WELD DEPOSIT EVALUATION FOR THE HPS 70W AND 100W STEELS

FINAL REPORT

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by

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EXECUTIVE SUMMARY

This work includes the results of an experimental research performed on several combinations of Submerged Arc Welding consumables needed for joining High-Performance Weathering steels having 70 and 100 ksi minimum yield strength, respectively (HPS 70W and 100W). The properties of deposits made with electrode wires and fluxes from different manufacturers were measured using standard destructive testing. Additionally, the effects of electrode polarity, heat input and number of electrodes were investigated. The ultimate scope of the work was to find undermatching (70 ksi yield strength) and matching (100 ksi) weld deposits to weld the 100W grade steels.

It was found that most electrode wire/flux combinations were able to provide adequate strength and weathering properties. However, as the heat input increased, the weld deposit properties deteriorated. Use of twin-arc or parallel electrode welding did not affect the results. The use of negative polarity (DCEN) instead of the more commonly used electrode-positive (DCEP) led to some improvement in weld properties. The results correlated well with those reported elsewhere by consumable manufacturers. It was also found that improper use of backing bars having high-carbon and sulfur content caused hot cracking at the root passes of most HPS 70W weld deposits. Therefore, welding of the high-performance steels to conventional steel products should be carefully weighed in the future.

1.0 BACKGROUND

The present study is part of a nationwide effort directed toward finding better steels to cost-effectively build bridges for America's infrastructure. The research effort was led by the Federal Highway Administration, the Office of Naval Research and the American Iron and Steel Institute. Since improved weldability was one of the criteria chosen, welding consumable manufacturers and some bridge fabricators have been also involved in the project. LeTourneau University has been involved mostly in simulative weldability testing for hydrogen-induced cracking susceptibility. However, because wire electrode/flux combinations were not tested for the weathering grades (minimum 1% Nickel) having 70 and 100 ksi minimum yield strength, some new combinations of consumables had to be evaluated. Submerged Arc Welding (SAW) wire electrode and flux combinations from different manufacturers were to be independently tested for mechanical properties.

2.0 OBJECTIVE

The scope of this work was to evaluate the weld deposit mechanical properties for several combinations of SAW welding wires and fluxes. The effects of the heat input, electrode polarity and number of wire electrodes on the weld properties were to be quantified using standard multipass all-weld-metal (AWM) testing. The results were to be compared with those reported by consumable manufacturers and bridge fabricators.

3.0 METHODOLOGY

Several combinations of SAW wire electrode and fluxes were used for the experiments. For the 70 ksi target yield strength, two wire types, LA 85 and ENi4 were used, in combination with the standard 800H as well as the modified 800 HP fluxes. The need for these non-conventional wire/flux combinations was the minimum 1% Ni required in the deposit, as well as a minimum 25 ft.lb at -25°F impact toughness in order to match the base metal properties. For the 100 ksi target yield strength, one solid (SA 120 from ESAB) and one metal-core (MC 120 from Lincoln Electric) were used in combination with the 800H flux from Lincoln.

Plates 1.0 -inch in thickness were used for SAW welding with a 20 degree included angle, 0.625-inch root gap and a 0.375-inch thick backing bar. The plates were restrained for the entire one-sided welding sequence and a standard bead placement sequence learned from Lincoln Electric was used. The tensile and Charpy specimens were removed from the all-weld-metal deposit according to Figure 5.1, ANSI/AWS D1.5-98 Welding Code, Structural Steels to ensure zero dilution with the base metal i.e. in the center of the weld deposit.

Submerged Arc Welding was performed at four distinct arc energies: 40, 70, 100 and 130 kJ/in. The preheat and interpass temperatures for the lower (40 and 70 kJ/in) heat inputs was 200-250°F, while for the higher (100 and 130 kJ/in), the preheat and interpass temperature was maintained at 400-450°F (see selected welding parameters used, Appendix I; all other parameters can be available upon request).

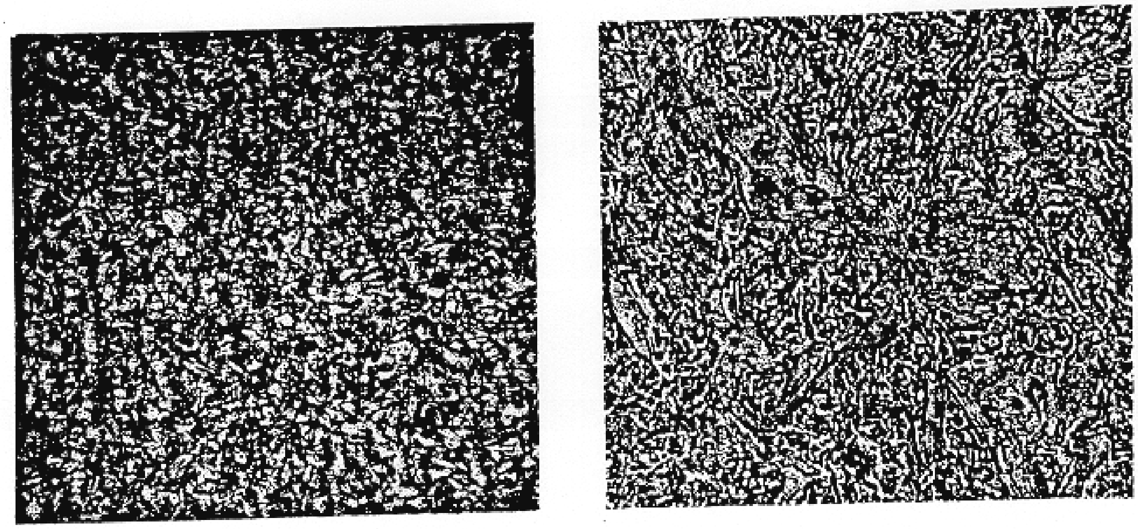
Mechanical testing, chemical analysis and diffusible hydrogen testing were performed by outside certified laboratoies. Selected test reports are included in Appendix II; all other results are on file and will be made available on request. Finally, typical macro- and microstructures from selected welds were examined using optic and electron microscopy as well as hardness measurements.

