SSC-305

INVESTIGATION OF STEELS FOR IMPROVED WELDABILITY IN SHIP CONSTRUCTION PHASE II

SHIP STRUCTURE COMMITTEE

1981

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SR-1256

1981

Much of the modernization taking place in the world shipbuilding industry in the last decade has centered around the use of new, more efficient welding techniques. The potential increase in productivity with new high-deposition rate welding processes is considerable. However, in order to take full advantage of the benefits of the new welding practices, additional metallurgical control appears necessary for minimizing heat-affected zone and weld-metal property degradation.

The Ship Structure Committee is now sponsoring a project directed toward determining the weld procedure and metallurgical control necessary to develop adequate toughness in the weldment, using high-deposition rate welding procedures. This report describes the second phase of that work.

Clyde T. Lusk, Jr.
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

The purpose of the present three-phase investigation is to develop economical ship-plate steels with improved heat-affected-zone (HAZ) toughness when welded at high heat inputs. The first phase consisted of a literature review aimed at identifying economical compositions and processing methods that were expected to result in steels having good HAZ toughness when welded at high heat inputs. This review resulted in the selection of 20 steels to be melted and evaluated at the Research Laboratory.

The present report summarizes Phase II. During this phase, the 20 laboratory-melted steels were produced with compositional variations in the content of titanium, nitrogen, vanadium, boron, calcium, and rare-earth metals. These steels were rolled to 1-inch-thick plate and normalized. Thermal cycles occurring in the HAZ near the fusion line of high-heat-input welds were simulated in samples of all these steels. On the basis of the toughness and microstructure of these simulated-weld samples, eight of the laboratory-melted steels were selected for welding along with three commercially produced ship steels. In addition to submerged-arc (SA) welding at a typical heat input of 75 kJ/inch, two high-heat-input welding processes were used: (1) electroslag welding (ES) at about 1000 kJ/inch and (2) two-pass SA welding at 180 kJ/inch per pass.

Charpy V-notch tests of the HAZ of these steels showed that the steel with the best HAZ toughness for the ES weld was a calcium-treated 0.08 percent vanadium steel with a low content of residual elements (Ni, Cu, Cr, and Mo). Several titanium steels without boron and also one with boron had good HAZ toughness when ES-welded. The HAZ toughness of the 0.08 percent vanadium steel and several of the titanium steels was also good when the steels were SA-welded at 180 kJ/inch. However, two of the three titanium steels that contained boron had poor HAZ toughness for a normal-heat-input (75 kJ/inch) SA weld. Overall, vanadium, low-residual-element steels, and titanium steels without boron appear to show promise of providing improved HAZ toughness in high-heat-input welds.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

```
°F
     -40      0      32   40   80   98.6  120   160   200  212
     |--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|
     -40      -20     0       20    37  40      60    80   100
°C                                                          °C
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CONTENTS

Introduction

The purpose of the present project is to develop economical
ship-plate steels having improved heat-affected-zone (HAZ) toughness
when welded with high-heat inputs. Phase I of this project con-
sisted of a literature search for steels that were reported to have
improved HAZ toughness when welded with high-heat inputs or when
heat-treated to simulate the thermal cycle in a weld HAZ. The
literature search also identified steels that had high grain-
coarsening temperatures and that should, therefore, have a narrow
coarse-grain weld HAZ. On the basis of this literature search, 20
steel compositions were selected for melting and evaluation at the
Research Laboratory. The results of the literature search, the
reasons for the selection of the various steel compositions, and
details of the testing program were presented in the report[1] on
Phase I of this project.

During Phase II, the 20 laboratory-melted steels were pro-
duced, and three commercially produced ship-plate steels were
obtained for comparison. The thermal cycles occurring in the HAZ
adjacent to the bond line were reproduced in samples of all the
investigated steels by using a Gleeble machine. On the basis of
the toughness results and microstructures of these Gleeble-treated
samples, eight steels in addition to the commercially produced
plates were selected for welding with typical and high-heat inputs.
The effects of the various alloying additions on the HAZ toughness
and microstructure were determined. Details of Phase II are
contained in the present report.

Materials and Experimental Work

Commercially Produced Plates

Three one-inch-thick (25 mm) plates of commercially produced
ship steels were included in the present program as reference
materials. One plate was a calcium-treated ABS V-051 steel produced
by Lukens Steel Company. The second plate was Nippon Steel
Corporation's HT-50S Class D plate developed for one-pass (high
heat input) submerged-arc welding. The third plate was ABS CS
steel produced by U. S. Steel Corporation (USSC). All of
the plates were received in the normalized condition.

Table I Chemical Composition of the Steels Investigated--Percent

No.	Steel Description		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Cb	V	Ti	Al	Ca	B	N	Ce
							Reference Laboratory-Melted Steels												
1	Reference ABS V-051	Aim	0.13	1.38	0.010	0.006	0.16	-	-	-	-	0.027	-	-	0.030	*	-	0.004	-
		Check	0.12	1.38	0.008	0.006	0.14	0.004	0.004	<0.003	0.006	0.023	<0.002	<0.002	0.027	<0.0003	0.0004	0.007	NA[1]
2	Reference ABS DS	Aim	0.14	1.25	0.010	0.020	0.22	-	-	-	-	-	-	-	0.030	-	-	0.004	-
		Check	0.13	1.29	0.011	0.022	0.22	0.003	0.002	<0.003	0.007	<0.005	<0.002	<0.002	0.030	NA	0.0003	0.005	NA
							Base Steel and Effects of S, Ca, Cb, V, REM, Residuals													
3	Base+S	Aim	0.12	1.35	0.010	0.020	0.30	0.20	0.15	0.15	0.04	-	-	-	0.030	-	-	0.008	-
		Check	0.11	1.40	0.009	0.023	0.28	0.18	0.14	0.13	0.04	-	<0.002	<0.002	0.030	NA	0.0001	0.008	NA
4	Base	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	-	0.030	-	-	0.008	-
		Check	0.11	1.35	0.009	0.007	0.29	0.18	0.15	0.14	0.04	-	<0.002	0.003	0.025	NA	0.0002	0.010	NA
5	Base+Ca	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	-	0.030	*	-	0.008	-
		Check	0.12	1.38	0.009	0.006	0.29	0.19	0.15	0.14	0.04	<0.005	<0.002	<0.002	0.030	<0.0003	0.0004	0.010	NA
6	Base+Cb-R[2]	Aim	0.12	1.35	0.010	0.006	0.30	-	-	-	-	0.025	-	-	0.030	*	-	0.008	-
		Check	0.11	1.37	0.008	0.006	0.28	0.004	0.004	<0.003	0.008	0.023	<0.002	<0.002	0.032	<0.0003	0.0003	0.009	NA
7	Base+Ca+V-R[2]	Aim	0.12	1.35	0.010	0.006	0.30	-	-	-	-	-	0.080	-	0.030	*	-	0.008	-
		Check	0.12	1.33	0.008	0.007	0.24	0.004	0.003	<0.003	0.008	<0.005	0.077	<0.002	0.027	<0.0003	0.0002	0.010	NA
8	Base+Cb+REM-R[2]	Aim	0.12	1.35	0.010	0.006	0.30	-	-	-	-	0.025	-	-	0.030	-	-	0.008	0.015
		Check	0.12	1.38	0.008	0.008	0.27	0.004	<0.002	<0.003	0.008	0.023	<0.002	<0.002	0.031	NA	0.0003	0.011	0.013
							B-Ti-REM-N Combinations													
9	Base+REM+B	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	-	0.030	-	0.003	0.005	0.015
		Check	0.11	1.37	0.008	0.008	0.27	0.18	0.14	0.14	0.04	<0.005	<0.002	<0.002	0.028	NA	0.0029	0.009	0.016
10	Base+REM+B+N	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	-	0.030	-	0.003	0.010	0.015
		Check	0.12	1.37	0.008	0.005	0.29	0.20	0.15	0.14	0.04	<0.005	<0.002	0.003	0.032	NA	0.0034	0.010	0.015
11	Base+REM+B+Ti	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.015	0.030	-	0.003	0.010	0.015
		Check	0.11	1.38	0.008	0.005	0.28	0.20	0.16	0.14	0.04	<0.005	<0.002	0.016	0.031	NA	0.0035	0.007	0.014

(Continued)

Table I (Continued)

No.	Steel Description		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Cb	V	Ti	Al	Ca	B	N	Ce
									Ti-N-B-Al Combinations										
12	Base+Ti+lowAl, heated once	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.013	0.010	-	-	0.005	-
		Check	0.12	1.36	0.012	0.007	0.31	0.18	0.14	0.14	0.04	<0.005	<0.002	0.017	0.012	NA	0.0001	0.006	NA
13	Base+Ti, heated once	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.013	0.030	-	-	0.005	-
		Check	0.12	1.37	0.010	0.008	0.32	0.18	0.14	0.15	0.04	<0.005	<0.002	0.017	0.030	NA	0.0001	0.006	NA
14	Base+Ti+N, heated once	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.025	0.030	-	-	0.010	-
		Check	0.11	1.42	0.011	0.008	0.33	0.20	0.14	0.13	0.04	<0.005	<0.002	0.030	0.032	NA	0.0001	0.011	NA
15	Base+Ti+N+B, heated once	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.025	0.030	-	0.003	0.010	-
		Check	0.11	1.37	0.008	0.007	0.28	0.18	0.14	0.14	0.04	-	<0.002	0.032	0.024	NA	0.0033	0.013	NA
									Ti-N-Ca-REM Combinations										
16	Base+Ti+Ca	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.020	0.030	*	-	0.008	-
		Check	0.12	1.40	0.009	0.006	0.28	0.18	0.14	0.14	0.04	<0.005	<0.002	0.025	0.032	<0.0003	0.0004	0.009	NA
17	Base+Ti+Ca	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.015	0.030	*	-	0.006	-
		Check	0.12	1.35	0.009	0.006	0.28	0.18	0.15	0.14	0.04	<0.005	<0.002	0.014	0.029	<0.0003	0.0004	0.009	NA
18	Base+Ti+REM+ Ca	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.015	0.030	*	-	0.006	0.015
		Check	0.11	1.37	0.011	0.006	0.28	0.18	0.15	0.14	0.04	<0.005	<0.002	0.015	0.032	<0.0003	0.0003	0.007	0.015
19	Base+Ti+B+ Ca	Aim	0.12	1.35	0.010	0.006	0.30	0.20	0.15	0.15	0.04	-	-	0.015	0.030	*	0.003	0.006	-
		Check	0.12	1.35	0.009	0.006	0.28	0.18	0.14	0.14	0.04	-	<0.002	0.014	0.028	<0.0003	0.0030	0.009	NA
									V-B										
20	Base+B-R-Si +V	Aim	0.12	1.35	0.010	0.006	0.04	-	-	-	-	-	0.06	-	0.030	-	0.003	0.007	-
		Check	0.12	1.34	0.012	0.006	0.05	0.004	0.003	<0.003	<0.003	<0.005	0.056	0.002	0.029	NA	0.0032	0.008	NA
									Commercially Produced Steels										
N[3]	HT-50S	Check	0.11	1.59	0.012	0.004	0.30	0.01	0.02	<0.003	0.007	<0.005	<0.002	0.021	0.019	-	0.0001	0.008	<0.01
L[4]	ABS V-051	Check	0.13	1.44	0.009	0.005	0.15	0.19	0.09	0.09	0.03	0.028	<0.002	-	0.050	0.0027	0.0001	0.011	<0.01
U[5]	ABS-CS	Check	0.12	0.99	0.007	0.017	0.19	0.11	0.08	0.06	0.02	<0.005	<0.002	<0.002	0.015	-	-	0.007	-

1) NA means none added and not analyzed.
2) R means without added residuals (Cu, Ni, Cr, and Mo).
3) Nippon HT-50S (D grade), heat No. TK4327.
4) Lukens V051 Frostline, heat No. B1430.
5) U. S. Steel, ABS-CS, heat No. 4G2382.

* Ca was added as a 20% Ca, 80% Fe proprietary additive. Canisters containing this additive were plunged into the ladle three times with a total amount of Ca which would amount to 0.027% in the steel if none were lost.

heats were induction-melted in a vacuum furnace and poured into 7- by 12- by 24-inch (178 by 305 by 610 mm) ingot molds. All the ingots were cooled to room temperature. Sixteen of the 20 ingots were reheated to 2350°F (1290°C) and rolled in the 24-inch direction to 5-inch-thick (127 mm) slabs, which were air-cooled to room temperature. These slabs were reheated to 2350°F and rolled longitudinally to 1-inch-thick plate in 12 passes of about 13 percent reduction per pass with a final-pass temperature of 1900°F (1040°C) as measured by an optical pyrometer.

