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Weldability of HSLA-65 Steel for Ship Structures

The higher strength and improved weldability of HSLA-65 steel provides advantages over conventional DH-36 steel for ship structures

BY P. J. KONKOL, J. L. WARREN and P. A. HEBERT

ABSTRACT. HSLA-65 steel (ASTM A945) is being considered to replace higher strength steels (HSS) such as DH-36. However, the 70-series consumables (70 ksi [482 MPa] minimum transverse weld tensile strength) used to join HSS (71 ksi [489 MPa] tensile strength) could produce a welded joint in HSLA-65 (78 ksi [537 MPa] tensile strength) with undermatched strength. The objective of this study was to determine the procedure limits for welding HSLA-65 with 70-series consumables.

Multipass weldments were made and evaluated in ½- to 1¼-in. (13 to 32 mm) thick HSLA-65 and ⅝-in. (16 mm) thick DH-36 steel plates by shielded metal arc (SMA), flux cored arc (FCA), gas metal arc (GMA) and submerged arc welding (SAW) at weld cooling rates from 3 to 75°F/s (1.7–42°C/s). Additional one-sided, high-energy-input, single-pass, multiwire submerged arc weldments were made with weld cooling rates less than 1°F/s (0.55°C/s).

The results showed that there was no cracking in the weld metal or heat-affected zone (HAZ) and that HSLA-65 did not exhibit excessive hardness or softness in the HAZ. Transverse weld tensile strengths were above the 78 ksi minimum specified. The measured HAZ CVN toughness in multipass welds was influenced by the toughness of the adjacent weld metal, but was capable of meeting base metal requirements. The single-pass, high-energy-input submerged arc weldments exhibited reduced HAZ CVN toughness; however, the degradation was not as severe when compared to the DH-36 HAZ toughness. The CVN toughness values of the weld metals at low weld cooling rates were lower than values obtained in electrode conformance testing. Weld metal toughness criteria need to be established for the intended applications.

Results from this study indicate that HSLA-65 can be welded using 70-series consumables over the range of procedures and cooling rates commonly used in shipyard fabrication while exhibiting adequate soundness and meeting specified minimum transverse weld tensile strength.

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Introduction

Historically, higher strength steels (HSS) are used in naval and commercial ship structural applications. These steels are typically produced by conventional hot rolling and/or normalizing to achieve the required mechanical properties. A typical grade is American Bureau of Shipping (ABS) grade DH-36, with a specified minimum yield and tensile strength of 51 and 71 ksi (351 and 489 MPa), respectively (Ref. 1). Steel producers are introducing newer production technologies to achieve improved strength, toughness and weldability in high-strength, low-alloy (HSLA) steels by combinations of such methods as 1) reduced carbon, alloy and residual element content, 2) microalloying (Nb, V, Ti), 3) controlled (low finishing temperature) rolling, 4) accelerated cooling from the rolling temperature and 5) direct quenching after rolling. The last three methods are known as thermomechanical controlled processing (TMCP). The objective of the above methods is to achieve a very fine ferrite grain size, which improves both strength and toughness.

KEY WORDS

HSLA-65
ASTM A 945
HAZ Toughness
Weld Metal Toughness
SMAW
GMAW
FCAW
SAW

Steel producers have demonstrated the ability to provide HSS with actual yield strengths of 65 ksi (448 MPa) and higher in lighter sections (up to 1¼ in. [32 mm] thick) when furnished to HSS requirements. The U.S. Navy is considering procuring structural steel, designated HSLA-65, to a new material specification with a 65 ksi minimum yield strength and 78 ksi (537 MPa) minimum tensile strength. The American Society for Testing and Materials (ASTM) has issued a material specification, A945 (Ref. 2), for procurement of HSLA-65. The chemical composition and mechanical property requirements for HSLA-65 are compared with HSS grade DH-36 in Tables 1 and 2.

To permit weight savings in ship construction and life-cycle costs through reduced component section thickness, HSLA-65 steel is being considered to replace, where feasible, HSS grades such as DH-36. To avoid associated increased fabrication costs, welding procedures and consumables already approved for joining HSS (70 series) are being evaluated for joining HSLA-65. Because the specified minimum transverse weld tensile strength for the 70-series consumables is 70 ksi (482 MPa), there was concern that the weld metals may, under certain conditions, be undermatching in both yield and tensile strength depending upon the consumables, procedures and techniques used in HSLA-65 weldments. Additionally, because the chemical composition and processing of HSLA-65 may differ from HSS, the effects of welding on

Table 1 — Chemical Composition Requirements for DH-36 and HSLA-65

Steel Type	C[a]	Mn	P	S	Si	Ni	Cr	Mo	Cu	Cb	V	Al	CE[d]	Pcm[e]
DH-36 (HSS)[b]	0.18	0.90–1.60	0.04	0.04	0.10–0.50	0.40	0.25	0.08	0.35	0.05	0.10	—	0.40	0.24
HSLA-65 (A945)[c]	0.10	1.10–1.65	0.025	0.010	0.10–0.50	0.40	0.20	0.08	0.35	0.05	0.10	0.08	0.37	0.17

(a) Single values are maximums.
(b) Per ABS Rules.
(c) Per ASTM A945.
(d) Typical carbon equivalent based on CE = C + Mn/6 + (CR + Mo + V)/5 + (Ni + Cu)/15.
(e) Typical carbon equivalent based on Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B.

Table 2 — Mechanical Property Requirements for DH-36 and HSLA-65 Steel

	Tensile Properties[a]				Charpy V-Notch Toughness (ft-lb)	
	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)		Longitudinal	Transverse
			8-in. gauge	2-in. gauge		
DH-36	51 min. (351 MPa)	71–90 (489–620 MPa)	19	22	25 @ −4°F (34 J @ −10°C)	17 @ −4°F (23 J @ −10°C)
HSLA-65	65 min. (448 MPa)	78–100 (537–689 MPa)	18[b]	22[b]	30 @ −40°F (41 J @ −40°C)	20 @ −40°F (27 J @ −40°C)

(a) For plates wider than 24 in., the test specimen is taken in the transverse direction.
(b) For plates wider than 24 in., the elongation requirement is reduced by two percentage points.

the properties of the HAZ, such as hardness, toughness and cracking susceptibility, need to be established.

The objective of this evaluation was to determine the procedure limits for welding HSLA-65 with 70-series consumables using representative shipyard processes and procedures. Weldments were made in commercially produced HSLA-65 by multipass shielded metal arc welding (SMAW), flux cored arc welding (FCAW), gas metal arc welding (GMAW) and submerged arc welding (SAW), and by single-pass, one-side, multiwire SAW. Select weldments were also made in DH-36 for comparison. Nondestructive inspection, transverse weld tension, longitudinal weld-metal tension, Charpy V-notch (CVN) toughness and Vickers hardness tests were conducted. The results are described herein.

Experimental Procedure

Description of Steels Used

Six different types of HSLA-65 and two types of HSS (DH-36) from four commercial producers were used in the welding trials. The plate descriptions are shown in Table 3. ASTM A945 permits HSLA-65 to be produced by any of several practices, including normalizing, quenching and tempering (Q&T) and thermomechanical controlled processing (TMCP), which includes controlled rolling (CR), accelerated cooling (AC) and direct quenched and tempering (DQT). To date, only Q&T and CR have been used to produce HSLA-65. HSS has historically been produced by hot rolling or normalizing, but about half of current production of HSS is by CR. The microstructures of a CR HSLA-65 plate and a CR DH-36 plate are shown in Fig. 1. The reduced carbon content and more intensive CR of the HSLA-65 result in less pearlite banding and a finer ferrite grain size than in the DH-36.