4.0 RESULTS AND DISCUSSION

Selected all-weld-metal (AWM) properties and chemical compositions are shown in Tables I and II in Appendix III. For comparison, relevant results on some of the same wire/flux combinations reported by Lincoln Electric and ESAB are shown in Appendix IV.

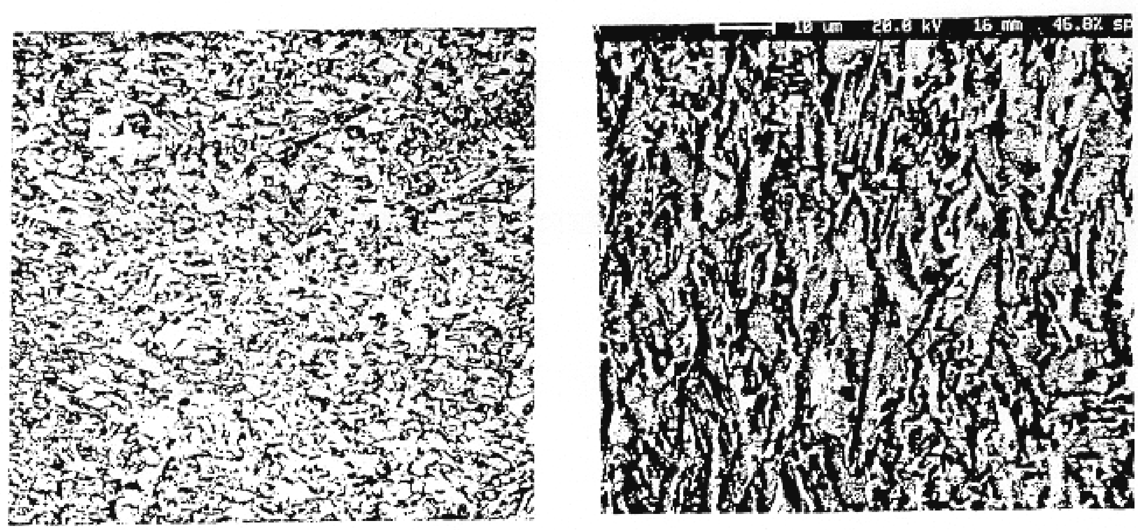
4.1 Effect of Heat Input

Regardless of consumable type, increasing heat input caused the deterioration of all mechanical properties. Generally, fewer weld passes and lower cooling rates associated with the high (130 kJ/in) heat input have resulted in coarser grain sizes rich in proeutectoid ferrite and bainite, microstructures with lower strength and toughness than the mixtures of fine-grained lower bainite, acicular ferrite and martensite typical to the low, 40 kJ/in heat input (see Figures 1-5).



(a)

400 X 800 X



(b)

Figure 1. Weld metal typical microstructures as shown at different magnifications using optical (400 X) and electron microscopy (800 X), 2 % Nital/picral etch. (a) is LA 85/800HP sample # 237252, (b) is ENi4/800H # 232919, welded at 40 kJ/in.