As discussed in the report[1] on Phase I of this project, the literature indicates that to produce the fine titanium nitride particles that restrict grain coarsening, the cooling rate of the ingot down to 2010°F (1100°C) must be fast enough (≥9°F or 5°C per minute) to prevent the formation of coarse titanium nitride particles. Furthermore, some investigators state that the steel must not be reheated more than once above about 2000°F (1095°C). Cooling rates for slabs from continuous casters exceed this specified cooling rate and so do those for the small laboratory-melted steels in the present investigation. Continuous-cast slabs are generally heated only once for rolling to plate, so the titanium nitrides should not coarsen; whereas ingots, or at least the outer and cooler portions of ingots, are generally reheated twice above 2000°F—once for rolling to slab and once for rolling to plate.

In the present investigation, four steels containing titanium, Steels 12, 13, 14, and 15, were processed in a manner that simulates the commercial production of plate from continuous-cast slabs. That is, these four ingots were reheated only once and rolled directly to plate. The heating temperature was 2350°F, and the ingots were rolled straightaway to 1-inch-thick plate in 15 passes of about 12 percent reduction each, with a final pass temperature of 1900°F. Several other titanium-containing steels shown in Table I (Steels 11 and 16 through 19) were among the 16 steels reheated twice for rolling, but according to the literature, other elements present in addition to the titanium (calcium and/or rare earth metals) permit such processing.[2,3]

Eight laboratory-melted steels were calcium treated. In production, calcium is often injected as a calcium silicide powder with an inert-gas carrier. The usual purpose of the calcium

As equipment to inject a calcium powder was not available at the Laboratory, cannisters containing a 20 percent calcium and 80 percent iron proprietary additive were secured to the end of a rod and plunged into the ladle. Because the reaction of calcium with the molten steel is highly exothermic, the calcium addition was made in three separate plunges to prevent the reaction from expelling the additive from the ladle. The total amount of calcium added would have amounted to 0.027 percent in the steel if none were lost.

Plate rolled from the first trial showed that the calcium addition was only partially effective in balling sulfides—some were strung out, some were short, and some were balled. Therefore, two more trials were made, one with the calcium silicide often used for production of commercial heats, and one with twice as much of the aforementioned calcium-iron additive. Sulfides in the plate from these two trials were also only partially balled and the inclusion content of these steels was undesirably greater. Therefore, the first of the above-described practices was used in making the eight calcium-treated steels.

The plates from the laboratory-melted steels were normalized by treating them in a 1675°F (913°C) furnace for one hour and air cooling them.

Mechanical Testing of Unwelded Plates

Eighteen transverse Charpy V-notch (CVN) specimens and duplicate 0.357-inch-diameter (9.07 mm) tension-test specimens were machined from the quarterthickness of each of the plates. The CVN specimens were tested over a range of temperatures to establish transition behavior and the tension-test specimens were tested at room temperature.

Gleeble Treatment

Before the Gleeble could be used to simulate the thermal cycles that occur in the HAZ near the fusion zone, it was necessary to determine the time-temperature cycles for the high-heat-input welding conditions that would be used in this study. Therefore, time-temperature measurements were made in an ES and in an SA weldment with embedded thermocouples. Because the ABS-specified location for Charpy V-notch testing is the plate quarterthickness on the last-pass side of a weldment, the thermocouples were placed at this position. As the location of the bond line could not be precisely predicted, seven thermocouples were used; one was placed

at the expected location of the bond line, and three were placed on each side of the center thermocouple at 0.030-inch (0.75 mm) increments from the expected bond-line location.

The highest temperatures recorded for surviving thermo-couples in the weldments were 2525°F (1385°C) for the ES weld and 2545°F (1396°C) for the SA weld. The data from this experiment are shown in Table II and were used in the Gleeble simulations, except that a peak temperature of 2525°F was used for both weld simulations so that differences caused by the two treatments would reflect differences in heating and cooling rather than differences in an arbitrarily chosen peak temperature. The location of this peak temperature in the HAZ is only a fraction of a millimeter from the bond line. A peak temperature of 2525°F was chosen rather than 2462°F (1350°C), as often reported in the literature for HAZ simulations, because for the high-heat-input welding conditions used in this study, the location in the HAZ that had a peak temperature of 2462°F was outside the very-coarse-grain region for the steel used in these trials.

Twenty transverse oversize CVN specimen blanks were machined from each of the 23 plates. Ten blanks from each plate were treated with the Gleeble by using one of the thermal cycles shown in Table II, and the other 10 blanks from each plate were treated in accord with the other thermal cycle except that a peak temperature of 2525°F was used in both instances. The CVN specimens machined from these blanks were tested over a range of temperatures to determine transition behavior.

Microstructure of Base
Plate and Gleeble Samples

Samples of the plates were examined with a light microscope. The microstructure of all the plates consisted of ferrite and pearlite. Ferrite grain size and pearlite content were determined with a Quantitative Television Microscope.[4] In addition, light micrographs of the Gleeble-treated specimens from each steel were prepared to show the prior austenite grain size and resulting microstructure.

Welding Procedures

In addition to the three commercially produced plates and the base steel from the laboratory heats, seven of the more promising steels were welded and evaluated. These seven steels were selected on the basis of the CVN test results from the Gleeble-treated samples, the microstructure of these samples, and a consideration of the alloy system to which the steels belonged.

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Table II Temperature Measurements in Weld
Heat-Affected Zones

Electroslag Weld		180 kJ/in. Submerged-Arc Weld	
Time, sec	Temperature, °F	Time, sec	Temperature, °F
0	75	0	192
600	500	4	232
660	1000	9	2545
690	2100	13	2505
700	2525	17	2381
708	2522	22	2232
712	2484	26	2090
717	2443	31	1965
721	2402	35	1843
725	2322	39	1730
729	2278	43	1632
734	2227	48	1550
742	2148	52	1483
759	2042	56	1428
768	2003	60	1380
776	1922	69	1301
785	1843	77	1241
802	1716	86	1195
819	1602	94	1160
836	1502	103	1133
853	1414	112	1104
874	1320	125	1052
899	1231	134	1019
933	1133	146	973
971	1046	168	915
1024	950	180	884
1066	869	205	831
1125	773	222	801
1185	695	266	738
1245	627	387	624
1305	574	498	552
1365	527	618	498
1425	490	679	475

All welds were made in a longitudinal direction. Plate
samples of each of the 11 steels were ES-welded at a heat input of
about 1000 kJ/inch (40 kJ/mm) and SA-welded in two passes at a
heat input of 180 kJ/inch (7.1 kJ/mm) per pass and in six passes at
a more typical heat input of 75 kJ/inch (3.0 kJ/mm). The joint
configurations and weld parameters are shown in Figure 1 and
typical chemical compositions of the electrodes are given in
Table III.

CVN Testing of Weldments

For the commercially produced plates, CVN specimens were
machined from the weldments in accordance with ABS and USCG
qualification requirements. The CVN specimens were machined from
the plate quarterthickness perpendicular to the weld direction with
the notch normal to the plate surface and located at the center of
the weld, at the bond line, and in the HAZ at distances of 1, 3,
and 5 mm from the bond line, Figure 2. Because the bond line was
rarely perfectly perpendicular to the plate surface over the entire
thickness of the CVN specimen, different portions of the notch were
generally at different distances from the bond line. Twelve CVN
specimens were machined from each of the five test locations and
tested in triplicate over a range of temperatures to determine
transition behavior.

For the laboratory-melted steels, tests were conducted only
on CVN specimens machined with the notch at the bond line and the
1- and 3-mm positions within the HAZ, but quintuplicate tests were
conducted at 0 and -40°F (-18 and -40°C) for each of these three
locations.

Hardness Traverses of Weldments

Diamond pyramid hardness measurements were made at the
plate quarterthickness in the center of the weld, in the base plate,
and in the HAZ at distances of 1 and 3 mm from the bond line.

Weld-HAZ Microstructure

Light micrographs of the HAZ from each of the 11 steels
selected for welding were prepared showing the microstructure at
the plate quarterthickness at magnifications of 50X, 200X, and
1000X.

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Table III Typical Electrode Composion—Percent

Electrode	Welding Process	C	Mn	Si	Cr	Ni	Mo	Cu
Armco W18	Submerged-arc	0.15	0.67	0.17	0.06	1.80	0.16	0.25
Linde M1-88	Electroslag	0.06	1.65	0.35	0.25	1.50	0.40	-

Note: Above is filler metal manufacturer's data.

SUBMERGED-ARC JOINT

— 20° —

5/16"
R.O.

STEEL & Cu BACKUP

NORMAL-HEAT-INPUT SAW
ARMCO W18 ELECTRODE
LINCOLN 880 FLUX
600 AMPERES CURRENT
32 VOLTS
15.5 IPM TRAVEL
6 PASSES—75 KJ/in. EACH

HIGH-HEAT-INPUT SAW
ARMCO W18 ELECTRODE
LINCOLN 880 FLUX
600 AMPERES CURRENT
30 VOLTS
8 IPM TRAVEL
2 PASSES—180 KJ/in. EACH

ESW JOINT

— 1" —

LINDE M188 ELECTRODE
LINDE 124 FLUX
450 AMPERES CURRENT

37 VOLTS
120 IPM WIRE SPEED
1 PASS—≈1000 KJ/in. EACH

Figure 1. Joint configuration and Weld
parameters used in current
investigation

T/4

a b c d e

NOTCH LOCATION a - CENTER OF WELD
b - FUSION LINE
c - HAZ, 1 mm FROM FUSION LINE
d - HAZ, 3 mm FROM FUSION LINE
e - HAZ, 5 mm FROM FUSION LINE
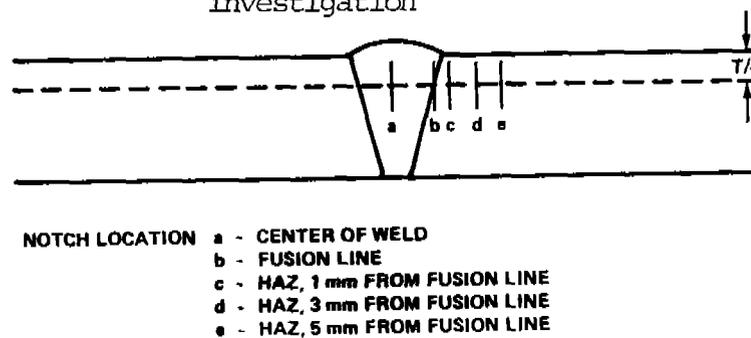
Figure 2. Schematic of Notch Location for
CVN impact specimens

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Results and Discussion

Base Plate

The tensile properties and CVN transition temperatures of the plates investigated are shown in Table IV, and individual CVN test results are given in Appendix Table A. Steel 4 is the base steel in the present study, and its chemical composition was chosen to provide a yield strength of about 50 ksi (345 MPa). The CVN 15 ft-lb (20J) transition temperature (V_{15}) of Steel 4 was -150°F (-100°C) and its 50 percent shear-fracture-appearance transition temperature (V_{50}) was -15°F (-25°C).

As will be shown subsequently, the only laboratory-melted steels in this investigation that showed significant improvements in HAZ toughness were those that contained titanium (Steels 11 through 19) and one steel that contained vanadium (Steel 7). Table IV shows that, as a group, these titanium steels had base-metal toughness considerably inferior to that of the titanium-free steels. The base-metal toughness of the vanadium steel, Steel 7, however, was about the same as that of the reference steel.

The microstructure of all the plates consisted of ferrite and pearlite. As Table V shows, the ferrite grain size of all the steels was fine, ranging from about ASTM No. 8 to 10. Because of the low-carbon content of the steels, the pearlite content was also low, ranging from 12 to 23 percent.

Gleeble-Treated Steels

Individual CVN test results from the Gleeble-treated specimens are shown in Appendix Table B for the ESW simulation and in Appendix Table C for the 180 kJ/inch SAW simulation. Table VI shows the average CVN energy absorbed at 0°F (-18°C) and -40°F (-40°C) for each of the steels.

Table VI also shows the Rockwell B hardness of the Gleeble-treated samples. No significant correlation between hardness and toughness of these samples is apparent.

Light micrographs of all the Gleeble-treated steels were prepared at a magnification of 50X to show the prior austenite grain size and at 200X to show finer details of the microstructure. Prior austenite grain-size ratings for these samples are given in Table VI. In many instances, particularly for the coarser grain samples, the prior austenite grain boundaries were outlined by a continuous network of ferrite so that the grain size was well defined. For some samples, the prior austenite grain boundary was less distinct and, in a few instances, unratable.