Multipass SMAW, FCAW, GMAW and SAW Parameters

Nineteen multipass weldments were made with the SMAW, FCAW, GMAW and SAW processes using parameters representative of the lowest and highest weld cooling rates in normal shipyard production. Representative nominal parameters and welding consumables are shown in Table 4. The groove geometry was a type B2(S)V.2 per MIL-STD-22D (Ref. 3) (single bevel) in an effort to obtain a near straight-sided HAZ for notch toughness testing. Welding was performed in the 1G (flat) position for GMAW and SAW and both 1G and 3G (vertical) for SMAW and FCAW. The weld

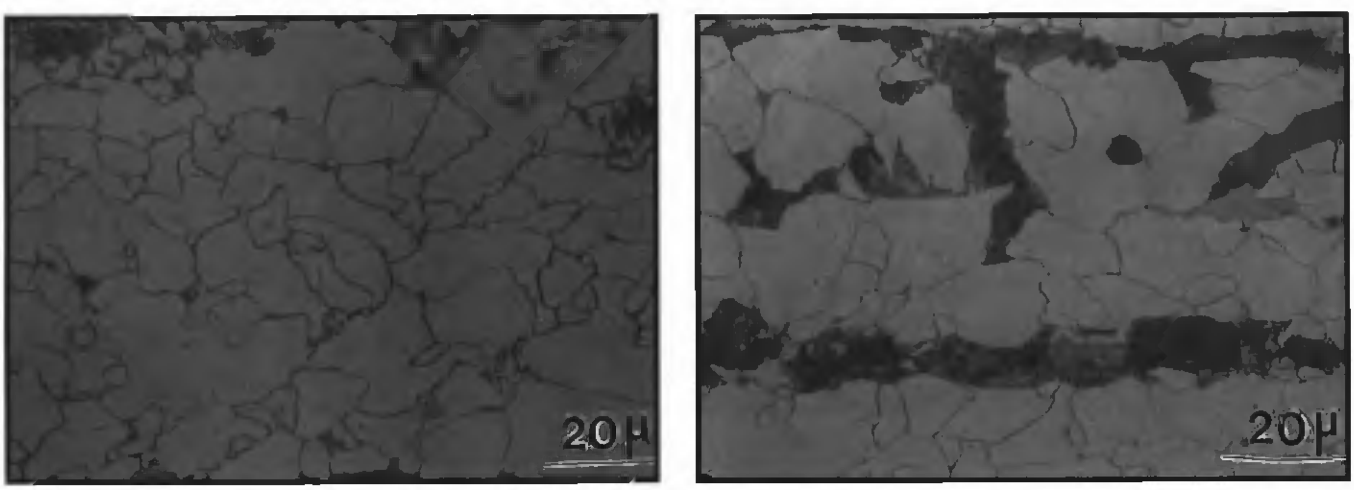

Fig. 1 — Microstructures of ⅜-in. thick HSLA-65 and HSS (DH-36) plates. A — Control-rolled HSLA-65, Steel B; B — control-rolled HSS, Steel C.

metal cooling rates were calculated using modifications to the Rosenthal equation, which incorporates process-specific parameters (Ref. 4). All weldments were inspected by visual, magnetic particle, radiographic and ultrasonic testing per the relevant NAVSEA standards and acceptance criteria for surface ship fabrication. Three of the weldments initially contained rejectable porosity or incomplete fusion, which were repaired prior to subsequent testing.

Single-Pass, Multiwire SAW Parameters

Shipyards may employ a single-pass, one-sided, SAW process in which two or three large-diameter electrodes are fed into a common molten weld pool. The choice of number of electrodes and energy input is usually governed by the plate thickness and the weld bead geometry consistent with sound welding practice. However, to determine the effects of extremely high energy input, *i.e.*, the worst-case condition parameters on the mechanical properties of HSLA-65, several plates of HSLA-65 were joined by the three-wire SAW process at excessively high energy input. Similar weldments were made in DH-36 for comparison. The weldments were made using three electrodes in a single pass from one side in a single-V groove, with the root supported by a flux-covered copper backing bar. The welding parameters are shown in Table 5. For each steel, two different electrode types were used: Class EL8 per AWS A5.17 (Ref. 4), which is a carbon-manganese steel composition, and Class EA1 per AWS A5.23 (Ref. 7), which is a carbon-manganese-molybdenum low-alloy steel composition. Normally, a two-electrode technique would be used for the ⅝-in. thick (16 mm) weldments, but for these weldments three electrodes were used to achieve the highest possible energy input. The weldments were examined by ultrasonic inspection. The weldments were sound, except for one small region of centerline cracking that was attributed to nonoptimum welding parameters.

Mechanical Testing of Weldments

Each weldment was machined into two transverse weld, reduced-section tensile specimens, two longitudinal all-weld-metal tensile specimens and several sets of weld-metal and HAZ Charpy V-notch (CVN) specimens in accordance with AWS B4.0 (Ref. 8). For the multipass welds, each set consisted of five CVN specimens per test temperature with the upper surface of the specimen located $1/16$ in. (1.6 mm) below the plate surface. For the single-pass welds, only two specimens per test temperature and location were obtained. One set of HAZ CVN specimens was located with the centerline of the notch on the weld interface and one set with the centerline of the notch in the HAZ 1 mm (0.04 in.) away from the weld interface. In several weldments additional sets of CVN specimens were obtained with the notch located 5 mm (0.20 in.) away from the weld interface and in unaffected plate material. The side of the weldment that contained the more near-vertical weld interface was used for the HAZ notch locations. Representative sections of ½-in. (13-mm) and 1¼-in. (32-mm) thick weldments with the CVN notch tip locations for the weld interface and 1- and 5-mm HAZ locations are shown in Figs. 2A and 2B, respectively. For the single-pass submerged arc weldments, the position of the notch was also located in the HAZ as close as possible to the weld interface, similar to that described in MIL-STD-248D (Ref. 9) and in Appendix III to the AWS *Structural Welding Code — Steel* (Ref. 9) (identified here as "All HAZ"). The CVN requirements for HSLA-65 weld metals and HAZ have not been established; thus, the weld metals were generally tested at –20°F (–29°C) to compare values with the filler metal specification requirements and the HAZs were tested at –40°F (–40°C), to compare with the base metal requirements. Representative weld metals were also tested at –40°F (–40°C), because the ABS rules (Ref. 1) state that, for steels not listed in the rules, the weld metal toughness must meet the base metal requirements. The single-pass submerged arc weld metals and HAZs were also tested at –4°F (–10°C) to compare with DH-36 base metal requirements. On representative weldments, Vickers hardness traverses using a 1-kg load were obtained on transverse sections across the weld region $1/16$ in. below the plate surface.