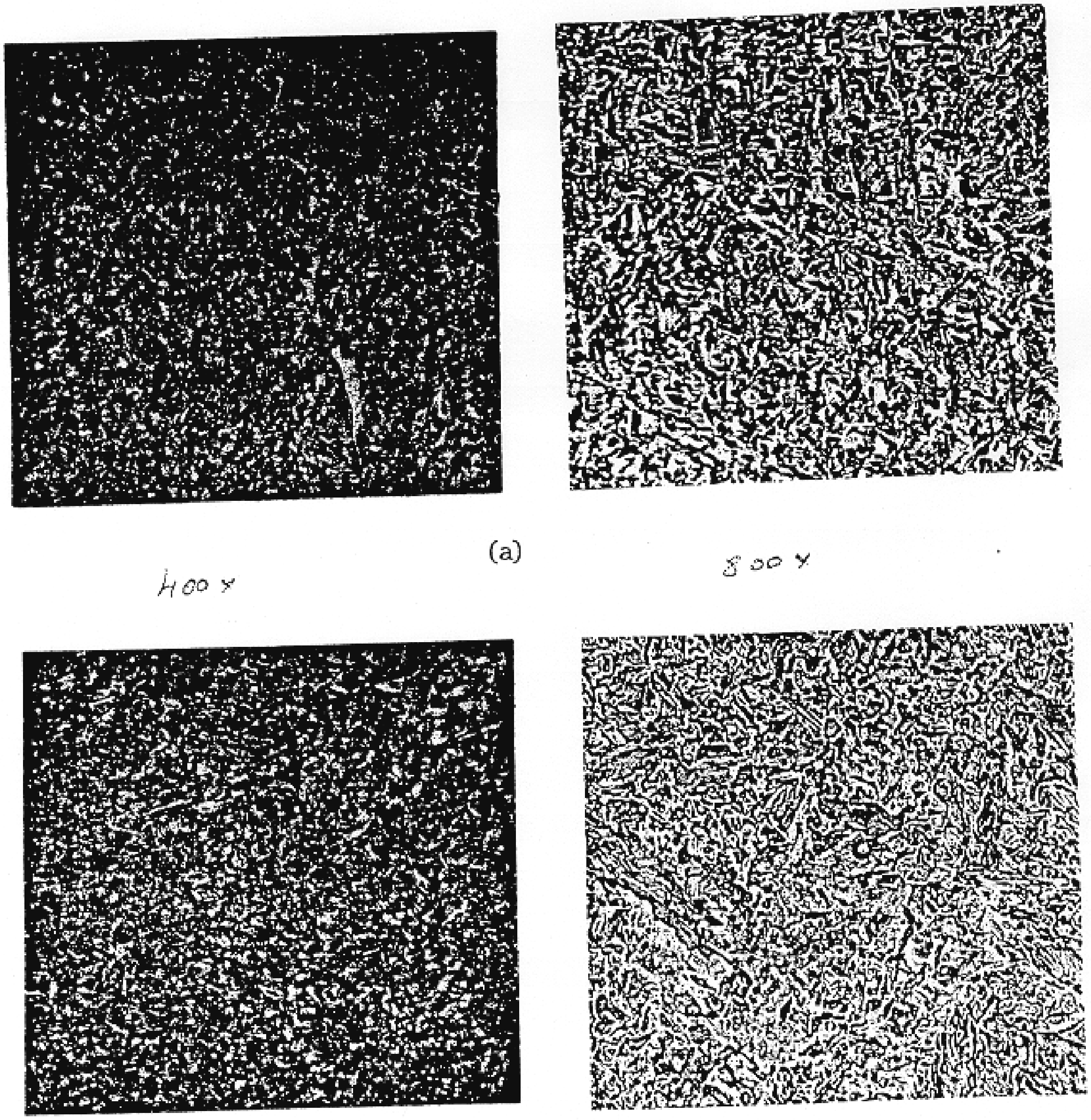
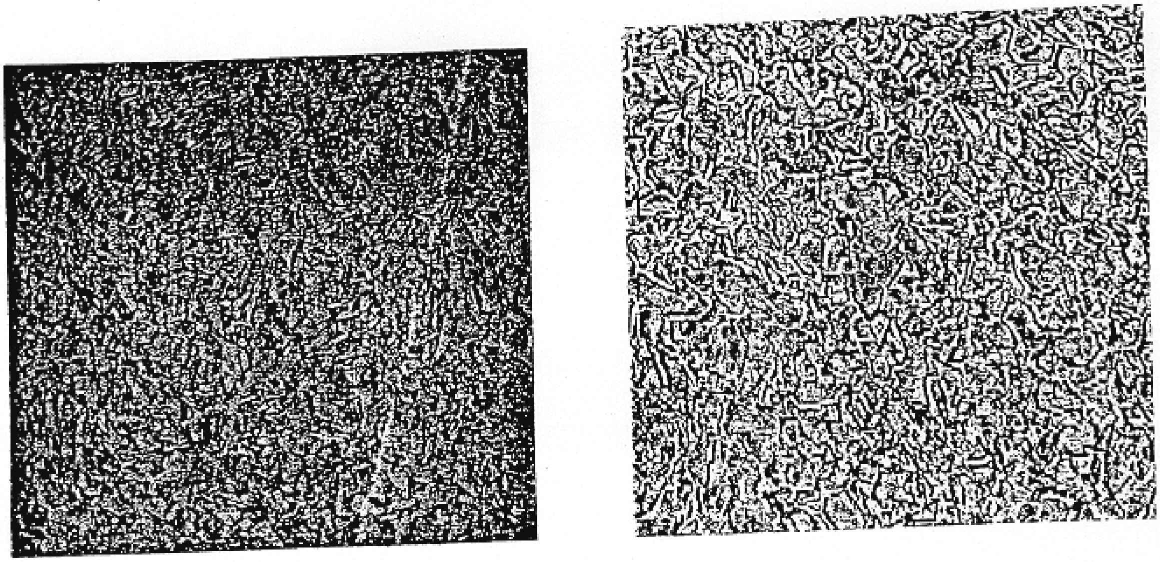
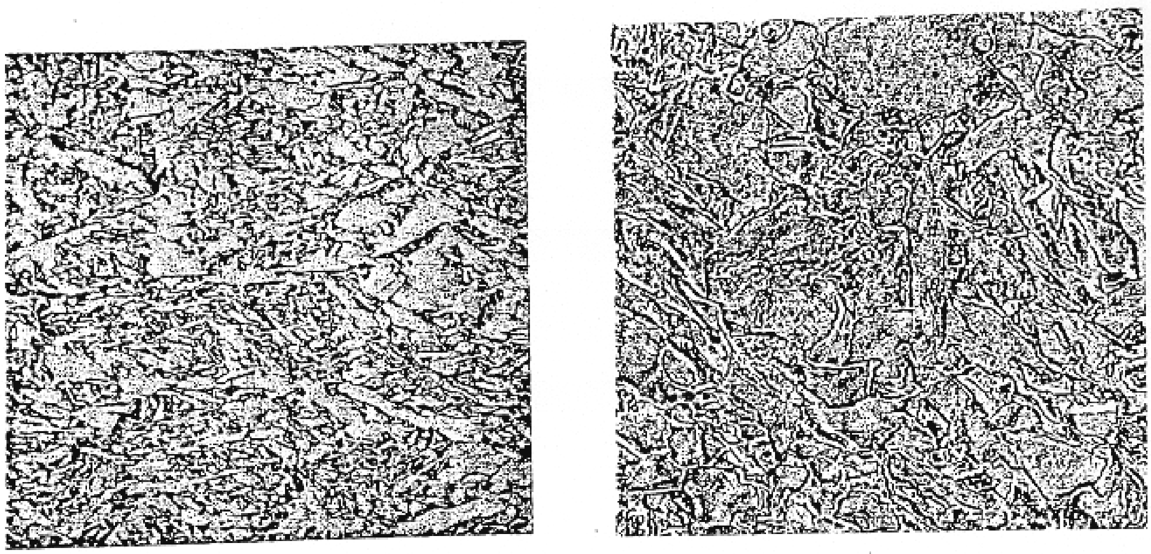