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Table IV Transverse Mechanical Properties of
the Plates Investigated

Table V Mic
the
Pla

| Steel | Tensile Properties* | | | | Charpy V-Notch Transition Temperature, °F | | Steel | Pearlit % |
	Yield Strength, ksi	Tensile Strength, ksi	Elongation in 1.4 In., %	Reduction of Area, %	15 ft-lb	50% Shear		
1	50.1	67.8	34.5	72.4	-125	-40	1	15
2	44.4	65.6	34.0	65.9	-80	-10	2	21
3	49.9	70.8	32.5	67.9	-140	-20	3	18
4	50.0	70.3	35.0	74.0	-150	-15	4	13
5	52.2	73.8	33.0	73.2	-190	0	5	19
6	51.5	70.9	34.5	73.6	-155	-35	6	16
7	52.6	71.7	34.0	73.2	-130	-10	7	14
8	51.3	71.0	35.3	77.5	-145	-75	8	12
9	47.1	70.7	34.3	74.8	-175	-35	9	17
10	47.3	71.1	34.0	73.1	-155	-5	10	22
11	44.8	70.0	35.0	77.0	-45	20	11	20
12	48.2	70.1	34.0	71.7	-90	30	12	17
13	47.5	70.3	33.5	70.2	-80	30	13	16
14	48.3	71.0	33.5	71.2	-95	20	14	17
15	46.8	69.3	34.0	71.0	-60	60	15	15
16	47.3	70.8	34.5	73.5	-60	30	16	18
17	49.5	71.5	34.0	72.9	-105	40	17	18
18	46.5	70.8	35.5	78.1	-70	-40	18	16
19	44.3	69.1	34.5	70.7	-55	60	19	17
20	43.5	64.4	35.0	70.9	-100	-20	20	18
N	51.4	72.9	34.5	75.5	-105	0	N	23
L	56.0	75.4	33.5	76.5	-170	-75	L	22
U	43.5	64.9	35.5	66.9	-70	10	U	17

* Average of duplicate tests of 0.357-inch-diameter specimens.

* Determined by the
microscope.

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Table VI   CVN Energy, Prior Austenite Grain Size, and
Hardness of the Gleeble-Treated Samples*

	ESW Simulation				180 kJ/in. SAW Simulation				Steels Selected for Welding
	Energy Absorbed, ft-lb		Hardness,	Prior Austenite Grain Size,	Energy Absorbed, ft-lb		Hardness,	Prior Austenite Grain Size,	
Steel	0°F	-40°F	R_B	ASTM No.	0°F	-40°F	R_B	ASTM No.	
1	16	13(6)	94.0	0.0	28(4)	18(3)	93.0	1.0	
2	21(8)	16(4)	85.0	0.0	26(7)	20(2)	90.5	0.5	
3	9	**	91.0	0.5	10	**	92.5	1.0	
4	12	**	96.0	0.0	8	**	93.0	0.5	X
5	10	**	91.0	1.0	**	**	93.5	2.0	
6	11	**	90.0	0.5	9	**	94.5	1.0	
7	35(3)	17(2)	95.5	0.0	15	11	92.0	0.5	X
8	7	**	88.0	1.0	5	**	92.0	2.0	
9	10	**	89.0	2.0	7	**	90.5	2.0	
10	6	**	93.0	0.0	8	**	93.0	2.0	
11	26(7)	9	93.0	2.5	11	**	97.0	1.0	X
12	16	**	91.0	0.0	28(4)	13(7)	95.0	2.0	X
13	18	11	91.0	0.5	27(6)	12(8)	94.0	1.5	
14	12	**	89.0	1.0	18	7	92.5	NR+	
15	34(5)	12(7)	90.0	NR+	35(2)	18(3)	92.0	NR+	X
16	35(3)	12(7)	95.0	NR+	18	12(8)	94.0	2.5	
17	34(5)	16(4)	90.0	2.0	25(8)	17(5)	91.0	1.5	X
18	73(1)	17(2)	95.0	2.5	32(3)	9	93.0		X
19	53(2)	43(1)	92.0	2.0	44(1)	28(1)	94.0	2.0	X
20	18	11	90.5	0.0	20	15(6)	93.0	1.0	
L	6	**	95.5	1.5	10	**	93.5	1.5	X
N	31	8	89.5	NR+	64	30	84.0	7.0	X
U	13	**	86.0	0.0	16	8	92.5	1.5	X

  * Parentheses indicates the energy ranking of the laboratory melted steels.
 ** Not tested   + NR means not ratable

Examples of the microstructure in the Gleeble-treated samples are shown in Figures 3 through 13 (A and B) for the 11 steels selected for welding. For the Gleeble-treated specimens, the samples with the finer prior austenite grain sizes usually, but not always, had the better toughness, particularly if the unratable-grain-size samples are assumed to be fine grain, which is likely to be the case.

Effect of Chemical Composition on the
Toughness of Gleeble-Treated Samples

For this discussion, the toughness values of Steel 4 (the base steel) shown in Table VI (12 ft-lb at 0°F for ESW and 8 ft-lb at 0°F for SAW) will be used for comparing the toughness of the other Gleeble-treated steels. For the remainder of this discussion of composition, to avoid constant repetition of "toughness of the Gleeble-treated steel," the following comparison refers only to Gleeble-treated steels and their toughness values shown in Table VI.

Steel 1. This steel was considerably better than Steel 4 for the SAW simulation (28 versus 8 ft-lb at 0°F) and somewhat better for the ESW simulation. The major differences in composition between these steels are that Steel 1 contains columbium and Steel 4 contains residuals and higher nitrogen.

Steel 2. The toughness of this reference steel was considerably better than that of the base steel for both weld simulations. Steels 2 and 4 are similar except that Steel 2 contains lower nitrogen, higher sulfur, and no residual-element additions.

Steel 3. The toughness of this 0.023 percent sulfur steel was not significantly different from that of the 0.007 percent sulfur base steel.

Steel 5. The addition of calcium to this steel did not improve its toughness compared with that of Steel 4.

Steel 6. The differences between Steels 6 and 4 are that calcium and columbium were added to Steel 6 and the residual elements (Cu, Ni, Cr, and Mo) present in Steel 4 were not added to Steel 6. These differences did not result in any significant difference in toughness. A puzzling result is that the toughness of Steel 6 was lower than that of reference Steel 1 which has a very similar composition.

Steel 7. This calcium-treated, vanadium, no-added-residual steel had improved toughness especially for the ESW simulation (35 versus 12 ft-lb at 0°F).

Figure 3. Micrographs of
Gleeble-treated
and welded
samples of Steel 4.
Nital Etch. 40X.

HAZ/weld

C. 75 kJ/inch SAW weld

HAZ/weld

A. Gleeble simulation
SAW 180 kJ/inch.

D. 180 kJ/inch SAW weld

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

14

Figure 4.   Micrographs of
             Gleeble-treated
             and welded
             samples of Steel 7.
             Nital Etch.   40X.

C.   75 kJ/inch   SAW weld

HAZ/weld

A.   Gleeble simulation
     SAW 180 kJ/inch.

D.   180 kJ/inch   SAW weld

HAZ/weld

B.   Gleeble simulation
     ESW 1000 kJ/inch.

E.   1000 kJ/inch   ES weld

15

Figure 5. Micrographs of
Gleeble-treated
and welded
samples of Steel 11.
Nital Etch. 40X.

C. 75 kJ/inch SAW weld

A. Gleeble simulation
SAW 180 kJ/inch.

HAZ/weld

D. 180 kJ/inch SAW weld

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

16

Figure 6.   Micrographs of
            Gleeble-treated
            and welded
            samples of Steel 12.
            Nital Etch.   40X.

C.   75 kJ/inch SAW weld

HAZ/weld

A.   Gleeble simulation
     SAW 180 kJ/inch.

D.   180 kJ/inch SAW weld

HAZ/weld

B.   Gleeble simulation
     ESW 1000 kJ/inch.

E.   1000 kJ/inch ES weld

17

Figure 7. Micrographs of
Gleeble-treated
and welded
samples of Steel 15.
Nital Etch. 40X.

C. 75 kJ/inch SAW weld

A. Gleeble simulation
SAW 180 kJ/inch.

D. 180 kJ/inch SAW weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

18

Figure 8. Micrographs of
Gleeble-treated
and welded
samples of Steel 17
Nital Etch. 40X.
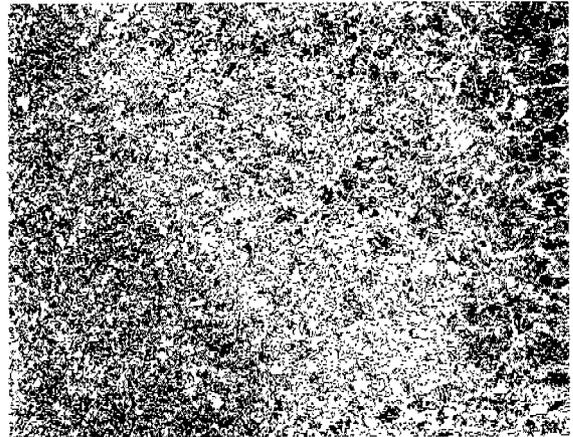
C. 75 kJ/inch SAW weld

HAZ/weld

A. Gleeble simulation
SAW 180 kJ/inch.

D. 180 kJ/inch SAW weld

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

19

Figure 9. Micrographs of
Gleeble-treated
and welded
samples of Steel 18.
Nital Etch. 40X.
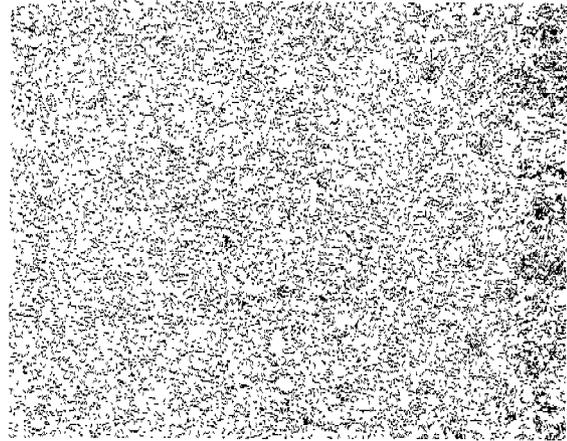
C. 75 kJ/inch SAW weld

HAZ/weld

A. Gleeble simulation
SAW 180 kJ/inch.

D. 180 kJ/inch SAW weld

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

C. 75 kJ/inch SAW weld

Figure 10. Micrographs of
Gleeble-treated
and welded
samples of Steel 19.
Nital Etch. 40X.
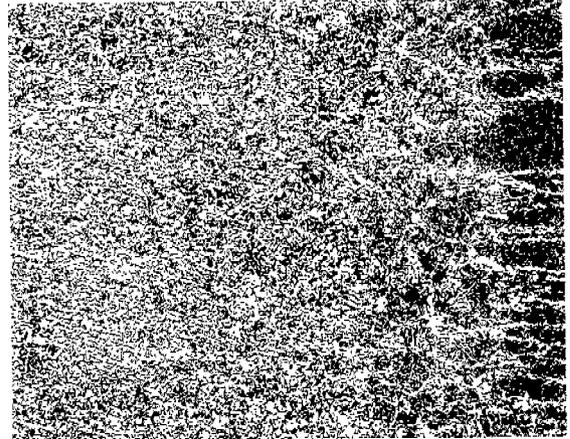
A. Gleeble simulation
SAW 180 kJ/inch.

D. 180 kJ/inch SAW weld

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

Figure 11. Micrographs of
Gleeble-treated
and welded
samples of Steel L.
Nital Etch. 40X.

C. 75 kJ/inch SAW weld

HAZ/weld

D. 180 kJ/inch SAW weld

A. Gleeble simulation
SAW 180 kJ/inch.

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

22

HAZ/weld

Figure 12. Micrographs of
Gleeble-treated
and welded
samples of Steel N.
Nital Etch. 40X.

C. 75 kJ/inch SAW weld

HAZ/weld

A. Gleeble simulation
SAW 180 kJ/inch.

D. 180 kJ/inch SAW weld

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

23

E. 1000 kJ/inch ES weld

C. 75 kJ/inch SAW weld

Figure 13. Micrographs of
Gleeble-treated
and welded
samples of Steel U.
Nital Etch. 40X.

HAZ/weld
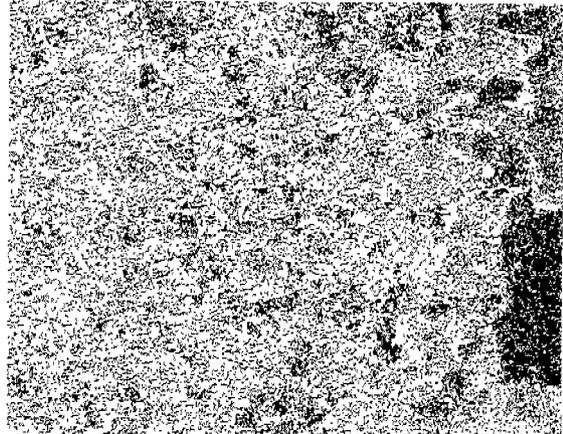
A. Gleeble simulation
SAW 180 kJ/inch.