Table 3 — Descriptions of DH-36 and HSLA-65 Plates Used

Code	Steel Type	Processing	Thickness (in.)
A	HSLA-65	Quenched & Tempered	½ (13 mm)
B	HSLA-65	Control Rolled	⅝ (16 mm)
C	DH-36	Control Rolled	⅝ (16 mm)
D	DH-36	Normalized	⅝ (16 mm)
E	HSLA-65	Quenched & Tempered	1-¼ (32 mm)
F	HSLA-65	Control Rolled	½ (13 mm)
G	HSLA-65	Control Rolled	¾ (19 mm)
H	HSLA-65	Control Rolled	1 (25 mm)

Table 4 — Nominal Multipass Welding Parameters

Process	Electrode	Shielding gas or flux	Thickness (in.)	Preheat/ interpass Temperature (°F)	Energy input (kJ/in.)	Cooling rate @ 1000°F (°F/s)
SMAW	MIL-7018M	—	½	70/450	55	9
			1-¼	70/150	45	60
FCAW	MIL-71T-1HYM	Ar + 25% CO_2	½	70/200	52	12
			1-¼	100/150	43	67
GMAW	MIL-70S-3	Ar + 5% CO_2	½	70/200	51	13
			1-¼	70/150	40	69
SAW	EM12K, EM13K,	MIL-F2, MIL-F3	½	70/200	66	3
	EL12		1-¼	70/150	45	39

Table 5 — Single-Pass, Multiwire Submerged Arc Welding Parameters

Electrode	Flux	Plate thickness (in.)	Energy input (kJ/in.)	Cooling rate @ 1000°F (538°C) (°F/s)
EL8, EA1	PFI-50	⅝ (16 mm)	294 (11.6 kJ/mm)	0.4 (0.22°C/s)
		1-¼ (32 mm)	490 (19.3 kJ/mm)	0.4 (0.22°C/s)

Results and Discussion

Mechanical Properties of SMA Weldments

The tensile and CVN toughness properties of the SMA weldments, arranged in order of increasing weld cooling rate, are shown in Appendix Table A-1. The all-weld-metal yield and tensile strengths and transverse weldment tensile strength values are summarized in Fig. 3A. Only the weld metal CVN values at –20°F and HAZ values at –40°F (1-mm location) are summarized in Fig. 3B for comparison

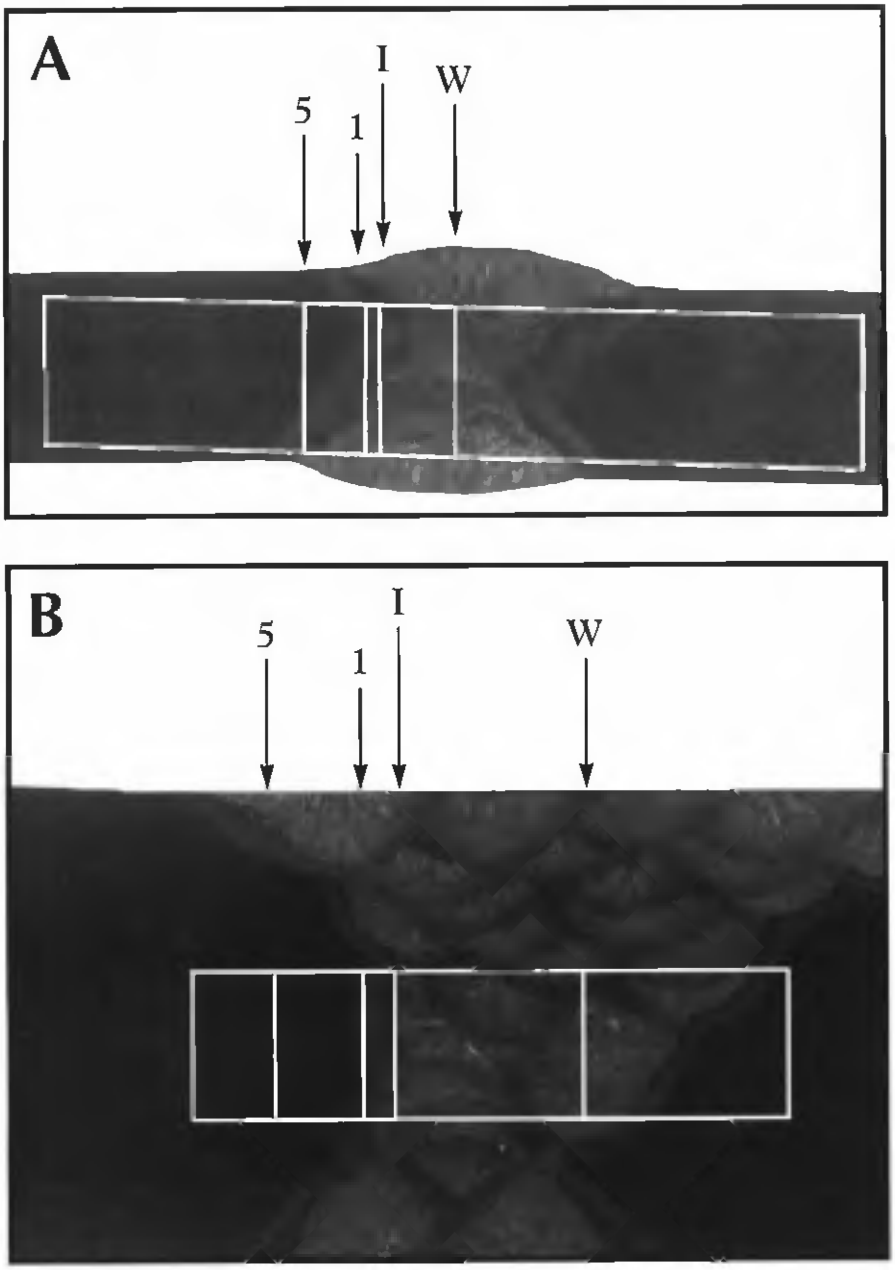

Fig. 2 — Transverse weldment sections showing locations of Charpy V notch. A — ½ in. FCA Weldment 3; B — 1¼-in. submerged arc Weldment 9. W = weld metal, I = weld interface, 1 = 1 mm, 5 = 5 mm.

with electrode and base metal specifications, respectively. As is required for welding procedure qualification, the transverse weld tensile strengths readily exceeded the 78 ksi minimum specified for HSLA-65 base metal. The base metal fractures occurred away from the HAZ and exceeded 78 ksi tensile strength, indicating that the MIL-7018M electrodes provided sufficient strength to be used for HSLA-65 materials. The all-weld-metal tensile data show that, with the exception of a marginally low tensile strength for Weldment 1, the weld metals met the specified minimum HSLA-65 base metal requirements for yield strength, tensile strength and elongation. As expected, the weld metal yield and tensile strengths generally increased with increased weld cooling rate. Weldment 14 was essentially a duplicate of Weldment 1 but with a 15/16-in. (24-mm) root opening (vs. 0–3/16 in. [5 mm] for all other weldments) to determine whether base metal dilution or admixture or a wider band of potentially undermatched strength weld metal would affect joint strength and thus joint efficiency. As shown, the large root opening had little effect on weldment strength, principally because the weld metal properties did not change significantly.

The CVN toughness results for the SMA weldments (Fig. 3B and Appendix Table A-1) show that the HSLA-65 base metal requirement of 20 ft-lb (27 J) at –40°F was readily met in the weld metal and HAZ. The 50 ft-lb (68 J) at the –20°F requirement specified for MIL-7018M quality conformance testing (Ref. 11) was not met at the low weld cooling rates; however, quality conformance testing conditions are generally more favorable for obtaining higher weld metal CVN values than the thinner section, narrow root, higher deposition rate weldments in the present study. Weldment 14, deposited with the 15/16-in. root opening, exhibited improved weld metal toughness compared to Weldments 1 and 5, indicating that weld joint design and welding technique can also affect weld metal CVN values. The HAZ CVN values exhibited wide variations, both within a set and among the weldments, but still meet the HSLA-65 base metal requirements. The variation in values is attributed to the difficulty in measuring HAZ toughness by the CVN test, particularly in a multipass weldment, in which it is difficult to obtain a straight-sided weld interface and HAZ.