Figure 2. Weld metal typical microstructures as shown at different magnifications using optical (400 X) and electron microscopy (800 X), 2 % Nital/picral etch. (a) is MC120/800H sample # 241039, (b) is SA120/800h # 232921, welded at 40 kJ/in.

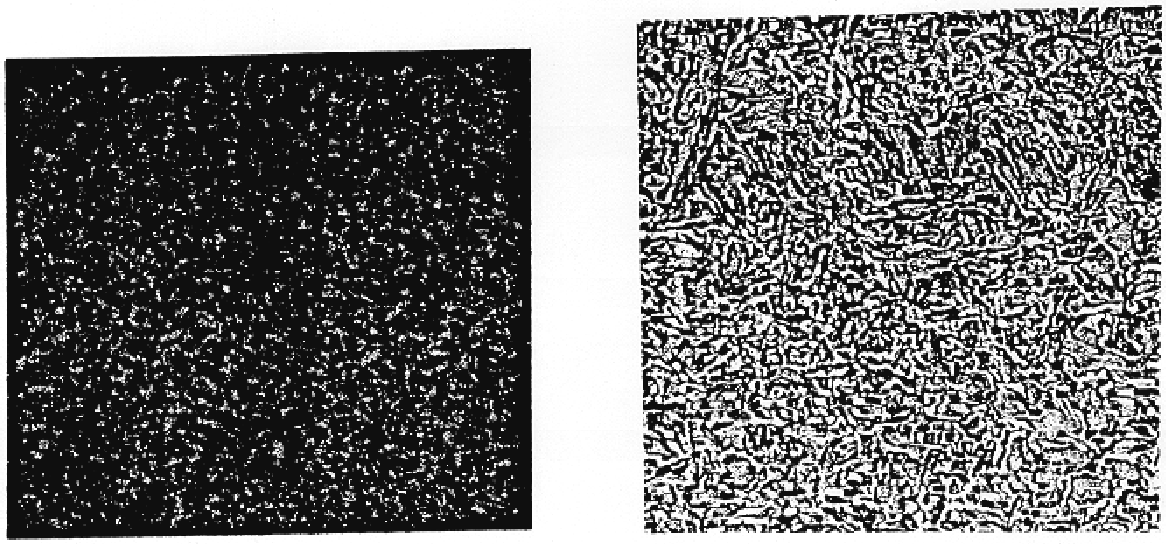


(a)

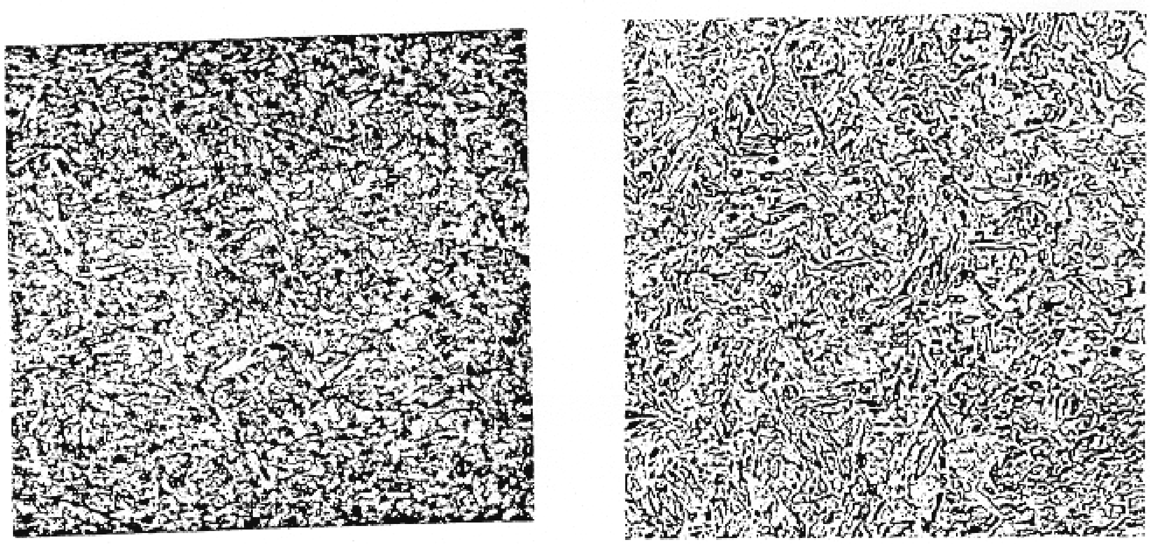


(b)

Figure 3. Weld metal typical microstructures as shown at different magnifications using optical (400 X) and electron microscopy (800 X), 2 % Nital/picral etch. (a) is LA85/800HP sample # 237251, (b) is ENi4/800H # 232922, welded at 130 kJ/in.