D. 180 kJ/inch SAW weld

HAZ/weld

B. Gleeble simulation
ESW 1000 kJ/inch.

E. 1000 kJ/inch ES weld

24
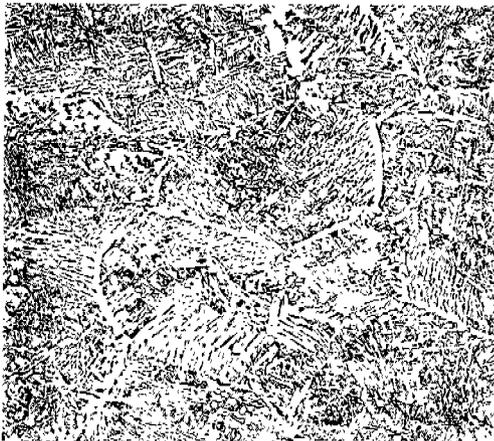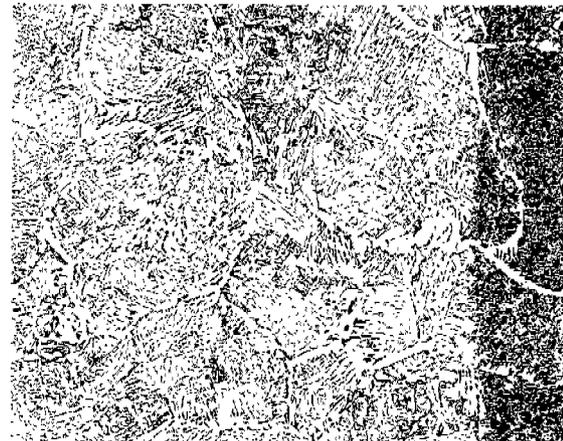
Steels 8, 9, and 10. Steels 8, 9, and 10 did not show any toughness improvement over Steel 4 for either weld simulation. All three steels contained rare-earth-metal (REM) additions, and the total REM content of the steels was approximately twice the cerium content shown in Table I. The REM additions to these steels were effective in balling the sulfides. Steel 8 also contained columbium but had no added residuals. Steels 9 and 10 contained boron.

Steel 11. This steel contained titanium in addition to a boron and REM addition. Steel 11 had about the same toughness as the base steel for the SAW simulation, but was better than the base steel for the ESW simulation (26 versus 12 ft-lb at 0°F).

Steels 12, 13, 14, and 15. These four titanium steels were heated only once for rolling, whereas all the other laboratory-melted steels were heated twice. All four steels showed some improvement over the base steel but Steel 15, which contained boron, was considerably better than Steels 12, 13, and 14, particularly for the ESW simulation. For this simulation, Steels 12, 13, 14, and 15 absorbed 16, 18, 12, and 34 ft-lb, respectively, at 0°F. Steel 14, which contained about twice as much titanium and nitrogen as Steel 13 but otherwise had the same nominal composition, had poorer toughness than Steel 13 for the SAW simulation. The difference in aluminum content between Steels 12 and 13 (0.012 versus 0.030%) did not result in any significant difference in toughness.

Steels 16, 17, 18, and 19. These four steels all had calcium additions, contained titanium, and were reheated twice for rolling. Steel 18 was REM-treated, and Steel 19 contained boron. All four of these steels had considerably better toughness than the base steel for both weld simulations and, overall, the boron-containing steel was the best of this group, as was the boron-containing steel in the group of Steels 12 through 15. Even though these steels were heated twice above 2000°F, their toughness was generally good. However, because none of the steels that were heated once had the same composition as those heated twice, no conclusion can be drawn as to the effect of reheating twice.

Steel 20. This steel did not have residual elements added, had a low silicon content (0.05%), and contained vanadium and boron. This steel had better toughness than the base steel and somewhat better toughness than the other vanadium steel in this investigation (Steel 7) for the SAW simulation, but it was not nearly as tough as Steel 7 for the ESW simulation (18 versus 35 ft-lb at 0°F).

Steels L, N, and U. Neither Steel L nor Steel U was significantly better than the base steel except that Steel U was somewhat better than the base steel for the SAW simulation (16 versus 8 ft-lb at 0°F). For the SAW simulation, Steel N was the best steel investigated, but for the ESW simulation many of the other steels in this investigation were better. This commercial steel is recommended by its producer for high-heat-input SA welds but not for ES welds.

Welded Steels

Primarily on the basis of the toughness of the Gleeble-treated samples, and to a lesser extent of the microstructure and alloy system to which the steels belonged, eight laboratory-melted steels (Steels 4, 7, 11, 12, 15, 17, 18, and 19) were selected for welding in addition to the three commercially produced steels. These 11 steels are identified in the last column in Table VI. Although Table VI shows that Steels 1 and 2 had good toughness, these steels are laboratory-melted versions of commercial steels and were included in the investigation for information only; they were not part of the alloy investigation and thus were not selected for welding. Although the Gleeble-treated samples of Steel 4 did not have good toughness, it was the base steel in this study and was welded for comparison. Steel 16 had good toughness but was not welded because Steel 17 had somewhat better toughness and belonged to the same alloy system (Ti-N). The toughness values of the Gleeble-treated samples of Steel 11 were not very good but the microstructure of these samples was very fine and it was selected for that reason.

Toughness of Weldments

Each of the 11 steels selected for welding was ES-welded at a heat input of about 1000 kJ/inch and SA-welded at heat inputs of 180 and 75 kJ/inch. Individual CVN test results obtained from these weldments are given in Appendix Tables D, E, and F for the ES weld and the 180 and 75 kJ/inch SA welds, respectively. Average CVN energy absorbed at 0°F (-18°C) and -40°F (-40°C) for tests at the fusion line and 1- and 3-mm HAZ locations are shown in Tables VII, VIII, and IX for these three welding processes. Parent-plate-toughness values are also shown in these tables for comparison. For each of comparison, the results from Tables VII, VIII, and IX for the 1- and 3-mm HAZ locations are shown in Table X.

ES Weldments. Referring to Table X it is apparent that the base steel (Steel 4) had the poorest toughness at the 1-mm test location of all the laboratory-melted steels that were ES-welded.

Table VII Charpy V-Notch Impact Properties
of ESW Joints Investigated (Heat
Input of Approximately 1000 kJ/in)

| | Energy Absorbed, ft-lb | | | | | | | |
| | at 0°F | | | | at -40°F | | | |
Steel	Plate	FL*	1 mm	3 mm	Plate	FL	1 mm	3 mm
4	105	11	12	46	76	11	6	41
7	106	28	63	62	76	13	33	60
11	110	29	29	64	20	13	9	24
12	65	20	38	46	44	21	18	27
15	65	26	35	41	31	9	16	21
17	31	22	53	51	55	29	17	15
18	226	36	65	87	137	19	14	31
19	52	42	45	50	24	13	35	44
N	121	65	44	91	96	34	8	70
L	163	32	9	7	133	10	5	8
U	40	27	24	30	25	20	11	16

* Fusion line.

Table VIII Charpy V-Notch Impact Properties
of SAW Joints Investigated (Heat
Input of 180 kJ/in)

| | Energy Absorbed, ft-lb | | | | | | | |
| | at 0°F | | | | at -40°F | | | |
Steel	Plate	FL*	1 mm	3 mm	Plate	FL	1 mm	3 mm
4	105	29	29	34	76	15	16	24
7	106	48	55	85	76	16	19	66
11	110	45	47	39	20	29	19	22
12	65	67	49	57	44	38	35	43
15	65	50	40	44	31	24	25	21
17	81	51	54	62	55	19	22	44
18	226	60	47	68	137	15	18	34
19	52	62	51	49	24	39	24	29
N	121	53	51	91	96	21	21	57
L	163	34	20	71	133	14	10	46
U	40	37	28	27	25	29	16	20

* Fusion line

Table IX Charpy V-Notch Impact Properties of SAW Joints Investigated (Heat Input of 75 kJ/in)

| | Energy Absorbed, ft-lb | | | | | | | |
| | at 0°F | | | | at -40°F | | | |
Steel	Plate	FL*	1 mm	3 mm	Plate	FL	1 mm	3 mm
4	105	53	69	73	76	34	26	44
7	106	120	101	100	76	49	52	78
11	110	81	76	28	20	65	23	8
12	65	74	68	61	44	43	50	45
15	65	66	59	43	31	45	37	33
17	91	100	89	59	55	71	66	43
18	226	121	133	117	137	89	75	63
19	52	74	49	16	24	52	42	8
N	121	109	112	108	96	76	76	89
L	163	77	138	141	133	25	132	115
U	40	44	42	35	25	44	40	33

* Fusion line.

Table X Comparison of HAZ Toughness for the Three Welding Conditions Investigated

	CVN Energy Absorbed, ft-lb													
	0°F							-40°F						
	ESW		SAW 180 kJ/in.		SAW 75 kJ/in.		Minimum Value for any Weld and	ESW		SAW 180 kJ/in.		SAW 75 kJ/in.		Minimum Value for any Weld and
Steel	1 mm	3 mm	1 mm	3 mm	1 mm	3 mm	Either Position	1 mm	3 mm	1 mm	3 mm	1 mm	3 mm	Either Position
4	12	46	29	34	69	73	12	6	41	16	24	26	44	6
7	63	62	55	85	101	100	55	33	60	19	66	52	78	19
11	29	64	47	39	76	28	28	9	24	19	22	23	8	8
12	38	46	49	57	68	61	38	18	27	35	43	50	45	18
15	35	41	40	44	59	43	35	16	21	25	21	37	33	16
17	53	51	54	62	89	59	51	17	15	22	44	66	43	15
18	65	87	47	68	133	117	47	14	31	18	34	75	63	14
19	45	50	51	49	49	16	16	35	44	24	29	42	8	8
N	44	91	51	91	112	108	44	8	70	21	59	76	89	8
L	9	7	20	71	138	141	7	5	8	10	46	132	115	5
U	24	30	28	27	42	35	24	11	16	16	20	40	33	11

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These toughness comparisons will be based on the 1-mm location rather than the 3-mm location because this location generally has poorer toughness for the high-heat-input welding processes. The two steels with the best toughness at -40°F (-40°C) for the 1-mm position were Steels 7 (vanadium steel) and 19 (titanium-boron steel). It should be noted, however, that at the -40°F test temperature the base-plate toughness of the vanadium steel was about triple that of the titanium-boron steel. Four other titanium steels (12, 15, 17, and 18) had considerably better toughness than that of the base steel at the 1-mm location.

180 kJ/inch SA Weldments. All the laboratory-melted steels had reasonably good HAZ toughness for the 180 kJ/inch welds, as shown in Table X. Steels 7 and 19, which had the best HAZ toughness for the ES weld, had good HAZ toughness for this weld, but were not the best. The highest toughness steel at -40°F (35 ft-lb) for this weld condition was Steel 12, the titanium steel that was only reheated once for rolling.

75 kJ/inch SA Weldments. All the steels welded had good HAZ toughness for the 75 kJ/inch heat input SA welds except Steels 11 and 19 at the 3-mm position. Both these steels contained titanium and boron. The low toughness of Steel 19 at the 3-mm position would be a serious deterrent to the use of this titanium-boron steel even though it had very good HAZ toughness when ES-welded because any steel selected for high-heat-input welding should also be suitable for more typical heat inputs.

Hardness of Weldments. Hardness measurements were made in the base plate, weld metal, and the 1- and 3-mm locations in the HAZ for all the weldments, and are shown in Appendix Table G. No correlation was found between HAZ hardness and toughness.

Overall HAZ Toughness for all Welding Conditions. To be usable for ship construction, a steel must be weldable under typical heat inputs. In Table X, minimum CVN energy values for 0 and -40°F test temperatures for any of the three welding conditions are shown. The steel having the highest toughness (19 ft-lb) for its worst test location is Steel 7. For the -40°F test temperature, four titanium steels—Steels 12, 15, 17, and 18—are nearly as tough (14 to 18 ft-lb).

Comparison of Toughness of Weld
HAZ With Gleeble-Treated Samples

Table XI shows results of CVN tests of Gleeble-treated samples side-by-side with results from weld HAZ CVN tests at the 1-mm position. Actually, the thermal cycles of the Gleeble-treated specimens are representative of a zone closer to the fusion line

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Table XI CVN Energy Absorption (ft-lb) of Gleeble-Treated
Samples and HAZ of Welds at 1-mm Position

| | ES Weld | | | | SA Weld | | | |
| | 0°F (-18°C) | | -40°F (-40°C) | | 0°F | | -40°F | |
Steel	Gleeble Simulation	Weldment	Gleeble Simulation	Weldment	Gleeble Simulation	Weldment	Gleeble Simulation	Weldment
4	12	14	*	7	8	29	*	16
7	35	58	17	33	15	56	11	22
11	26	29	9	11	11	47	*	19
12	16	38	*	19	28	51	13	34
15	34	34	12	17	35	42	18	24
17	34	49	16	19	25	54	17	26
18	73	70	17	15	32	46	9	18
19	53	46	43	34	44	51	28	25
L	6	9	*	5	10	20	*	10
N	31	44	8	8	64	51	30	21
U	13	24	*	11	16	28	8	16

* Not tested.