Mechanical Properties of FCAW Weldments

Figure 4A and Appendix Table A-2 show that the MIL-71T-1 weld metals readily exceeded the HSLA-65 specified 78 ksi minimum tensile strength at all cooling rates and all transverse weld tensile specimens fractured in the base metal. However, the weld metal CVN toughness was often low (Fig. 4B), lower than the 20 ft-lb at –20°F specified in electrode conformance testing (Ref. 12), especially at low weld cooling rates. The HAZ toughness also appeared to be low; however, as will be discussed, the low HAZ toughness is attributed to the low weld metal toughness, in which CVN specimens at the weld interface and 1-mm location often contain significant amounts of weld metal under the notch region. As shown in the Appendix tables, the HSLA-65 base metals exhibited excellent CVN toughness.

Two of the weldments (15 and 16) were made in HSS (DH-36) base metal to provide a direct comparison with the HSLA-65 weldments (Weldments 3 and 10). It initially appeared that use of HSS resulted in better weld metal toughness; however, metallographic examination of Weldments 3 and 15 indicated that Weldment 15 had been weld-repaired, which resulted in substantial grain refinement due to the additional weld passes, thus improving the weld toughness. (Samples of Weldments 10 and 16

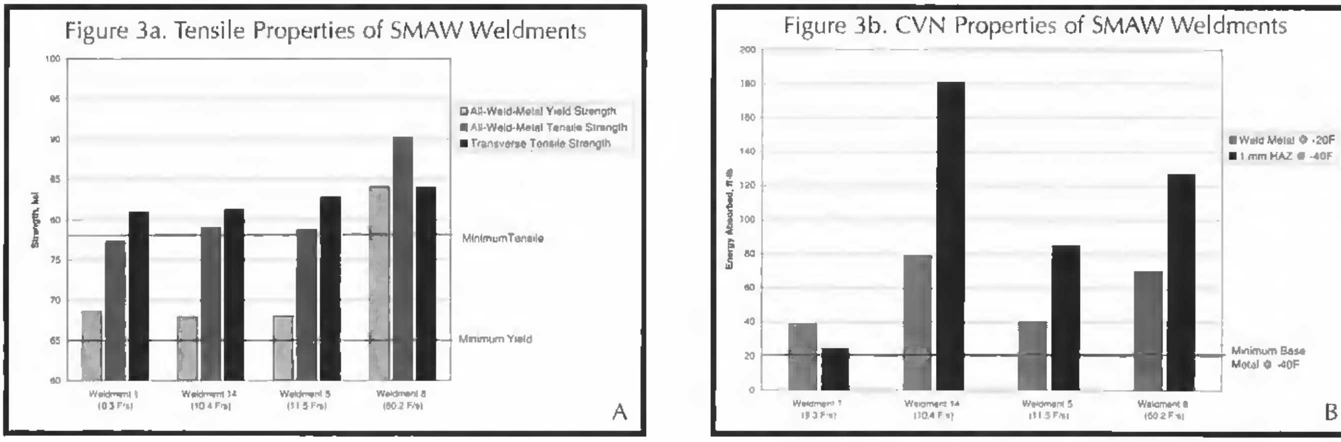

Fig. 3 — A — Tensile properties of SMA weldments; B — CVN properties of SMA weldments.

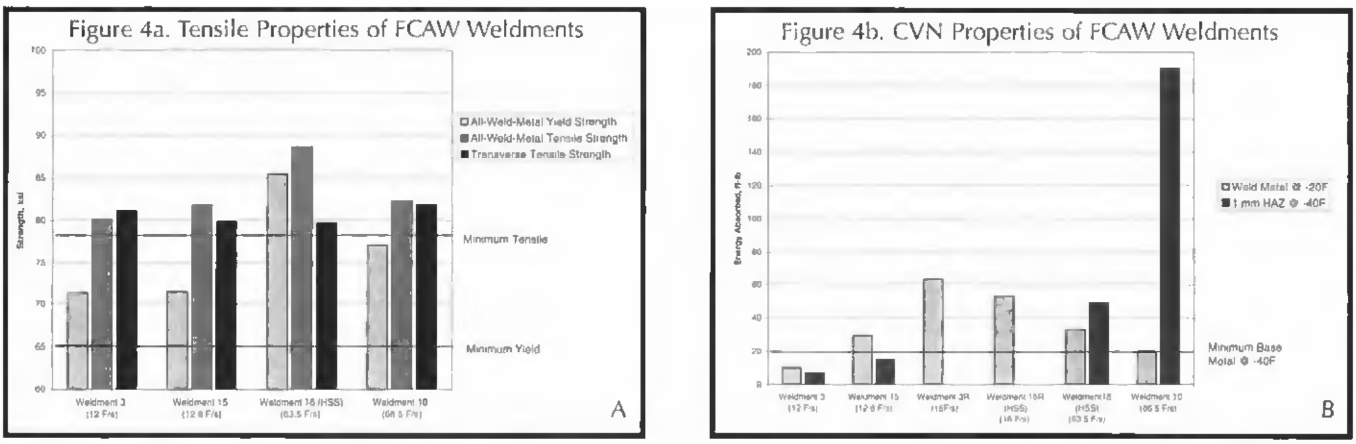

Fig. 4 — A — Tensile properties of FCA weldments; B — CVN properties of FCAW weldments.

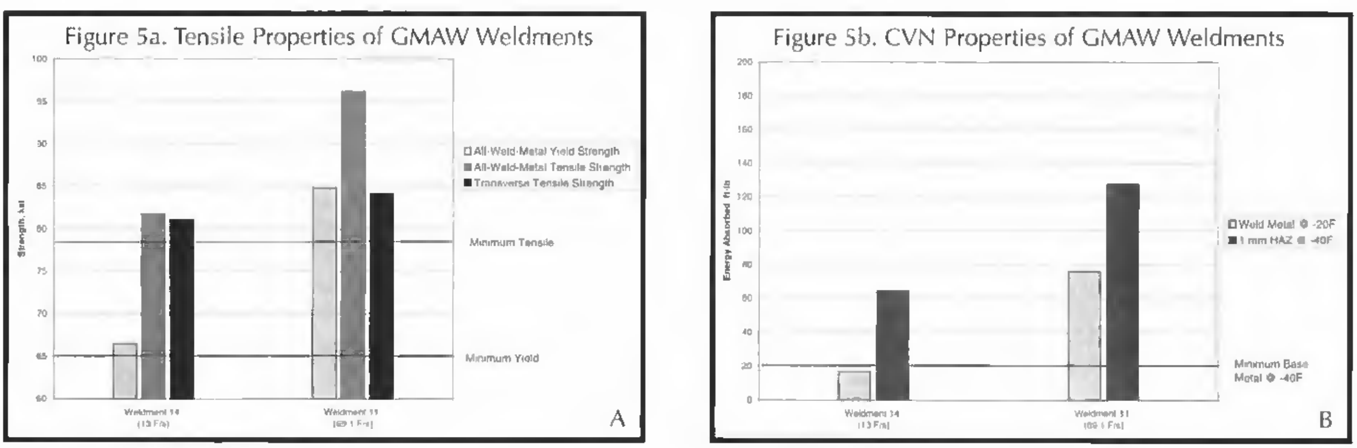

Fig. 5 — A — Tensile properties of GMA weldments; B — CVN properties of GMA weldments.

were not available for microstructural comparison.) To verify that base metal type (HSLA-65 vs. HSS) should not significantly affect weld metal toughness in multipass welding, two additional weldments, 3R and 15R, were fabricated using conditions similar to Weldments 3 and 15 except that the repeat weldments were ⅝ in. thick compared to ½ in. thick for the original weldments. As shown, the weld metal CVN toughness was similar regardless of base metal type. Additionally, the weld metal toughness of the repeat welds was substantially higher than in the original weldments, indicating that welding technique can have a major effect on CVN toughness.