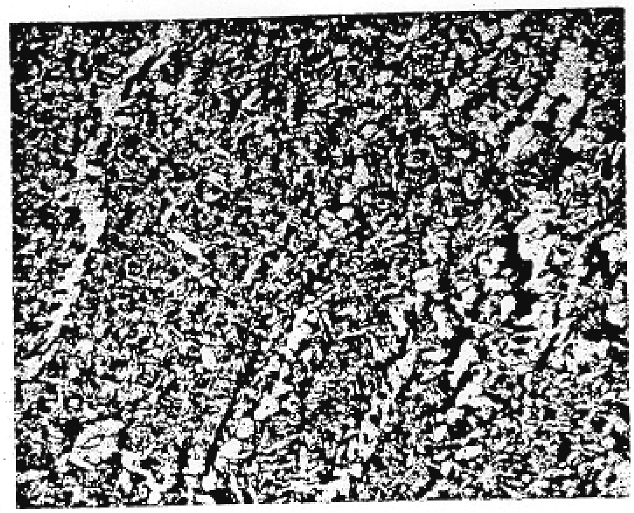


400x (a) 500 x

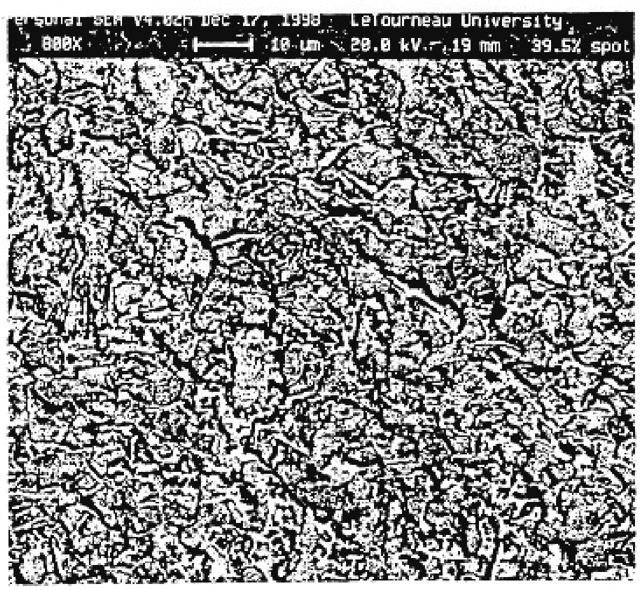


(b)

Figure 4. Weld metal typical microstructures as shown at different magnifications using optical (400 X) and electron microscopy (800 X), 2 % Nital/picral etch. (a) is MC120/800H sample # 241040, (b) is SA120/800h # 232920, welded at 130 kJ/in.



(a)



(b)

Figure 5. Weld metal typical microstructures as shown at different magnifications using optical (400 X) and electron microscopy (800 X), 2 % Nital/picral etch, ENi4/800H welded at 100 kJ/in using twin wires, Sample # 247014.

As expected, there were some differences between the microstructures and average hardnesses of the deposits welded using solid- vs. metal-core wire electrode, as well as welded using the "standard" 800H and the modified 800 HP fluxes. Figure 6 shows that weld metal average hardnesses also decrease with heat input (Hardness is proportional with the Ultimate Tensile Strength). However, these measurements alone would not be sufficient to accurately predict the mechanical behavior of the weld deposit.

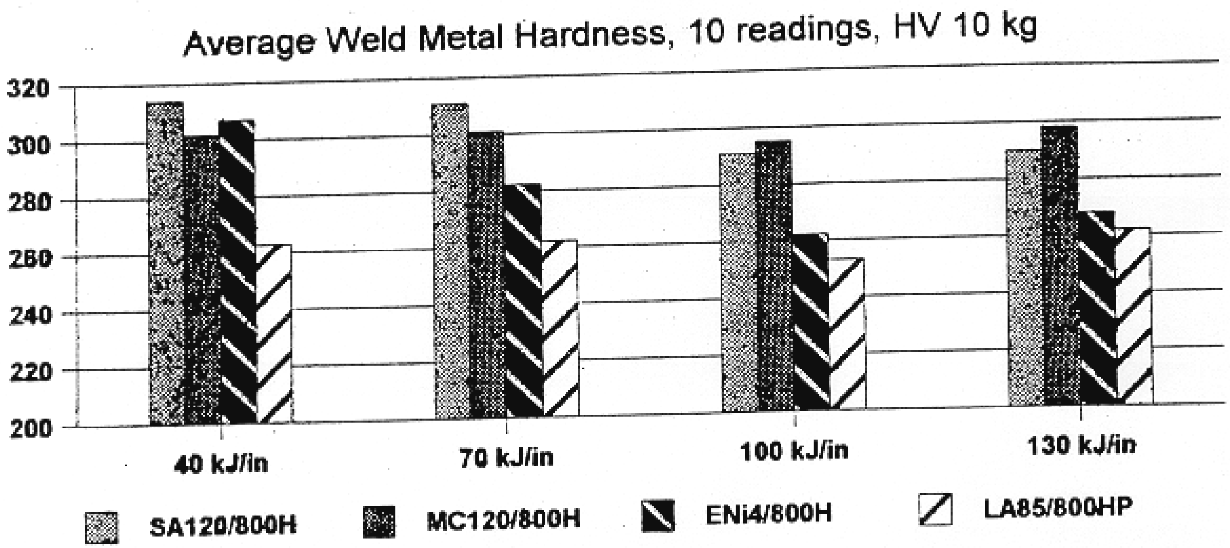


Figure 6. Average hardness (HV 10 kg load) taken at random throughout the weld deposits.