than 1 mm, but fusion-line test specimens from the weldments generally extend into the weld metal so that the 1-mm location test specimen would be expected to be more like the Gleeble-treated specimens.

Considering the scatter in the data, which is apparent in the Appendix tables where individual test results are reported, the results shown in Table XI for the ES weldment and the Gleeble simulation are surprisingly close. For the SA weld, the results for the two techniques are not nearly as close, and usually the weldment tests yielded higher toughness values. This poorer agreement between weldment tests and Gleeble samples is to be expected because of the geometry of the fusion zone in this two-pass weld, which was never perpendicular to the plate surface at the notch location. An example of the position and length of the notch in a CVN specimen at the 1-mm HAZ location is shown in Figure 14B for a typical 180 kJ/inch SA weld used in this investigation. Figures 14A and 14C are typical weldments for the 75 kJ/inch SA and ES weld conditions.

Microstructure of Weldments

Micrographs of the HAZ region of the weldments are given in Figures 3 through 13 (C, D, and E) for each of the 11 steels welded. In each micrograph of the weldments, the weld metal is on the right side and the bond line is about one-half inch from the right side of the micrograph. Generally, the micrographs of the Gleeble-treated samples show a microstructure similar to that in the weld HAZ near the bond line.

Finer details of the microstructure in the HAZ are shown in Figure 15 for the ES weldments and in Figure 16 for the 180 kJ/inch SA weldments. The HAZs of several of the weldments contain numerous small grains of martensite, examples of which are indicated by the arrows on the micrographs of Figures 15A for Steel 4 and 15C for Steel 11. Although the HAZs with large amounts of the martensite tend to have poorer toughness than the martensite-free ones, the correlation is not very strong. For example, Steel 19, when SA-welded, had a considerable amount of martensite in the HAZ, as shown in Figure 16H, but the HAZ had good toughness.

Conclusions

Steel 7, the calcium-treated 0.08 percent vanadium steel with low residual content, appears to have the best combination of HAZ toughness and base-plate strength and toughness. For CVN tests at 0°F (-18°C) this steel had the best, or nearly the best HAZ

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A. SAW weld. 75 kJ/inch

Vertical line
shows lengths
and location of
1-mm position
notch in CVN
specimen at
t/4 thickness

B. SAW weld. 180 kJ/inch
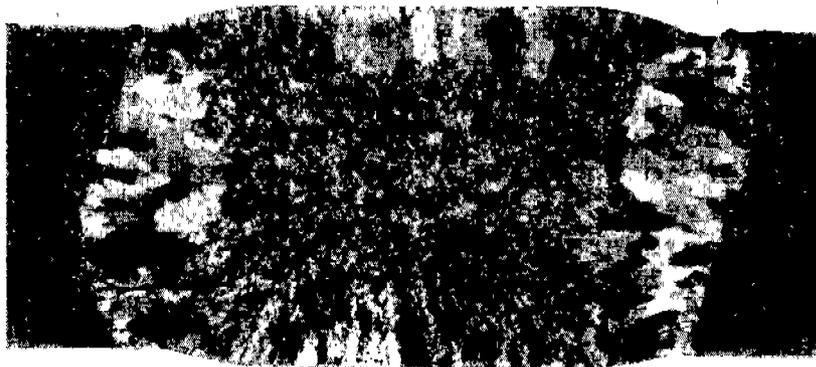
C. ES weld. 1000 kJ/inch

Figure 14. Macrographs of typical joints for the three welding
conditions used

A. Steel 4
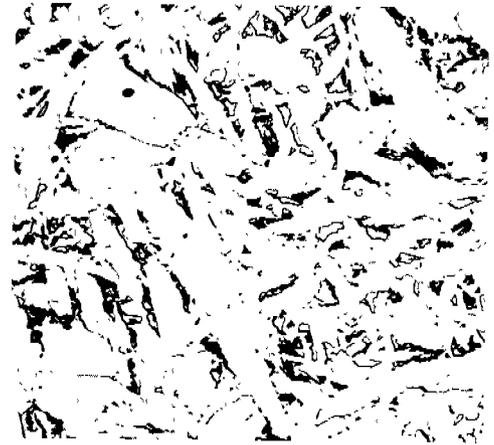
D. Steel 12
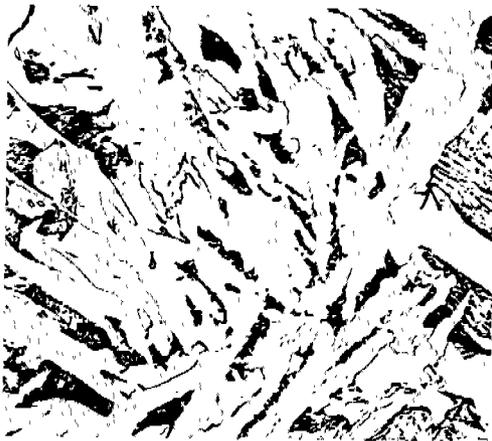
B. Steel 7
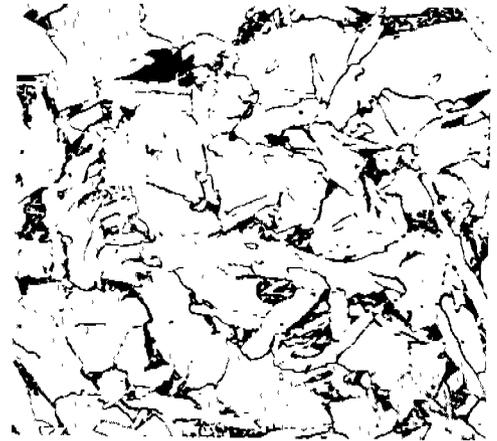
E. Steel 15

C. Steel 11

F. Steel 17

Figure 15   Micrographs of the HAZ of the ES-weldments.
Nital Etch.   800X

33
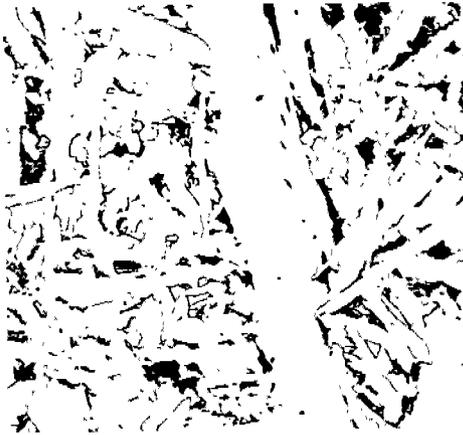
G. Steel 18

H. Steel 19

J. Steel L

I. Steel N

K. Steel U

Figure 15 Micrographs of the HAZ of the ES-weldments.
Nital Etch. 800X   (Continued)

34
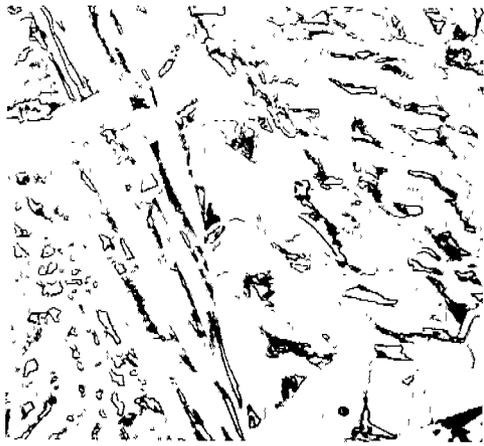
A. Steel 4
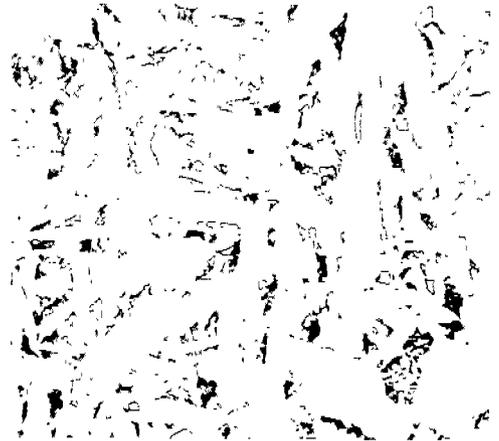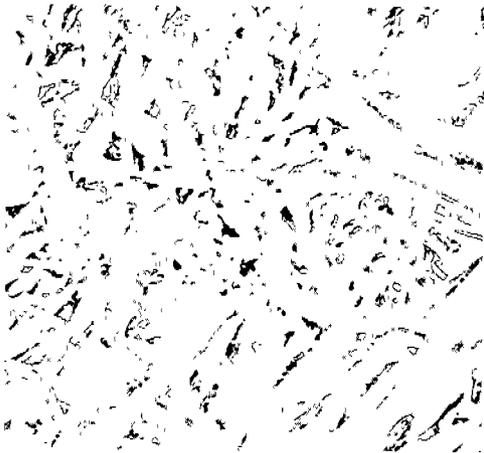
D. Steel 12

B. Steel 7
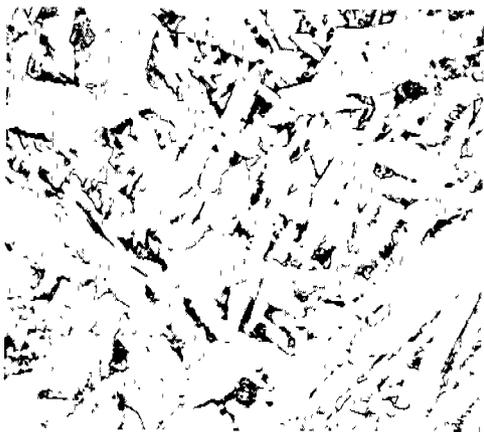
E. Steel 15

C. Steel 11

F. Steel 17

Figure 16   Micrographs of the HAZ of the 180 kJ/inch SA-weldments.
Nital Etch.   800X.
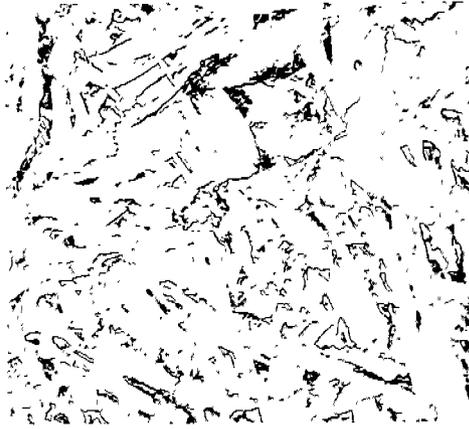
G. Steel 18
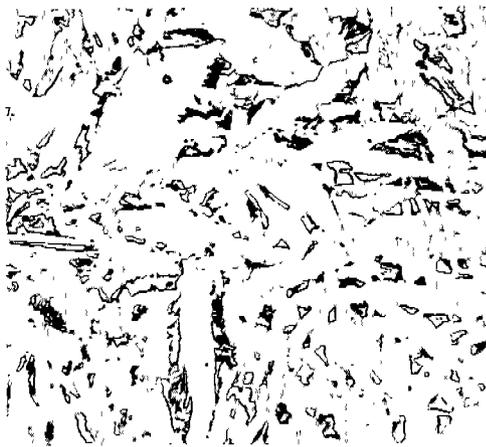
H. Steel 19

J. Steel L

I. Steel N

K. Steel U

Figure 16 Micrographs of the HAZ of the 180 kJ/inch SA-weldments.
Nital Etch. 800X.

toughness for all three welding conditions used. Furthermore, the base-plate strength and toughness of this steel were substantially better than those of any of the titanium steels studied. The literature has indicated that vanadium in amounts in excess of about 0.10 percent had detrimental effects on HAZ toughness[5,6] and that about 0.06 percent vanadium may have a slightly beneficial effect.[6] Consequently, the very good HAZ toughness of Steel 7 was unexpected. The improved toughness of Steel 7 compared with the base steel may have resulted from its lower hardenability, which in turn resulted from the near absence of copper, nickel, chromium, and molybdenum in this steel (about 0.5% in the base steel).

Several of the titanium steels had very good HAZ toughness for all three welding conditions used. Two of the three titanium steels that also contained boron had very good HAZ toughness for the high-heat-input welding processes but had poor toughness at the 3-mm HAZ location for the 75 kJ/inch SA weld. The one titanium-boron steel (Steel 15) that did not exhibit this reduced toughness was reheated only once for rolling and also contained about twice as much titanium as the other two titanium-boron steels. Additionally, the titanium-boron steels had the poorest base-plate toughness of all the investigated steels so that the boron addition to these titanium steels is not an attractive method of producing a steel with improved HAZ toughness.