Mechanical Properties of GMAW Weldments

As shown in Fig. 5A and Appendix Table A-3, the MIL-70S-3 weld metal easily met the HSLA-65 specified tensile requirements at the low weld cooling rate and greatly exceeded the requirements at the fast cooling rate, although adequate

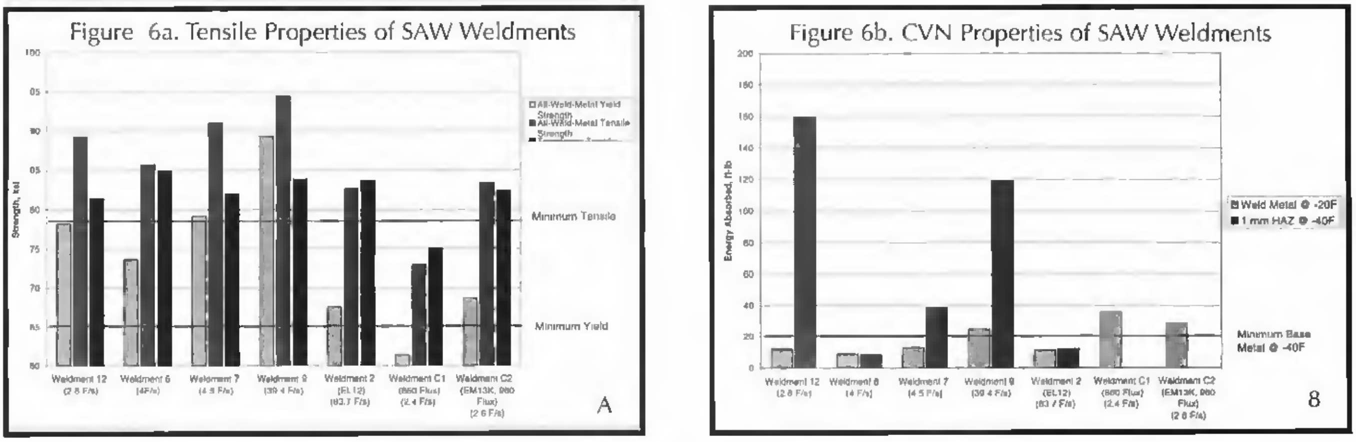

Fig. 6 — A — Tensile Properties of submerged arc weldments; B — CVN properties of submerged arc weldments.

ductility was still achieved.

The weld metal CVN toughness was high in the fast cooling rate weld metal, (Fig. 5B), but marginally failed the 20 ft-lb at –20°F specified for the electrode conformance testing (Ref. 13).

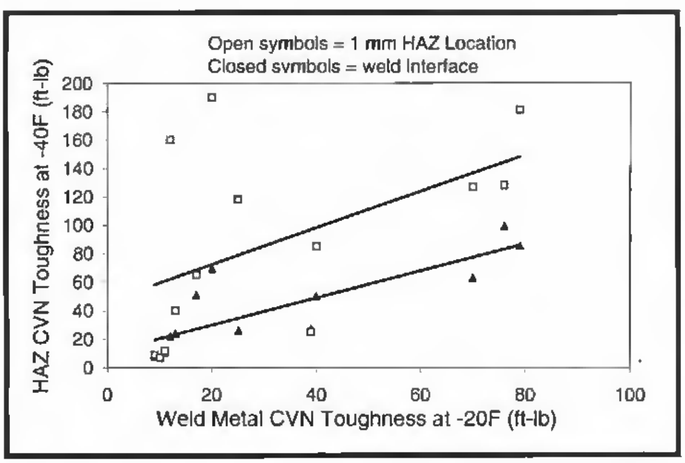

Fig. 7 — Effect of weld metal toughness on measured HAZ toughness.

Mechanical Properties of Submerged Arc Weldments

Figure 6A and Appendix Table A-4 show that, with the proper electrode/flux combination, the specified 78-ksi minimum transverse weld tensile strength for HSLA-65 submerged arc weldments can be achieved, even at cooling rates as low as 2.6°F/s (1.4°C/s). As shown for Weldment C1, when the all-weld-metal yield and tensile strengths are below the minimums specified for HSLA-65 base metal, fracture in the transverse weld tensile test occurs in the weld metal below 78 ksi. This confirms that for pure tension loading, the weld metal must be matching or overmatching in tensile strength (Ref. 14). The weld metal CVN toughness is also dependent upon the electrode/flux combination. As shown in Fig. 6B, the EM12K electrode with flux 780 resulted in very low CVN toughness at –20°F when deposited at very low weld cooling rates (Weldments 12, 6 and 7). Use of flux 860 improved toughness but at the expense of weld metal yield and tensile strength (Weldment C1). Use of flux 960 with EM13K electrode resulted in the best combination of strength and toughness (Weldment C2) and would satisfy AWS F7A2-EM13K conformance test requirements of 20 ft-lb at –20°F (Ref. 5).

Effect of Weld Metal Toughness on Measured HAZ Toughness

As mentioned above, it is difficult to obtain meaningful measurement of the CVN toughness in the HAZ of a multipass weldment because of the often irregular

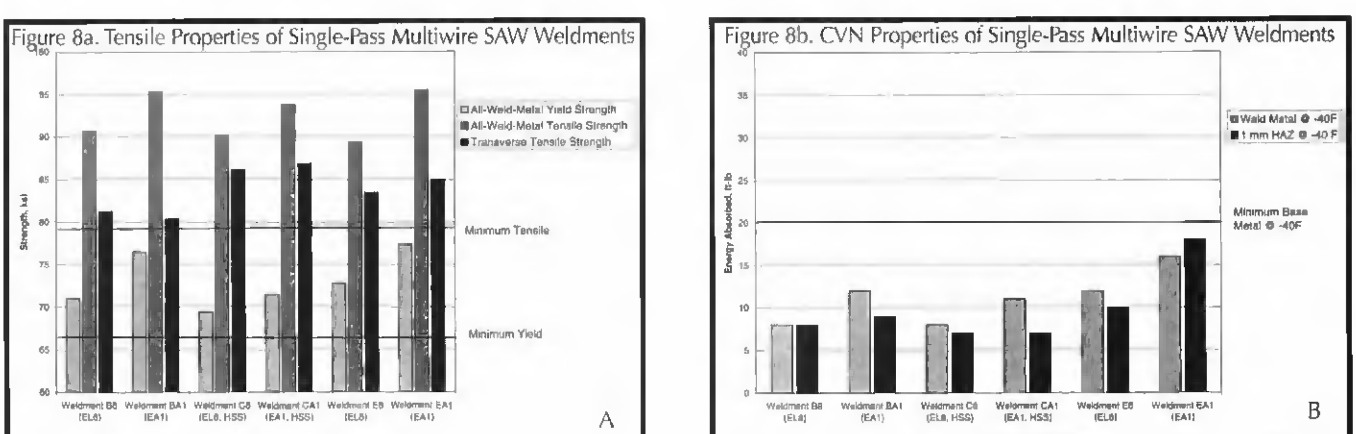

Fig. 8 — A — Tensile properties of single-pass, multiwire submerged arc weldments; B — CVN properties of single-pass, multiwire submerged arc weldments.