The drop in mechanical properties with increasing heat input is typical to high strength weld metals (Refs. 6,7). Plotting the average Charpy toughness values against the corresponding yield strength (Figure 7), it can be seen that an optimum properties can be obtained at "moderate" heat input range or cooling rates. The worst combination of toughness and yield strength can be expected at low cooling rates estimated at 3-5 deg.F/second at 400-450°F interpass temperature and heat input of 130 kJ/in for the 1-inch-thick plate (Ref. 7). The typical microstructure at these low cooling rates is dominated by lower bainite and grain boundary proeutectoid ferrite. At the high end, cooling rates of 16-20 deg. F/second can be expected for 200-250°F interpass and 40 kJ/in heat input. At these cooling rates, the majority of microstructure can be expected to be martensite and acicular ferrite. More work should be performed on correlating the theoretical cooling rates with microstructures and mechanical properties.

Based on the present study in which the heat input was varied in 30 kJ/in increments, it is hard to predict the exact heat input limit beyond which the deposit yield strength drops below the minimum required values of 70 and 100 ksi, respectively. Regression analysis seems to indicate that this upper limit for 70 ksi is somewhere between 80-100 kJ/in and for 100 ksi is between 50-80 kJ/in (Figures 8-10), depending on polarity and wire electrode/flux

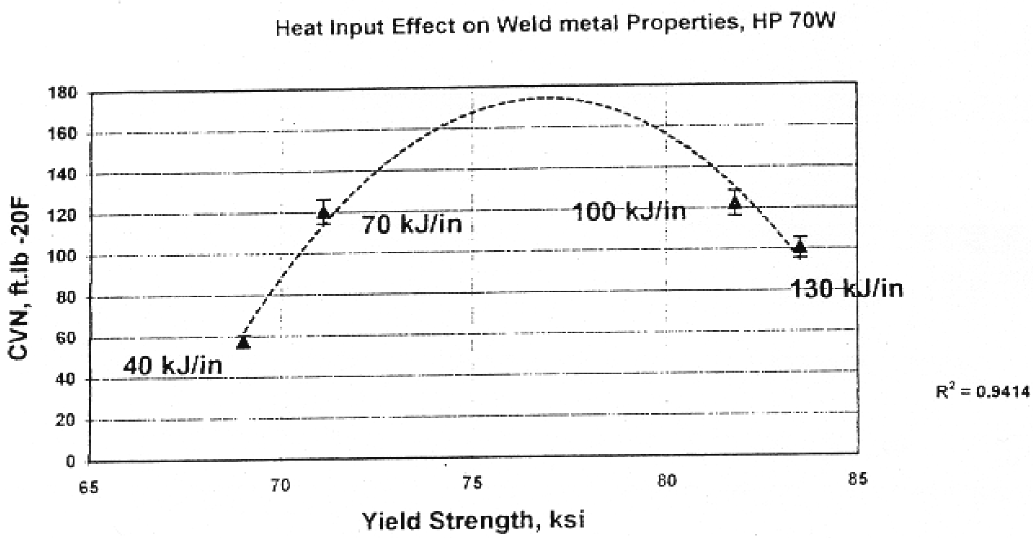
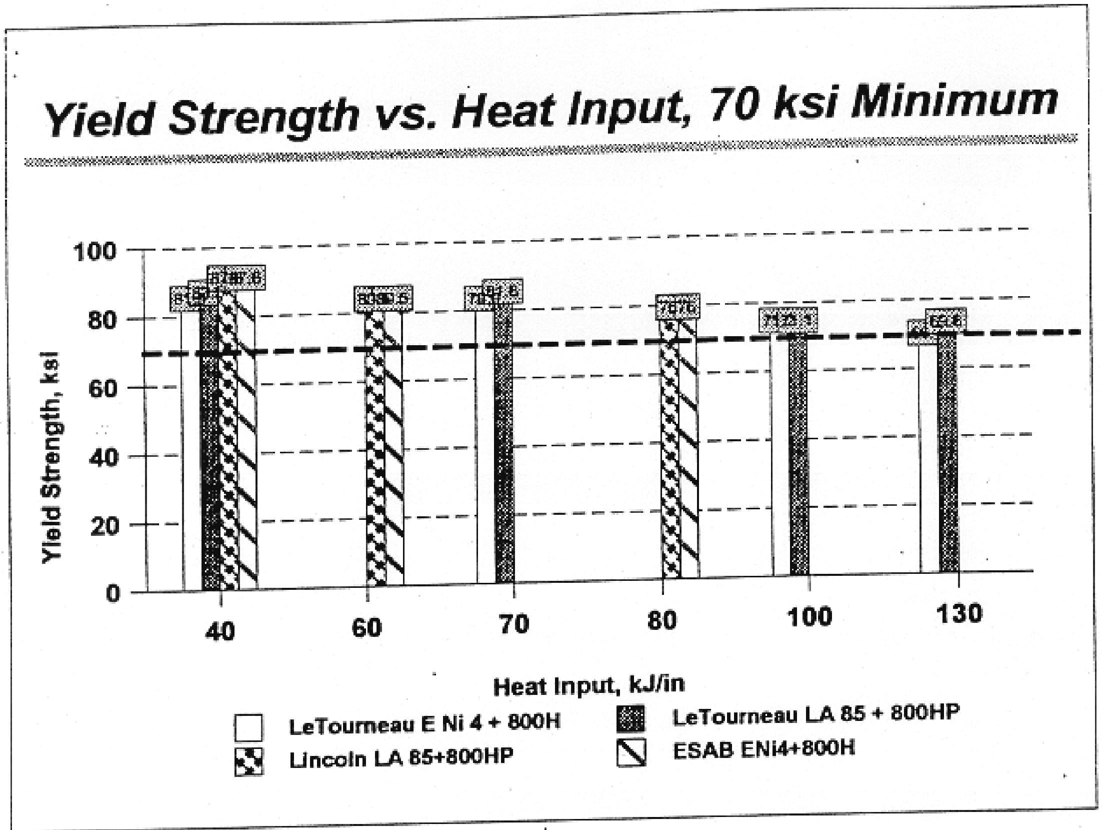
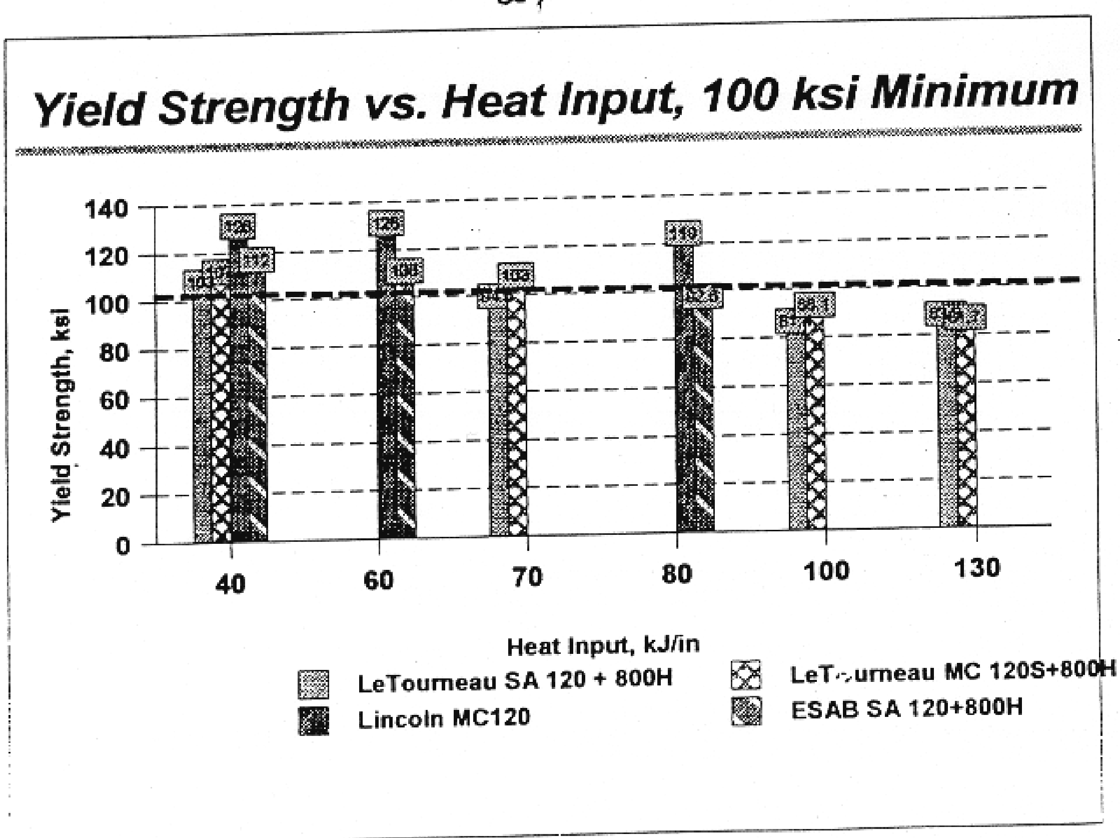


