of melts, appeared to promote an undesirable effect, especially during the later stages of solidification of very large-size ingots. Aluminum in steel is known to serve several purposes; chiefly, aluminum deoxidizes the melt, affects melt fluidity, reduces elemental segregation by promoting columnar to equiaxed transition, and reduces the overall hardenability through the effect of refined grain size of end products. In steels, "deoxidation has been found to affect fluidity, both insufficient deoxidation and overdeoxidation causing decreased fluidity" (Ref 17). The fluidity issue may manifest more dramatically when very large-size, voluminous melts are teemed into very large-size ingots.

It appeared that a simultaneous, though well-intended, reduction in both aluminum and sulfur contents of the melt perhaps significantly reduced melt fluidity and allowed feeding difficulties to occur, especially at the later stages of solidification of very large ingot. These difficulties likely caused shrinkage cavities to develop near the ingot top while increasing the degree of chemical segregation, thereby leading to retention of poorly consolidated regions during plate manufacturing.

This comparative analysis indicates that aluminum and sulfur contents of very large-size HY-100 steel melts used for producing very large-size heavy-gauge plates must be restored to the 1983 First Article qualification test practice levels. Restoration to 1983 First Article practice offered the most cost-effective means to obtain fully consolidated heavy-gauge steel plates with required through-thickness ductility for critical U.S. Navy applications. Future drafting of supplementary requirements of procurement specification of heavy-gauge HY-100 plates is expected to benefit directly from this finding.

5. Conclusions

These two U.S. Navy-related case studies clearly illustrate both the need to strengthen materials specification and how the materials community can remain vigilant in adopting innovative methods and renewed understanding of the relationships among chemical composition, processing, microstructure, and mechanical properties for a continuous strengthening of materials specifications.

References

1. "Navy Ships: Lessons of Prior Programs May Reduce New Attack Submarine Cost Increases and Delays," GAO Report to Congressional Requesters, GAO/NSIAD-95-4, U.S. General Accounting Office, Oct 1994, p 7
2. K. Sampath, Constraints-Based Modeling Enables Successful Development of a Welding Electrode Specification for Critical Navy Applications, *Welding J.,* Vol 84 (August), 2005, p 131s-138s
3. "Electrodes and Rods: Welding, Bare, Solid, or Alloy Cored; and Fluxes, Low Alloy Steel," MIL-E-23765/2E (SH), April 1994
4. "Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding," A5.28 American Welding Society, 2005
5. "Steel Plate, Alloy, Structural, High-Yield Strength (HY-80 and HY-100)," MIL-S-16216K (SH), June 1987
6. K. Sampath, Meeting Specification, Failing Expectations, *Conf. Proc. Use of Bainitic and Bainitic-Martensitic Steels in Current or Developing Applications,* Sept. 2004 (New Orleans, LA), MS&T, p 425-432
7. P.W. Holsberg and R.J. Wong, Welding of HSLA-100 for Naval Applications, in *Weldability of Materials,* R.A. Patterson and K.W. Mahin, Ed., ASM International, 1990, p 219-239
8. W. Steven and A.G. Haynes, The Temperature of Formation of Martensite and Bainite in Low-Alloy Steels, *J. Iron Steel Inst.,* Vol 183 (No. 8), 1956, p 349-359
9. K.J. Irvine and F.B. Pickering, Low-Carbon Bainitic Steels, *J. Iron Steel Inst.,* Vol 184 (No. 12), 1957, p 292-309
10. W.C. Leslie, *The Physical Metallurgy of Steels,* McGraw-Hill International Book Co., Kogakusha, Inc., Tokyo, Japan, 1981, p 201-205
11. N. Yurioka, H. Suzuki, S. Ohshita, and S. Saito, Determination of Necessary Preheating Temperature in Steel Welding, *Welding J.,* Vol 62 (No. 6), 1983, p 147s-153s
12. R.J. Wong and M.D. Hayes, *The Metallurgy, Welding and Qualification of Microalloyed (HSLA) Steel Weldments*, American Welding Society, 1990, p 450-489
13. K. Sampath, R.S. Green, D.A. Civis, H. Dong, and P.J. Konkol, Evaluation of New High-Performance Electrodes for GMA Welding of HSLA-100 Steel, in *High Performance Structural Steels,* R. Asfahani, Ed., ASM International, 1995, p 179-188
14. P. Jhaveri, W.G. Moffatt, and C.M. Adams, Jr., The Effect of Plate Thickness and Radiation on Heat Flow in Welding and Cutting, *Welding J.,* Vol 41 (No. 1), 1962, p 12s-16s
15. Heavy-Gauge Steel Plate Manufacturer's Report, June 27, 1983, on Testing for Waiver of First Article Inspection Clause in MIL-S-16216J (SH), April 10, 1981, including Amendment 1, August 16, 1982
16. "NCEMT TR 00-69," Concurrent Technologies Corporation, Johnstown, PA, 2000
17. R.W. Heine, C.R. Loper, and P.C. Rosenthal, *Principles of Metal Casting,* Tata McGraw-Hill Publishing Co., New Delhi, India, 1976, p 414