shape of the weld interface. Figures 2A and 8 show the locations of the Charpy V notch for the weld interface, 1-mm and 5-mm locations on the vertical side of the weld groove. The weld interface and 1-mm locations will contain varying amounts of weld metal, coarse-grain HAZ, fine-grain HAZ and base metal under the Charpy V notch, depending upon the particular local geometry of the weld interface. As can be seen in Fig. 2A, the weld interface and 1-mm locations contain significant amounts of weld metal in the plate of the notch. Thus, the measured HAZ toughness would be affected by the weld metal toughness. This effect is shown in Fig. 7, which plots HAZ CVN toughness vs. weld metal CVN toughness for the multipass HSLA-65 weldments. (The HAZ was tested at −40°F for comparison with the base metal specification, and the weld metal was tested at −20°F to compare with electrode specifications.) In spite of the scatter, there is a clear trend of decreasing HAZ toughness with decreasing weld metal toughness. The only HAZ values that fall below the 20 ft-lb at −40°F specified for HSLA-65 were associated with weld metals that exhibited less than 20 ft-lb at 0°F. For specimens in which the notch could be located entirely within the HAZ, it is still possible for the surrounding base metal or weld metal to affect notch toughness values. Compared to a sharp-notched fracture toughness specimen (e.g., CTOD), the blunt Charpy V notch creates a large plastic zone in ductile material that may encompass the adjacent base metal and/or weld metal (Ref. 6). If a steep gradient in toughness exists from the HAZ to a low toughness weld metal, the crack will tend to divert into the adjacent weld metal even though it may exhibit greater hardness (Ref. 15).

Some loss in HAZ toughness from the base metal toughness of HSLA-65 is to be expected due to the known effects of increased prior-austenite and ferrite grain size, precipitate coarsening, release of combined nitrogen and development of residual stresses. It appears that although the HSLA-65 HAZ toughness in multipass welds is somewhat lower than the excellent base metal values observed, it is still higher than some of the low toughness weld metals and would meet HSLA-65 base metal CVN requirements.

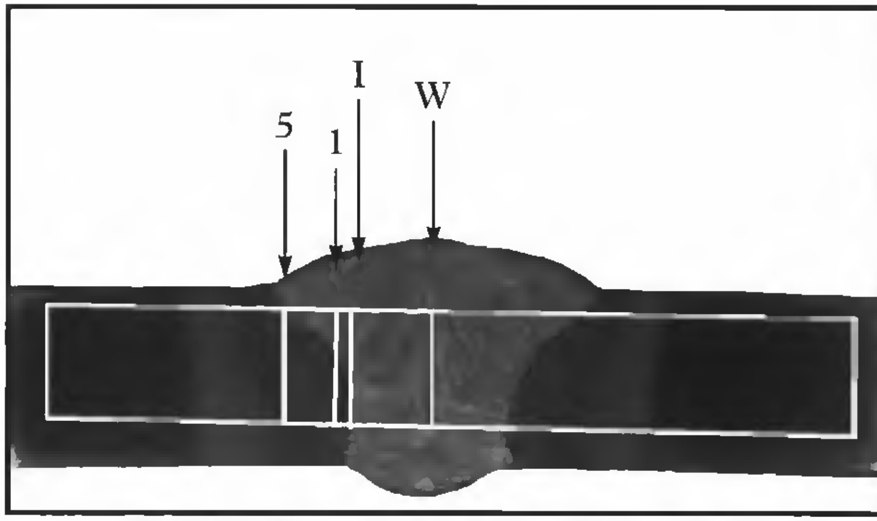

Fig. 9 — Transverse weldment sections showing locations of Charpy V notch in ⅝-in., single-pass submerged arc weldment.

Mechanical Properties of Single-Pass Submerged Arc Weldments

As shown in Fig. 8A and Table A-5, all specimens fractured in the base metal, which indicates that the EL8/PFI-50 and EA1/PFI-50 electrode/flux combinations result in overmatching strength weld metals at the extremely high energy inputs used (294 and 494 kJ/in. [11.6 and 19.5 kJ/mm] for the ⅝- and 1¼-in.-thick weldments, respectively). The fracture locations were in unaffected base metal, away from the HAZ, indicating that the HAZs of neither the HSLA-65 nor the DH-36 were excessively softened by the resultant low weld cooling rates. The tensile strengths readily met the 78 ksi minimum specified for HSLA-65. The yield and tensile strengths and ductility of the all-weld-metal tensile specimens readily met the HSLA-65 base metal requirements. As expected, the low-alloy EA1 weld metals were several ksi higher in strength and slightly lower in ductility than the carbon-manganese EL8 weld metals

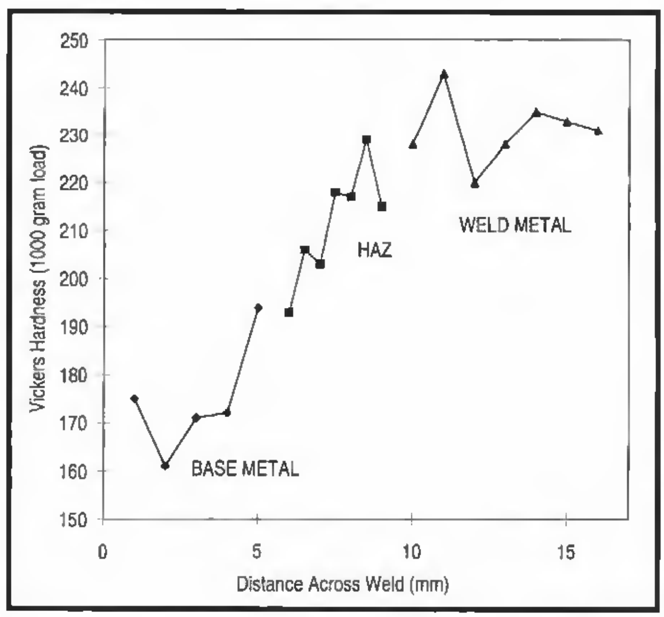

Fig. 10 — Microhardness of HSLA-65 single-pass, multiwire submerged arc Weldment B8.

The EA1 weld metals are generally higher in CVN toughness than the EL8 weld metals — Fig. 8B. The weld metals do not meet the HSLA-65 requirement of 20 ft-lb at −40°F, but they do meet the DH-36 requirement of 17 ft-lb (23 J) at — 4°F, Appendix Table A-5. As mentioned previously, the objective of this task was not to optimize a procedure for single-pass, one-sided SAW of HSLA-65 but to evaluate the weldments under worse- case welding conditions.

The HAZ toughness in these weldments exhibited a substantial drop in CVN toughness compared to the base metals. Although the HSLA-65 HAZ values are low (17–92 ft-lb [23–125 J] at −4°F), the DH-36 is even lower (6–23 ft-lb [8–31 J] at −4°F). Thus, the HAZ of both steels would not meet their respective CVN requirements for HSLA-65 and DH-36 base metal. In addition to the factors discussed for multipass welds, the low values can be attributed to the extremely low cooling rate of 0.4°F/s

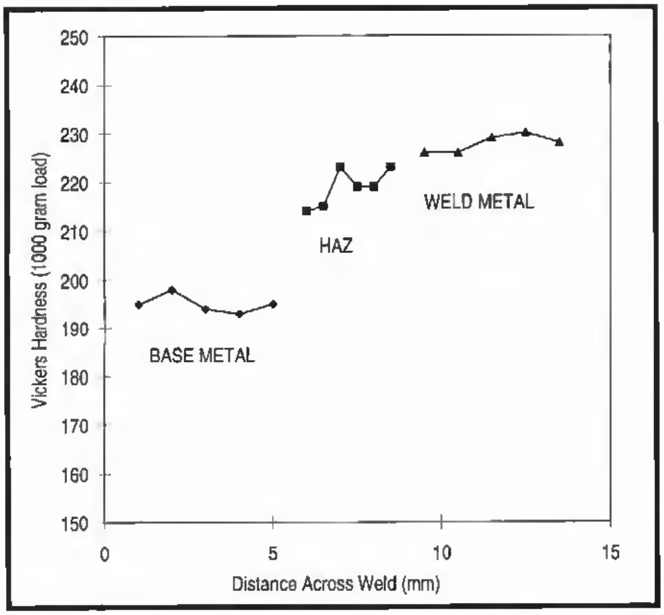

Fig. 11 — Microhardness of DH-36 single-pass, multiwire submerged arc Weldment C8.