Figure 7. Weld metal yield strength versus toughness for the heat inputs used, HPS 70W, ENi4/800H consumable.

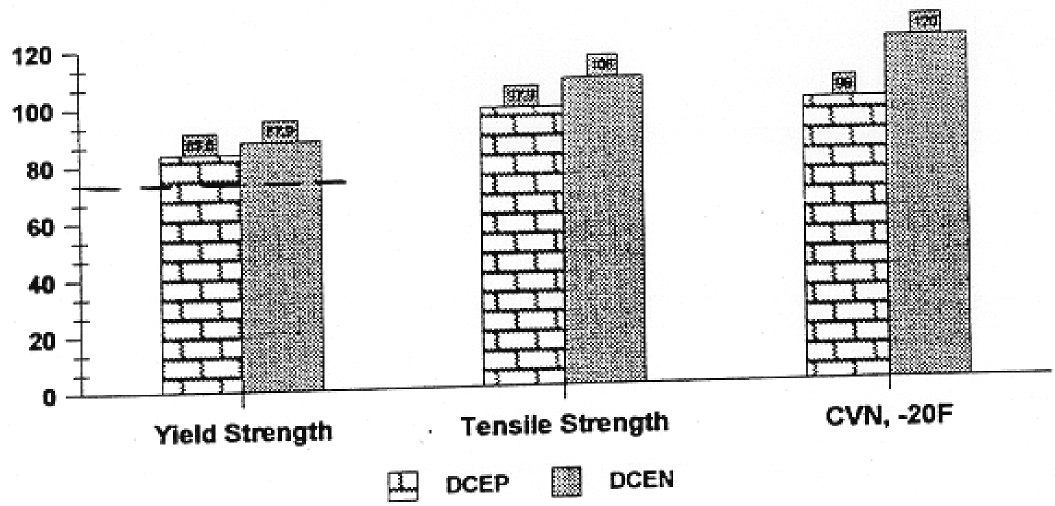

Yield Strength vs. Heat Input, 70 ksi Minimum
Yield Strength, ksi
100
80
60
40
20
0
40
60
70
80
100
130
Heat Input, kJ/in
LeTourneau E Ni 4 + 800H
LeTourneau LA 85 + 800HP
Lincoln LA 85+800HP
ESAB ENi4+800H

a)