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APPENDIX A Individual Transverse Charpy V-Notch Test Results from the Investigated Plates

Steel	Test Temperature, °F	Energy Absorbed, ft-lb	Shear-Fracture Appearance, %	Lateral Expansion, mils
1	0	107,102,107	70,70,70	80,71,78
	-40	81,74,90	50,45,50	66,61,69
	-80	59,53,40	25,25,20	55,42,32
	-100	10,30,35	5,10,10	6,21,25
	-120	18,20,15	5,5,5	11,13,10
	-140	9,6,6	5,5,5	4,2,5
2	77	55,60,56	100,100,100	61,66,61
	0	35,35,35	60,65,55	42,38,39
	-20	25,25,26	35,35,40	30,29,31
	-40	21,20,20	25,25,25	27,22,23
	-60	19,20,17	15,15,15	20,20,17
	-80	12,17,15	10,10,10	12,16,14
3	0	52,57,52	90,90,90	51,55,51
	-20	42,51,41	40,55,45	41,49,40
	-40	40,39,34	40,40,40	38,38,36
	-80	28,31,25	15,10,15	27,29,24
	-120	17,17,17	5,5,5	12,11,11
	-140	14,16,16	5,5,5	10,11,12
4	0	98,108,108	60,70,60	75,82,79
	-40	62,83,83	25,35,35	54,67,66
	-80	65,50,66	15,10,15	52,41,53
	-120	51,24,36	15,10,10	38,16,28
	-140	35,15,9	10,5,5	23,7,5
	-160	10,9,10	5,5,5	5,4,5
5	0	102,100,107	50,50,55	73,72,73
	-80	52,52,68	20,20,25	42,41,54
	-120	45,45,47	15,15,15	34,35,36
	-160	28,28,12	10,10,5	19,19,9
	-180	23,13,24	5,5,5	14,8,12
	-200	6,6,5	5,5,5	7,5,5
6	0	113,170,115	70,65,70	80,81,77
	-40	95,99,83	40,45,40	73,74,64
	-80	70,37,58	35,20,25	59,31,47
	-120	37,45,47	15,15,15	30,36,37
	-140	7,18,8	5,5,5	5,13,6
	-160	9,9,12	5,5,5	6,6,7
7	0	113,101,105	60,60,60	76,72,74
	-20	83,84,87	35,40,40	64,64,67
	-40	84,73,71	30,25,25	61,57,54
	-80	75,60,57	20,15,15	61,47,46
	-120	26,15,19	10,5,5	21,10,13
	-140	7,18,8	5,5,5	5,13,6
8	0	226,237,221	100,DNB,100	77,DNB,82
	-40	138,178,190	60,100,100	86,91,89
	-80	108,112,127	40,45,50	81,91,89
	-120	87,91,96	30,30,30	67,70,74
	-140	82,12,18	25,5,5	66,8,11
	-160	10,8,8	5,5,5	9,6,8
9	0	130,113,119	90,55,60	86,80,82
	-80	72,79,74	25,30,25	58,66,61
	-120	77,51,45	20,15,15	62,40,33
	-140	65,45,30	20,15,10	51,38,26
	-160	37,20,17	10,5,5	13,9,7
	-180	10,15,15	5,5,5	7,11,9
10	0	85,87,102	50,55,60	72,70,77
	-40	87,89,77	35,35,30	69,74,62
	-80	39,62,60	10,20,20	33,49,47
	-120	35,43,35	10,15,10	28,34,25
	-140	35,26,15	10,10,5	25,20,15
	-160	10,7,12	5,5,5	4,2,6
11	40	160,230,129	65,DNB,55	90,DNB,86
	20	111,117,127	50,50,50	78,82,84
	0	70,130,131	25,40,50	56,89,96
	-40	16,10,35	5,5,10	17,10,19
	-60	9,9,11	5,5,5	9,9,10
	-80	7,9,5	5,5,5	4,6,3

Steel	Test Temperature, °F	Energy Absorbed, ft-lb	Shear-Fracture Appearance, %	Lateral Expansion, mils
12	77	107,98,100	99,85,90	81,81,81
	0	60,62,72	25,25,30	53,54,62
	-40	48,35,48	20,15,20	45,35,44
	-80	25,10,38	10,5,10	21,11,32
	-100	10,5,9	5,5,5	7,3,6
	-120	4,9,5	5,5,5	2,6,2
13	77	90,96,95	95,95,95	79,79,82
	0	43,63,59	25,30,30	43,56,53
	-40	50,45,44	25,20,20	46,42,42
	-60	27,19,35	15,10,15	25,20,30
	-80	10,17,20	5,5,10	12,18,21
	-100	7,9,11	5,5,5	6,7,8
14	40	85,95,94	55,60,60	71,76,73
	20	78,71,68	50,50,45	62,59,56
	0	55,64,55	25,30,25	48,55,49
	-40	44,46,43	15,15,10	39,41,38
	-60	31,23,35	10,10,10	28,21,30
	-80	13,16,10	5,5,5	11,15,9
15	77	93,107,103	60,60,70	80,84,82
	40	81,75,81	40,40,40	71,64,68
	0	63,62,69	25,25,30	54,54,58
	-40	22,50,20	15,20,15	25,42,21
	-60	26,12,12	15,10,10	24,13,12
	-80	8,9,8	5,5,5	9,10,9
16	77	121,116,115	70,65,65	85,83,83
	40	108,106,115	50,55,60	78,78,78
	0	83,63,63	35,25,25	68,52,53
	-40	21,63,65	10,20,20	22,52,55
	-60	11,15,18	5,10,10	11,12,16
	-80	8,8,7	5,5,5	9,9,7
17	40	106,94,94	50,50,55	75,72,72
	0	83,65,94	40,30,45	68,55,74
	-40	50,63,52	20,25,20	44,52,45
	-80	19,31,41	10,15,20	17,26,34
	-100	8,18,30	5,5,10	7,13,20
	-120	5,8,4	5,5,5	1,3,1
18	0	206,234,238	100,DNB,DNB	84,DNB,DNB
	-20	219,188,238	DNB,70,DNB	DNB,90,DNB
	-40	182,102,127	65,35,40	96,78,90
	-60	11,16,234	10,10,DNB	11,15,DNB
	-80	10,14,14	5,5,5	8,12,12
19	77	81,85,86	50,66,60	71,75,75
	40	60,71,66	40,40,40	55,64,71
	0	45,60,50	15,20,20	42,52,46
	-40	25,35,13	10,15,5	24,26,14
	-60	9,14,11	5,10,10	9,14,12
	-80	8,5,6	5,5,5	6,4,5
20	0	79,63,85	55,50,60	65,57,70
	-20	83,77,68	55,50,45	67,64,58
	-40	58,62,60	25,25,25	53,54,53
	-80	32,43,30	10,15,10	29,36,27
	-100	6,13,19	5,5,5	7,8,10
	-120	13,6,6	5,5,5	7,1,1
L	0	147,158,185	100,100,100	87,91,96
	-50	120,129,130	60,60,65	83,84,87
	-75	117,117,119	50,50,50	73,75,78
	-100	87,90,110	30,30,40	68,70,84
	-150	15,22,54	5,5,15	11,12,38
	-175	13,10,10	5,5,5	6,2,3
N	25	120,144,148	60,70,80	81,84,89
	0	118,121,123	50,50,50	81,82,81
	-25	103,106,107	35,40,40	80,80,77
	-50	89,90,91	30,30,30	64,66,68
	-100	15,38,40	5,10,10	13,32,33
	-125	6,6,12	5,5,5	1,2,9
U	77	76,73,75	100,100,100	77,73,74
	40	61,61,55	85,90,85	59,61,54
	0	36,38,45	35,35,45	40,41,45
	-40	25,24,25	20,15,15	28,26,27
	-60	15,20,17	5,10,5	14,20,16
	-80	17,11,12	5,5,5	14,9,10

DNB means did not break

Steel	Test Temperature, °F	Energy Absorbed, ft-lb	Shear-Fracture Appearance, %	Lateral Expansion, mils
1	40	37,46,49	15,20,20	29,39,38
	0	12,17,20	5,5,5	11,13,17
	-20	16	5	12
	-40	15,6,18	5,5,5	8,3,12
2	40	32,30	35,35	33,31
	0	17,24,23	10,10,10	18,25,22
	-20	7,22	5,10	4,19
	-40	15,15,17	5,5,5	13,13,13
3	77	30,24	30,25	32,27
	40	17,20,16	10,10,10	20,19,18
	20	11,10	5,5	12,10
	0	6,10,10	5,5,5	5,10,10
4	77	41,52	20,25	36,43
	40	18,22,19	15,15,10	19,20,18
	20	14,15	10,10	13,14
	0	11,10,15	5,5,5	10,11,14
5	77	24,29	15,15	24,32
	60	20,18	15,10	22,17
	40	12,12	10,10	13,13
	0	10,9,10	5,5,5	9,12,10
6	77	46,14	20,10	36,16
	40	23,34,30	10,15,15	18,25,22
	20	21,15	10,10	18,12
	0	15,9,8	5,5,5	13,8,6
7	0	24,41,41	5,15,20	16,30,32
	-20	12,23	5,10	9,22
	-40	10,19,21	5,5,5	6,12,14
	-60	20,6	5,5	14,2
8	77	64,46	15,10	49,36
	40	18,18,20	5,5,5	13,13,16
	20	22,15	5,5	23,16
	0	8,6,8	5,5,5	4,5,4
9	77	50,62	30,35	43,53
	40	14,17,51	10,15,20	13,18,36
	20	15,16	10,15	15,15
	0	11,8,11	5,5,5	11,9,10
10	74	25,15	15,15	26,16
	74	12,31	5,15	13,31
	40	24,8,7	10,5,5	26,9,6
	0	6,6,6	5,5,5	6,4,6
11	0	34,18,25	20,10,15	29,17,23
	-20	13,13	5,5	11,12
	-20	9,11	5,5	6,10
	-40	8,10,8	5,5,5	7,8,8

Steel	Test Temperature, °F	Energy Absorbed, ft-lb	Shear-Fracture Appearance, %	Lateral Expansion, mils
12	40	60,49	45,35	48,40
	20	40,39	25,25	37,36
	0	16,10,23	15,5,15	16,7,24
13	40	60,56	40,40	48,47
	20	38,45	25,30	36,39
	0	21,15	15,15	24,18
	-40	11,10	5,5	11,8
14	60	30,42	30,35	31,38
	40	22,38	20,25	22,34
	20	18,20	20,20	20,21
	0	11,12	10,10	13,13
15	0	20,46,35	20,20,20	21,40,30
	-20	13,14,45	15,15,20	13,14,36
	-40	11,13,11	10,10,10	12,13,13
16	40	84,63	40,35	67,51
	0	14,50,40	10,20,20	14,43,37
	-20	15,16	15,15	15,16
	-40	10,10,15	10,10,10	11,11,15
17	0	40,27,36	20,15,20	33,23,31
	-20	12,13	10,10	12,14
	-20	37,9	20,10	31,9
	-40	10,22,15	10,10,10	11,18,14
18	0	99,95,24	40,40,10	74,73,21
	-20	80,10	30,10	63,12
	-40	30,9,12	10,5,10	25,10,12
	-60	11,10	5,5	11,10
19	0	60,54,44	35,20,15	53,48,43
	-40	41,45	15,15	36,37
	-60	20,28,22	10,10,10	19,23,20
	-80	7,7	5,5	7,6
20	74	40,45,54	25,30,35	34,41,48
	40	10,11	5,5	10,13
	0	6,19,30	5,5,10	6,15,23
	-40	11,10	5,5	12,9
L	100	13,17	10,10	16,16
	74	14,15,14	15,10,10	15,15,14
	40	9,8	5,5	8,8
	0	7,5,7	5,5,5	5,3,4
N	40	94,88	35,30	71,68
	20	74,60,73	25,20,25	62,52,61
	0	16,62,16	15,25,15	16,51,17
	-40	6,10	5,5	7,10
U	40	25,30,27	20,20,20	28,30,29
	20	12,14,29	10,10,15	13,15,27
	0	22,6,10	10,5,5	21,7,9

APPENDIX C   Individual Charpy V-Notch Test Result from SA-Weld-Simulation Gleeble Samples

Steel	Test Temp., °F	Energy Absorbed, ft-lb	Shear-Fracture Appearance, %	Lateral Expansion, mils
1	20	53,56	15,15	38,42
	0	11,31,42	5,10,10	9,22,32
	-40	10,10,35	5,5,10	10,8,24
	-60	9,18	5,5	8,10
2	0	23,25,29	10,10,15	22,22,27
	-40	18,19,20,21	5,5,5,5	16,17,18,20
	-60	3,13,14	5,5,5	2,12,14
3	RT	25,25,28	15,25,15	29,30,28
	40	13,17,21	10,10,10	15,19,20
	0	8,9,12	5,5,5	10,11,14
4	RT	27,31,33,37	15,15,15,15	26,29,34,38
	40	15,15,16	10,10,10	17,17,18
	0	8,8,9	5,5,5	10,10,9