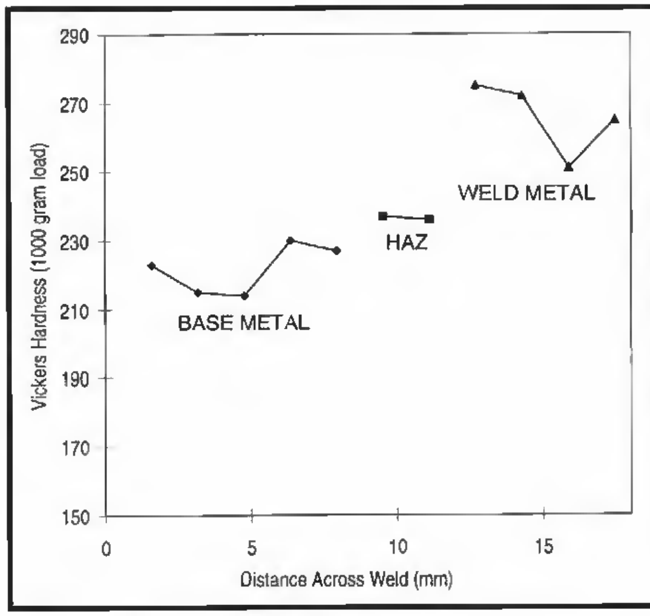

Fig. 12 — Microhardness of HSLA-65 multipass GMA Weldment 11.

Table 6 — Summary of Weldment Tensile and CVN Results

Welding Process	Transverse Weld Tensile Strength	Weld Metal CVN Toughness
SMAW (MIL-7018M)	Met base metal requirements[a].	Met base metal requirement.[b] Failed electrode requirement (50 ft-lb @ −50°F. Met 20 ft-lb @ −20°F.
FCAW (MIL-71T-1)	Met base metal requirements.	Failed base metal requirement. Met 20 ft-lb @ −20°F at high cooling rates.
GMAW (MIL-70S-3)	Met base metal requirements.	Met base metal requirement at high cooling rates. Met 20 ft-lb @ −20°F at high cooling rates. Failed base metal and weld metal requirements at low cooling rates.
Multipass SAW	Met base metal requirement with proper electrode/flux.	Failed base metal requirement. Met 20 ft-lb @ −20°F with proper electrode/flux.
Single-pass, high-energy-input SAW	Met base metal requirements.	Failed base metal requirement. Failed 20 ft-lb @ −20°F.

(a) 78 ksi minimum tensile strength per ASTM A945.
(b) 20 ft-lb @ −40°F per ASTM A945.

(0.2°C) at 1000°F (538°C), resulting in very coarse microstructures, and to lack of grain refinement normally seen in multipass welding. The lower toughness values for the DH-36 HAZ compared to the HSLA-65 HAZ is attributed to the lower base metal CVN toughness of the DH-36, which typically contains higher levels of carbon and residual elements.

In most of the single-pass multiwire submerged arc weldments, the CVN toughness at the weld interface is higher than at the 1-mm or all-HAZ locations. As shown in Fig. 9, the weld interface was not oriented normal to the plate surface; thus the Charpy V notch for location I was partially located within the weld metal. The higher CVN values are attributed to the higher weld metal CVN toughness. (Conversely, for the multipass weldments, in which the weld metal CVN toughness was often lower than the HAZ toughness, the weld interface toughness was generally lower than in other HAZ locations.) The location A as described in MIL-STD-248 (Ref. 9) and AWS D1.1 (Ref. 10) appears to contain a gradient of high to low peak temperature microstructural material.

For each pair of weldments, the weldments differ only in electrode type; thus no difference in HAZ toughness would be expected. Appendix Table A-5 shows that differences do exist, but there is no pattern to the differences, which may be due to having only two specimens available for testing per condition. Additionally, the all-HAZ location does not always exhibit higher toughness than the 1-mm location, which can be attributed to the presence of tougher weld metal in the crack plane of the 1-mm location. This scatter in HAZ toughness data again illustrates the difficulty in adequately characterizing the notch toughness of weld HAZs by the CVN test.

As mentioned previously, the single-pass, one-side submerged arc weldments were intentionally fabricated under worse-case conditions using excessively high energy input. This process has been successfully qualified for HSS and implemented in ship fabrication using more realistic welding parameters. Additional development would be needed to establish suitable procedure limits on single-pass, one-side SAW parameters for HSLA-65 steel.

Microhardness

The results of microhardness traverses from the base metal, through the HAZ and into the weld metal for representative HSLA-65 and DH-36 single-pass, one-side submerged arc weldments are plotted in Figs. 10 and 11. The HAZ and weld metals are harder than the base metals, *i.e.*, no excessive HAZ hardening or softening was observed. This is in agreement with the base metal fracture location in the transverse weld tension tests. Similar behavior was observed for the multipass weldments. Figure 12 shows the hardness levels in Weldment 11, which is a fast cooling rate multipass GMA weldment.

Summary of Weldment Tensile and CVN Results

The present data show that HSLA-65 can be welded with 100% joint efficiency using conventional 70-series welding consumables. The levels of weld metal CVN toughness attainable are determined by welding process, consumable type and welding procedure, *i.e.*, weld cooling rate. A summary of the transverse tensile and weld metal CVN results are shown in Table 6. Because the CVN requirements for weld metals in HSLA-65 have not been established and would depend upon applications and service conditions, the results are compared to two criteria: 20 ft-lb at −40°F, which is the HSLA-65 base metal transverse requirement, and 20 ft-lb at −20°F, which is a commonly used value for consumable conformance testing. Table 6 shows that only the SMA weld metal met the base metal CVN requirement at all cooling rates. The 20 ft-lb at −20°F criterion could be met in the submerged arc weld metal at all cooling rates, but only in high cooling rates in the FCA and GMA weld metals.

The HAZ CVN values are not summarized in Table 6 because of the difficulties in measuring HAZ toughness by the CVN test, in which the values are affected by the presence of various amounts of weld metal in the crack path due to irregularities in the weld interface geometry. However, as was shown for the single-pass submerged arc weldments, the HSLA-65 HAZ is tougher that the DH-36 HAZ. For the multipass weldments in which the weld-metal toughness meets the base metal requirement (MIL-7018-M in Appendix Table A-1), the measured HAZ toughness can also meet the base metal requirement. Additional material characterization and structural performance testing is needed to adequately characterize the HAZ of HSLA-65 weldments.

Conclusions

Results from this study indicate that HSLA-65 steel can be welded by SMAW, FCAW, GMAW and SAW using 70-series consumables over the range of procedures and cooling rates commonly used in shipyard fabrication while exhibiting adequate soundness and meeting specified minimum transverse weld tensile strength.

HSLA-65 has weldability equal to or better than HSS (DH-36) as evidenced by 1) lower carbon and carbon equivalent compared to HSS, 2) no hydrogen-assisted cracking was observed in the weldments welded without preheat at the fastest weld cooling rates, 3) no excessive hardening or softening was observed in the weld metals or HAZ and 4) improved HAZ toughness vs. that in HSS.

The weld metal CVN toughness was governed by welding process, consumable type and welding procedure, *i.e.*, weld cooling rate. CVN requirements for weld metals in HSLA-65 need to be established for the intended applications and service conditions.