5	RT	39,49	20,25	35,40
	40	15,18,22	5,5,10	12,16,21
	20	12,16	5,5	12,14
6	RT	39,48,54	20,20,20	36,37,44
	40	26,26,30,46	10,10,10,15	22,22,23,37
	0	8,8,11	5,5,5	6,7,9
7	40	25,35	15,20	20,24
	0	5,6,33	5,5,10	4,6,22
	-20	6,14,22	5,5,5	4,10,16
	-40	7,14	5,5	5,10
8	RT	12,15,17,38,42	20,10,20,15,20	16,16,20,30,35
	40	16,20,21	5,10,10	14,17,16
	0	4,6	5,5	3,5
9	RT	26,39,39	20,20,25	36,38,36
	40	15,20,32,36	10,10,15,15	16,21,28,31
	0	6,7,9	5,5,5	8,8,9
10	RT	9,12,28,34	5,5,10,30	12,14,28,34
	40	11,13,15,25	5,5,5,10	10,12,15,22
	0	7,9	5,5	7,8
11	40	24,41,44	10,10,10	18,30,32
	20	11,32,41	15,10,15	10,24,32
	0	7,7,10,19	5,5,5,5	6,7,10,16
12	20	25,45	25,35	26,37
	0	25,31	10,15	23,27
	-20	13,16	5,5	9,10
	-40	12,14	5,5	12,14

Steel	Test Temp., °F	Energy Absorbed, ft-lb	Shear-Fracture Appearance, %	Lateral Expansion, mils
13	20	26,32	20,25	21,29
	0	26,28	15,15	22,25
	-20	12,14	10,10	13,14
	-40	7,16	5,5	5,12
14	20	24,36	20,25	21,29
	0	12,18,25	10,10,15	13,20,23
	-40	6,7	5,5	5,6
15	0	19,39,47	15,20,20	18,33,42
	-40	15,15,19,21	10,10,10,10	15,16,18,22
	-60	6,8,18	5,5,5	10,10,16
16	RT	40,80	35,60	32,62
	40	59,67	35,40	44,48
	0	9,21,25	5,10,15	8,19,23
	-40	11,12,12	5,5,5	12,12,12
17	40	62,63,63	35,35,35	49,49,50
	0	13,29,33	10,20,20	14,25,25
	-40	13,14,19,21	5,5,5,5	14,15,17,20
18	40	80,87	40,40	54,56
	0	31,23,43	15,15,20	26,20,33
	-20	19,21	10,10	16,20
	-40	7,10,11	5,5,5	5,9,14
19	0	44,44	25,25	36,36
	-40	20,24,39	15,15,20	19,11,32
	-60	9,10,27,34,36	5,5,5,5,10	10,10,24,28,30
20	40	7,42	5,10	10,32
	0	13,15,33	5,5,10	10,10,24
	-20	3,25,27	5,5,5	2,18,18
	-40	11,18	5,5	6,14
L	72	10,18,19,22,27	10,10,10,15,15	5,10,10,10,13
	40	11,11,14	5,5,5	6,6,11
	0	7,11,11	5,5,5	5,6,8
N	0	60,67	25,25	49,54
	-40	7,41,43	5,10,10	5,18,20
	-60	5,5,12	5,5,10	3,3,6
	-80	5,5	5,5	3,3
U	74	35,30	40,35	38,30
	40	26,27,26	15,15,20	26,27,26
	0	16,11,20	5,5,10	14,10,18
	-40	3,12	5,5	2,9

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APPENDIX D   Individual Charpy V-Notch Data for Electroslag-Welded Steels (Heat Input of Approximately 1000 kj/in)

Steel	Temp., °F	Energy Absorbed, ft-lb FL	1 mm	3 mm	Shear-Fracture Appearance, % FL	1 mm	3 mm	Lateral Expansion, mils FL	1 mm	3 mm
4	0	11,11,16,12,7	15,12,26,10,8	50,52,60,36,37	5,5,5,5,5	10,10,15,10,10	30,30,35,25,25	11,11,16,11,9	11,11,16,9,11	42,46,52,32,41
	-40	13,12,10,7,10	6,5,6,7,10	46,18,50,39,39	5,5,5,5,5	5,5,5,5,5	30,10,30,25,15	9,10,8,5,8	5,4,5,6,10	39,18,43,34,34
7	0	72,34,17,11,34	27,48,68,73,72	60,61,65,31,74	15,10,5,5,10	10,20,25,30,30	30,30,35,15,40	52,29,12,8,22	21,33,52,53,53	46,48,53,26, 6
	-40	38,8,7,16,14	43,25,46,30,20	69,81,65,47,45	10,5,5,5,5	10,5,10,5,5	20,30,20,15,15	29,3,3,14,13	30,14,34,19,12	54,64,47,32,36
11	0	51,22,14,21,44	30,34,27,25,29	89,42,54,76,62	20,10,10,10,15	10,10,10,10,10	25,15,20,25,20	46,20,16,20,39	26,28,25,22,26	72,34,35,60,50
	-40	37,10,14,14,12	8,8,8,11,22	29,13,58,31,20	15,5,10,5,5	5,5,5,5,10	15,10,20,15,5	30,10,14,13,11	9,9,8,9,17	24,14,47,25,10
12	0	25,19,16,16,41	30,47,35,45,34	52,45,50,41,44	20,15,15,15,25	15,20,20,20,20	25,20,25,20,20	24,22,18,18,36	24,36,32,35,31	42,40,42,34,38
	-40	31,9,20,28,15	26,11,29,11,16	11,31,38	10,5,5,10,5	10,5,10,5,5	10,15,15	24,10,15,23,12	21,9,22,11,14	12,28,32
15	0	21,20,33,25,32	38,35,41,32,33	46,41,40,42,34	25,25,25,20,25	20,15,20,15,15	25,20,20,20,20	20,21,28,22,25	33,29,34,28,28	25,20,20,20,20
	-40	10,13,8,8,10	10,15,25,13,20	30,14,14,30,18	10,15,10,10,10	10,10,15,10,15	10,10,10,10,10	10,10,6,7,8	8,12,19,12,18	10,10,10,10,10
17	0	26,18,22,18,50	51,59,57,51,28	53,47,52,53,48	20,15,20,15,25	25,30,30,25,20	25,25,30,35,25	26,18,23,20,42	44,51,51,45,28	47,43,46,47,42
	-40	30,13,32,24,34	34,12,11,28,10	14,17,26,15,10	20,10,20,10,35	10,5,5,5,5	10,10,15,5,5	26,13,26,19,32	28,12,12,26,10	15,15,26,16,11
18	0	31,51,41,36,22	46,93,44,110,55	90,74,84,108,88	10,25,20,15,10	10,30,20,35,25	35,25,30,50,30	26,41,33,31,20	36,70,37,81,43	70,60,57,78,68
	-40	29,11,18,18,20	9,11,18,13,23	15,49,32,16,45	10,5,5,10,15	10,10,10,10,15	15,20,20,15,20	20,9,12,16,18	9,11,17,13,22	16,37,24,16,35
19	0	27,49,97,45,32	48,44,42,50,44	51,51,49,44,55	35,30,55,20,15	20,20,20,25,20	30,30,30,25,30	30,42,73,37,30	42,40,40,44,39	44,44,43,39,48
	-40	13,30,14,11,11	24,34,32,41,38	41,50,43,48,15	10,15,10,5,5	10,10,10,10,10	10,15,10,15,5	18,25,16,10,12	21,30,26,35,32	35,40,35,40,15

Steel	Temp., °F	WM	FL	1 mm	3 mm	5 mm	WM	FL	1 mm	3 mm	5 mm	WM	FL	1 mm	3 mm	5 mm
N	40	70,57,34	90,147,57	79,52,91			50,45,45	35,75,25	30,25,30			55,48,45	66,92,46	68,43,76		
	0	83,27,27	127,38,29	56,29,46	85,84,105	111,92,128	50,20,20	50,20,15	25,15,20	40,40,50	50,50,75	61,25,27	85,38,29	51,30,42	72,72,78	82,70,80
	-40	19,30,15	17,5,60	7,9,8	81,75,53	116,114,87	15,20,10	10,5,40	5,5,5	35,30,20	50,50,35	22,26,15	14,5,55	8,10,9	67,64,47	83,82,71
	-80	8,9,8	7,7,5	7,5,5	6,53,8	67,74,49	10,10,10	5,5,5	5,5,5	5,15,5	20,20,15	5,5,5	5,7,4	4,4,3	6,41,7	54,57,38
	-120				4,9,11	9,30,15				5,5,5	5,10,5				4,5,6	7,20,9
L	75	50,59,77	85,94,87	33,14,43	34,16,17		50,60,65	65,70,65	15,10,20	20,10,10		47,52,60	70,73,67	28,14,35	27,18,20	
	40	38,49,70	66,16,114	10,21,16	8,32,20		30,35,60	50,10,65	10,10,10	5,35,10		33,38,53	51,13,82	10,19,10	8,28,17	
	0	26,30,20	7,54,36	9,8,10	10,7,5	167,144,164	20,20,15	5,40,20	5,5,10	5,5,5	100,100,100	25,25,19	6,44,31	6,5,8	9,4,2	91,94,92
	-40	15,12,25	11,15,5	4,6,5	5,10,8	170,131,171	15,15,15	10,5,5	5,5,5	5,5,5	100,90,100	15,13,23	12,17,4	2,5,5	6,12,6	98,85,92
	-80				90,91,105						35,40,80					71,72,80
	-120				52,11,72						20,5,30					40,10,55
U	40	36,40,55	31,56,44	22,23,21	33,41,36	42,42,52	40,40,45	15,25,20	25,20,15	20,45,40	60,55,70	35,36,45	28,48,34	23,24,20	29,37,35	42,43,53
	0	25,18,27	46,25,10	22,22,28	21,38,31	32,30,34	20,15,20	15,10,10	10,10,10	10,15,30	30,25,30	24,18,25	36,14,10	19,23,22	18,33,30	31,30,34
	-40	12,11,11	20,20,21	12,10,12	18,15,14	24,26,20	10,10,10	5,5,5	5,5,5	5,5,5	20,20,15	11,10,10	12,12,13	8,10,8	13,11,9	24,25,17
	-80	6,6,5	6,8,4	5,5,5	6,8,5	11,9,13	5,5,5	5,5,5	5,5,5	5,5,5	5,5,5	5,5,4	5,6,2	3,4,2	3,5,3	9,7,9

APPENDIX E Individual Charpy V-Notch Data for Submerged-Arc Welded Steels (Heat Input of 180 kJ/in)

Steel	Temp., °F	Energy Absorbed, ft-lb FL	1 mm	3 mm	Shear-Fracture Appearance, % FL	1 mm	3 mm	Lateral Expansion, mils FL	1 mm	3 mm
4	0	24,30,28,29,55	25,31,33,30,26	33,53,28,34,34	30,30,35,30,50	35,35,40,40,35	35,50,35,40,45	21,26,26,25,44	23,28,32,28,24	29,44,27,30,31
	-40	21,16,15,15,15	12,20,13,19,17	25,25,23,21,23	20,15,15,15,15	10,15,10,20,15	25,25,25,25,25	20,18,15,17,15	13,20,12,19,18	25,24,24,20,24
7	0	60,28,30,71,54	79,81,42,33,43	91,77,86,86,83	30,15,15,35,30	40,45,20,25,30	40,35,40,50,40	46,23,26,53,44	59,60,33,30,37	73,53,67,65,67
	-40	38,11,13,15,20	17,18,21,36,16	65,66,44,68,78	20,10,10,10,15	20,20,20,25,20	25,25,20,30,30	30,8,10,12,18	17,14,17,27,13	52,49,38,52,63
11	0	65,43,44,42,49	41,47,59,35,52	40,63,25,25,51	45,35,35,35,40	40,45,50,40,45	30,35,25,25,30	54,36,35,33,39	33,37,46,28,41	33,46,26,24,39
	-40	38,13,31,21,36	24,13,15,24,17	24,20,12,21,29	20,15,15,20,20	20,15,15,20,15	20,20,20,20,20	35,15,29,22,32	21,15,17,22,18	21,19,14,20,24
12	0	79,60,74,68,51	45,52,50,32,74	25,63,52,56,62	40,45,45,45,30	30,30,30,25,50	30,40,35,35,40	62,54,58,56,42	38,43,43,28,68	26,50,42,45,52
	-40	40,41,13,32,44	16,47,36,25,45	56,47,17,46,39	20,20,15,20,20	15,20,20,15,20	25,20,15,20,20	33,32,14,29,37	15,38,32,23,37	46,41,18,38,31
15	0	46,56,48,47,54	49,38,40,41,40	39,52,48,31,45	40,50,35,45,50	35,40,30,30,35	35,40,40,30,40	39,46,40,42,44	42,32,33,34,32	34,43,41,26,38
	-40	32,21,15,20,35	25,25,20,27,24	28,23,18,22,13	20,15,10,20,20	20,20,15,20,15	20,20,15,20,15	29,19,16,20,28	22,20,18,22,21	23,22,17,20,15