This information will facilitate the certification and implementation of HSLA-65 steel in ship construction for reduced hull weight and lower fabrication and life-cycle costs.

Acknowledgments

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Appendix

Table A-1 — Mechanical Properties of SMA Weldments

Joint #	1	14[a]	5	8
Material	HSLA-65	HSLA-65	HSLA-65	HSLA-65
Thickness (in.)	1/2	1/2	1/2	1-1/4
Electrode Type	MIL-7018M	MIL-7018M	MIL-7018M	MIL-7018M
Cooling Rate (°F/s @ 1000°F)	9.3	10.4	11.5	60.2
Transverse Tensile Strength (ksi)	81.0	81.3	82.9	84.0
Fracture Location	Base	Weld	Weld	Base
All-Weld-Metal Yield Strength (ksi)	68.6	67.9	68.0	84.1
All-Weld-Metal Tensile Strength (ksi)	77.3	79.1	78.8	90.3
All-Weld-Metal Elongation (%)	25.5	23.0	23.8	26.6
Charpy V-notch Toughness (ft-lb)[b]				
Weld Metal @ −20°F	39	79	40	70
Weld Metal @ −40°F	—	44	37	—
Weld Interface @ −40°F	28	85	50	53
1 mm HAS @ −40°F	25	181	85	127
Base Metal @ −40°F	175	—	—	136

(a) Fabricated with 15/16 in. (24 mm) root opening.
(b) Average of five specimens.

Table A-2 — Mechanical Properties of FCA Weldments

Joint #	3	15	3R	15R	16	10
Material	HSLA-65	HSS	HSLA-65	HSS	HSS	HSLA-65
Thickness (in.)	1/2	1/2	5/8	5/8	1-1/4	1-1/4
Electrode Type	MIL-71T-1	MIL-71T-1	MIL-71T-1	MIL-71T-1	MIL-71T-1	MIL-71T-1
Cooling Rate (°F/s @ 1000°F)	12.0	12.6	16.0	16.0	63.5	66.5
Transverse Tensile Strength (ksi)	81.2	79.9	—	—	79.7	81.9
Fracture Location	Base	Base	—	—	Base	Base
All-Weld-Metal Yield Strength (ksi)	71.4	71.5	—	—	85.4	77.1
All-Weld-Metal Tensile Strength (ksi)	80.2	81.8	—	—	88.7	82.3
All-Weld-Metal Elongation (%)	24.3	17.3	—	—	24	26.0
Charpy V-notch Toughness (ft-lb)[a]						
Weld Metal @ −4°F	—	—	64	64	—	—
Weld Metal @ −20°F	10	29	63	53	33	20
Weld metal @ −40°F	—	11	—	—	17	—
Fusion Line @ −40°F	7	24	—	—	54	69
1 mm HAZ @ −40°F	7	15	—	—	49	190
5 mm HAZ @ −40°F	—	—	—	—	—	194
Base Metal @ −40°F	118	—	—	—	—	207

(a) Average of five specimens.

Table A-3 — Mechanical Properties of GMA Weldments

Joint #	4	11
Material	HSLA-65	HSLA-65
Thickness (in.)	1/2	1-1/4
Electrode Type	MIL-70S-3	MIL-70S-3
Cooling Rate (°F/s @ 1000°F)	13.0	69.1
Transverse Tensile Strength (ksi)	81.1	84.2
Fracture Location	Base	Base
All-Weld-Metal Yield Strength (ksi)	66.5	84.8
All-Weld-Metal Tensile Strength (ksi)	81.8	96.2
All-Weld-Metal Elongation (%)	23.0	25.5
Charpy V-Notch Toughness (ft-lb)[a]		
Weld Metal @ −20°F	17	76
Weld Interface @ −40°F	51	99
1 mm HAZ @ −40°F	65	128
Base Metal @ −40°F	121	133

(a) Average of five specimens.

Table A-4—Mechanical Properties of SAW Weldments

Joint #	12	6	7	9	2	C1	C2
Material	HSLA-65	HSLA-65	HSLA-65	HSLA-65	HSLA-65	HSLA-65	HSLA-65
Thickness (in.)	1	3/4	1/2	1-1/4	1/2	1	1
Electrode Type	EM12K	EM12K	EM12K	EM12K	EL12	EM12K	EM13K
Flux Type	780	780	780	780	780	860	960
AWS Filler Metal Designation	F7A2-EM12K	F7A2-EM12K	F7A2-EM12K	F7A2-EM12K	F7A0-EL12	F7A2-EM12K	F7A2-EM12K
Cooling Rate (°F/s @ 1000°F)	2.8	4.0	4.5	39.4	6.0	2.4	2.6
Transverse Tensile Strength (ksi)	81.4	84.9	81.9	83.8	83.7	75.1	82.4
Fracture Location	Base	Base	Base	Base	Base/Weld	Weld	Base/Weld
All-Weld-Metal Yield Strength (ksi)	78.2	73.6	79.2	89.3	67.6	61.4	68.7
All-Weld-Metal Tensile Strength (ksi)	89.2	85.7	91.1	94.4	82.6	73.0	83.4
All-Weld-Metal Elongation (%)	27.6	22.0	20.3	24.3	28.6	32.5	30.6
Charpy V-Notch Toughness (ft-lb)[a]							
Weld Metal @ −4°F	—	—	—	—	—	34	31
Weld Metal @ −20°F	12	9	13	25	11	36	29
Weld Metal @ −40°F	—	—	—	—	—	20	17
Weld Interface @ −40°F	22	8	24	26	11	—	—
1 mm HAz @ −40°F	160	9	39	119	12	—	—
5 mm HAZ @ −40°F	121	171	125	—	144	—	—
Base Metal @ −40°F	100	191	118	135	134	—	—

(a) Average of five specimens.

Table A-5 — Mechanical Properties of Single-Pass, Multiwire Submerged Arc Weldments[a]

Joint #	B8	BA1	C8	CA1	E8	EA1
Material	HSLA-65	HSLA-65	HSS	HSS	HSLA-65	HSLA-65
Thickness (in.)	5/8	5/8	5/8	5/8	1-1/4	1-1/4
Electrode Type	EL8	EA1	EL8	EA1	EL8	EA1
Transverse Tensile Strength (ksi)	81.3	80.4	86.2	86.9	83.5	85.0
Fracture Location	Base	Base	Base	Base	Base	Base
All-Weld-Metal Yield Strength (ksi)	71.0	76.5	69.4	71.5	72.8	77.4
All-Weld-Metal Tensile Strength (ksi)	90.7	95.3	90.2	93.8	89.4	95.5
All-Weld-Metal Elongation (%)	28.6	27.9	26.4	25.7	28.0	26.4
Charpy V-Notch Toughness (ft-lb)[b]						
Weld Metal @ −4°F	19	35	24	22	23	26
Weld Metal @ −40°F	8	12	8	11	12	16
Weld Interface @ −4°F	—	43	15	23	17	47
Weld Interface @ −40°F	—	14	9	15	10	28
1 mm HAZ @ −4°F	18	38	6	10	17	24
1 mm HAZ @ −40°F	8	9	7	7	10	18
All HAZ @ −4°F	47	24	8	6	18	92
All HAZ @ −40°F	9	10	4	5	16	26
Base metal @ −4°F	83	83	38	38	—	—
Base metal @ −40°F	75	75	18	18	163[c]	163[c]

(a) All welds had a calculated cooling rate of 0.4°F/s (0.22°C/s) at 1000°F (538°C).
(b) Average of two specimens.
(c) 7.5-mm subsize specimens.