17	0	35,55,50,49,71	43,33,65,73,54	63,73,61,62,53	30,40,40,40,50	35,30,35,40,35	40,50,35,35,30	30,46,39,41,54	35,31,45,55,40	47,59,48,48,40
	-40	18,25,17,18,22	25,20,45,19,22	48,47,45,41,35	15,20,15,15,15	25,20,35,25,20	25,25,25,20,15	18,24,16,19,20	22,20,30,21,20	38,36,35,35,30
18	0	60,56,88,63,43	56,25,27,64,59	118,26,70,60,73	35,30,40,35,25	25,15,15,30,30	50,20,35,30,35	30,46,66,50,37	46,23,26,50,48	84,26,56,48,58
	-40	14,19,14,13,17	16,15,21,23,16	40,38,17,53,25	15,20,15,20,20	20,20,25,25,20	25,25,15,25,15	17,18,13,13,17	14,15,30,22,15	36,30,16,39,19
19	0	46,64,82,70,52	52,50,45,51,55	56,40,50,50,47	55,60,70,60,50	50,50,45,50,50	50,45,45,35,35	48,55,67,62,48	47,46,48,42,49	49,38,43,41,43
	-40	36,42,39,35,42	28,33,22,19,21	35,20,40,21,30	25,30,25,20,25	25,25,25,25,25	25,20,30,30,20	36,38,37,30,37	27,28,23,22,23	31,20,35,21,26

Steel	Temp	Energy WM	Energy FL	Energy 1 mm	Energy 3 mm	Energy 5 mm	Shear WM	Shear FL	Shear 1 mm	Shear 3 mm	Shear 5 mm	Lat WM	Lat FL	Lat 1 mm	Lat 3 mm	Lat 5 mm
N	75	65,41,87					45,30,60					59,39,68				
	40	35,37,51	101,55,117	83,114,112	96,75,206		25,30,40	60,35,65	50,60,60	50,60,60		31,33,43	77,45,83	63,80,77	73,62,77	
	0	34,32,24	64,69,27	66,33,55	93,104,75	120,153,117	25,20,15	35,40,20	30,20,35	40,60,40	65,100,70	31,28,19	53,52,27	51,32,44	72,77,58	80,91,76
	-40	11,7,21	11,11,40	21,20,21	85,38,39	68,84,58	10,5,10	10,10,20	15,15,10	35,20,20	30,35,30	9,21,31	14,15,33	22,21,21	71,33,35	53,66,47
	-80		16,7,10	11,13,13	37,18,13	67,60,111		20,5,5	10,10,10	20,15,10	20,20,35		17,9,9	11,13,13	30,16,13	54,50,80
	-120				5,6,7						5,5,5					5,6,8
L	75	25,82,44	61,90,69	37,87,115			35,90,50	30,75,50	45,55,60			33,72,42	50,68,54	22,61,78		
	40	25,24,11	39,39,42	43,24,31	147,101,109	141,165,165	20,20,15	30,30,30	50,35,35	70,55,65	75,100,100	22,20,13	30,36,38	44,28,25	90,75,76	93,98,95
	0	10,10,21	47,16,40	23,17,21	74,40,100	140,140,165	10,5,10	20,10,25	25,20,20	35,25,60	80,80,100	14,13,21	38,16,35	25,19,22	56,37,74	94,95,97
	-40	8,5,5	22,11,8	11,11,9	28,28,83	169,120,140	5,5,5	10,5,5	5,5,5	30,30,45	100,60,75	7,4,4	20,10,8	9,8,8	23,25,45	95,88,94
	-80				34,51,65	14,30,100				20,20,20	10,10,55				39,41,47	26,22,72
U	40	64,58,43	42,40,60	38,35,35	40,37,38	43,47,36	80,80,70	60,60,70	40,50,55	60,50,50	70,70,60	57,56,41	42,41,53	40,36,37	41,42,42	44,48,38
	0	32,31,37	34,30,47	27,28,28	26,32,24	23,33,32	20,20,25	30,30,35	30,30,30	30,35,20	20,30,35	31,29,28	35,30,44	30,28,30	30,33,30	27,35,35
	-40	20,17,25	26,36,25	23,13,11	20,25,15	20,23,23	15,10,15	20,25,20	20,15,15	20,30,20	20,20,15	24,19,23	25,31,26	26,15,13	21,28,19	23,26,26
	-80	3,13,7	8,9,7	12,7,11	18,9,14	12,15,15	5,10,5	10,10,10	10,10,10	20,10,10	10,15,10	2,13,9	11,9,8	11,7,11	18,10,12	13,14,14

APPENDIX F Individual Charpy V-Notch Data for Submerged-Arc Welded Steels (Heat Input of 75 kJ/in)

Steel	Temp., °F	Energy Absorbed, ft-lb			Lateral Expansion, mils			Shear-Fracture Appearance, %		
		FL	1 mm	3 mm	FL	1 mm	3 mm	FL	1 mm	3 mm
6	0	48,62,50,62,34	38,62,74,83,71	77,73,70,70,75	40,50,41,51,32	37,49,56,61,55	61,60,59,58,57	35,40,40,55,35	35,45,50,60,50	50,45,40,40,55
	-40	18,43,33,26,55	24,27,29,25,27	34,48,48,48,35	18,37,25,21,42	21,24,27,22,27	30,39,36,42,34	20,35,25,20,40	20,25,25,25,25	25,35,30,35,35
7	0	120,88,123,121,119	81,107,96,99,110	98,110,94,108,90	85,55,75,79,81	56,76,65,67,74	71,88,70,76,69	60,50,55,60,60	45,65,55,55,60	45,35,55,60,55
	-40	11,55,104,25,66	33,27,51,80,71	77,84,72,84,70	13,39,66,23,50	31,27,38,58,54	64,64,57,65,55	20,30,45,30,35	35,30,35,40,45	35,40,35,40,30
11	0	91,101,83,64,69	72,61,73,95,83	37,26,20,13,53	71,70,69,55,55	54,46,53,65,63	31,22,17,14,39	50,50,55,45,45	60,35,35,60,50	85,10,10,5,25
	-40	48,62,70,65,68	18,16,34,18,49	21,6,8,0,8	37,44,49,49,50	15,13,25,17,34	16,6,7,6,6	20,35,40,50,30	20,5,5,10,20	5,5,5,5,5
12	0	73,64,78,69,92	86,74,60,71,53	67,72,60,45,55	54,50,53,50,65	60,50,43,53,41	50,53,47,39,45	35,30,35,30,55	59,45,30,40,25	35,40,30,20,25
	-40	40,54,47,41,22	50,48,50,51,49	36,48,29,57,50	32,42,36,32,21	37,35,39,40,37	29,30,25,42,30	20,25,25,20,10	20,20,25,30,20	15,30,10,20,20
15	0	101,40,58,68,71	59,56,62,62,48	44,48,43,36,43	73,34,41,51,53	46,41,47,48,38	36,39,34,29,34	70,35,40,45,50	40,40,45,45,40	25,30,25,20,25
	-40	46,42,48,42,65	33,45,40,38,31	33,31,34,37,20	35,33,36,32,46	26,35,30,30,25	25,23,26,28,15	25,25,30,25,45	25,30,30,10,25	20,15,20,20,15
17	0	100,97,94,108,103	85,87,97,95,85	62,57,63,56,58	75,72,67,78,78	58,63,67,65,62	48,47,62,47,50	60,55,50,60,80	40,40,45,45,50	25,35,35,30,35
	-40	66,80,90,64,66	71,54,84,57,71	45,26,41,49,43	50,62,66,48,51	53,114,59,42,50	35,24,34,39,33	30,50,55,40,30	30,25,35,25,30	15,10,15,20,15
18	0	135,124,126,114,108	124,124,143,160,132	129,111,111,82,130	87,83,83,78,76	82,75,90,94,84	87,78,77,61,90	60,35,55,60,50	50,55,60,60,50	55,45,45,35,35
	-40	113,92,120,21,61	83,77,26,141,66	74,62,60,54,66	74,65,83,24,46	58,53,26,97,49	55,48,47,41,53	35,35,50,45,75	30,35,20,50,25	20,20,20,20,20
19	0	100,90,72,61,56	60,42,42,53,53	18,15,16,16,14	68,63,52,116,42	42,29,30,41,42	16,14,16,16,14	60,50,40,35,30	25,20,20,25,25	10,10,10,10,10
	-40	52,74,35,64,41	44,42,40,41,42	9,7,8,7,11	37,55,26,48,34	30,29,27,30,31	7,6,7,6,9	30,40,20,35,25	25,25,20,20,25	5,5,5,5,5

Steel	Temp., °F	WM	FL	1 mm	3 mm	5 mm	WM	FL	1 mm	3 mm	3 mm	WM	FL	1 mm	3 mm	5 mm
9	0	89,80,93	120,102,105	110,111,115	101,113,109	97,107,87	64,64,67	86,76,78	82,81,80	75,85,80	97,84,75	70,60,70	60,65,60	55,35,60	35,40,35	45,50,40
	-40	52,46,56	61,73,94	81,71,77	74,99,94	91,82,51	41,38,46	48,54,70	54,57,40	59,75,71	70,54,45	45,40,45	40,45,50	45,40,45	35,45,50	35,30,20
	-80	26,21,18	69,42,17	51,20,48	78,75,64	58,65,68	23,16,14	52,31,18	40,19,38	62,58,52	47,51,54	30,30,25	35,20,15	25,20,25	30,30,25	15,20,20
	-120	14,10,16	17,9,20	11,10,13	9,31,36	11,7,12	12,7,12	11,8,14	9,8,11	6,20,24	5,5,10	10,10,15	10,5,10	10,5,10	5,10,10	5,5,5
1	0	70,71,64	61,40,130	126,141,146	113,141,170	128,165,94	55,57,51	46,31,85	82,93,93	83,93,98	85,94,77	50,60,50	35,25,60	30,80,85	70,70,100	70,100,60
	-40	34,64,53	21,36,17	165,101,130	138,110,98	107,115,112	28,49,41	18,29,17	96,76,91	91,82,74	79,83,81	40,50,45	20,25,10	100,60,70	60,45,30	50,60,60
	-80	19,27,15	8,34,6	123,22,111	128,112,80	82,101,112	15,23,15	6,24,4	85,16,76	90,82,61	82,72,82	15,20,15	5,20,5	30,15,50	50,50,40	30,50,50
	-120	10,8,12	13,9,7	6,14,23	23,51,65	22,72,67	8,8,10	9,6,5	3,16,20	16,36,49	16,55,51	5,5,5	5,5,5	5,5,10	10,20,20	10,25,20
11	40	134,94,107	61,135,36	58,60,57	51,52,53	63,54,50	88,75,81	53,56,31	52,54,54	51,53,54	59,54,50	100,75,90	65,90,100	90,90,90	70,70,70	80,80,65
	0	100,88,66	56,40,35	50,41,36	37,33,36	44,36,36	74,69,51	50,37,36	48,40,37	35,33,37	44,35,35	80,70,60	50,40,65	50,60,40	30,30,30	60,40,40
	-40	68,65,81	38,52,41	35,41,43	30,35,35	33,41,32	53,51,65	38,47,39	36,38,39	31,35,33	33,41,31	50,60,70	55,70,55	95,40,55	25,30,25	20,40,20
	-80	23,48,23	36,27,31	20,25,15	15,20,18	6,17,9	20,34,20	31,22,27	16,20,14	12,15,14	8,13,7	35,35,25	30,25,30	30,20,15	5,5,5	5,5,5

APPENDIX G   DPH Hardness of Butt-Welded Joints Investigated

		SAW 75 kJ/in.			SAW 180 kJ/in.			ESW		
			HAZ	HAZ		HAZ	HAZ		HAZ	HAZ
Steel	Base	Weld	1 mm	3 mm	Weld	1 mm	3 mm	Weld	1 mm	3 mm
4	145	187	174	166	181	179	166	199	185	164
7	148	193	185	163	192	194	175	209	202	188
11	144	185	211	199	179	184	179	192	178	178
12	147	178	170	160	176	161	160	201	184	163
15	144	196	189	173	184	168	168	196	169	168
17	145	203	185	162	181	164	165	199	177	167
18	146	184	201	175	190	190	165	195	181	164
19	143	186	193	183	192	180	182	191	169	175
L	156	209	206	181	201	203	191	215	205	198
N	146	204	170	163	200	184	160	199	160	151
U	135	213	167	158	189	172	165	192	166	159

Hardness, DPH

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