Yield Strength vs. Heat Input, 100 ksi Minimum
Yield Strength, ksi
140
120
100
80
60
40
20
0
40
60
70
80
100
130
Heat Input, kJ/in
LeTourneau SA 120 + 800H
LeTourneau MC 120S+800H
Lincoln MC120
ESAB SA 120+800H

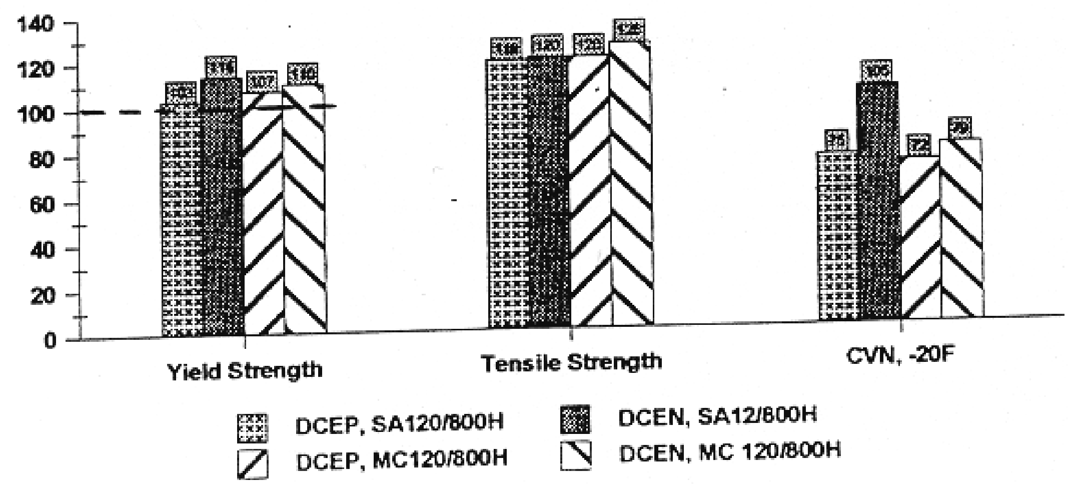
Effect of Electrode Polarity, 70W

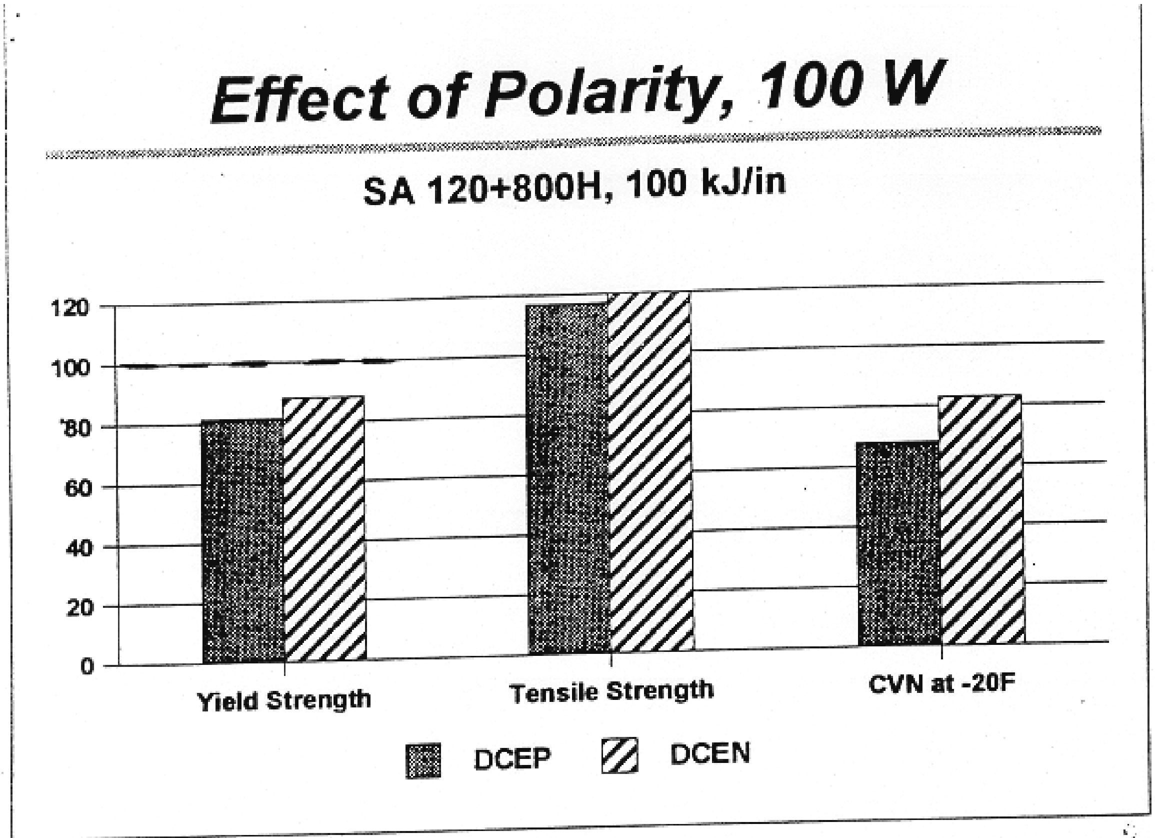
LA 85 + 800HP, 40 kJ/in



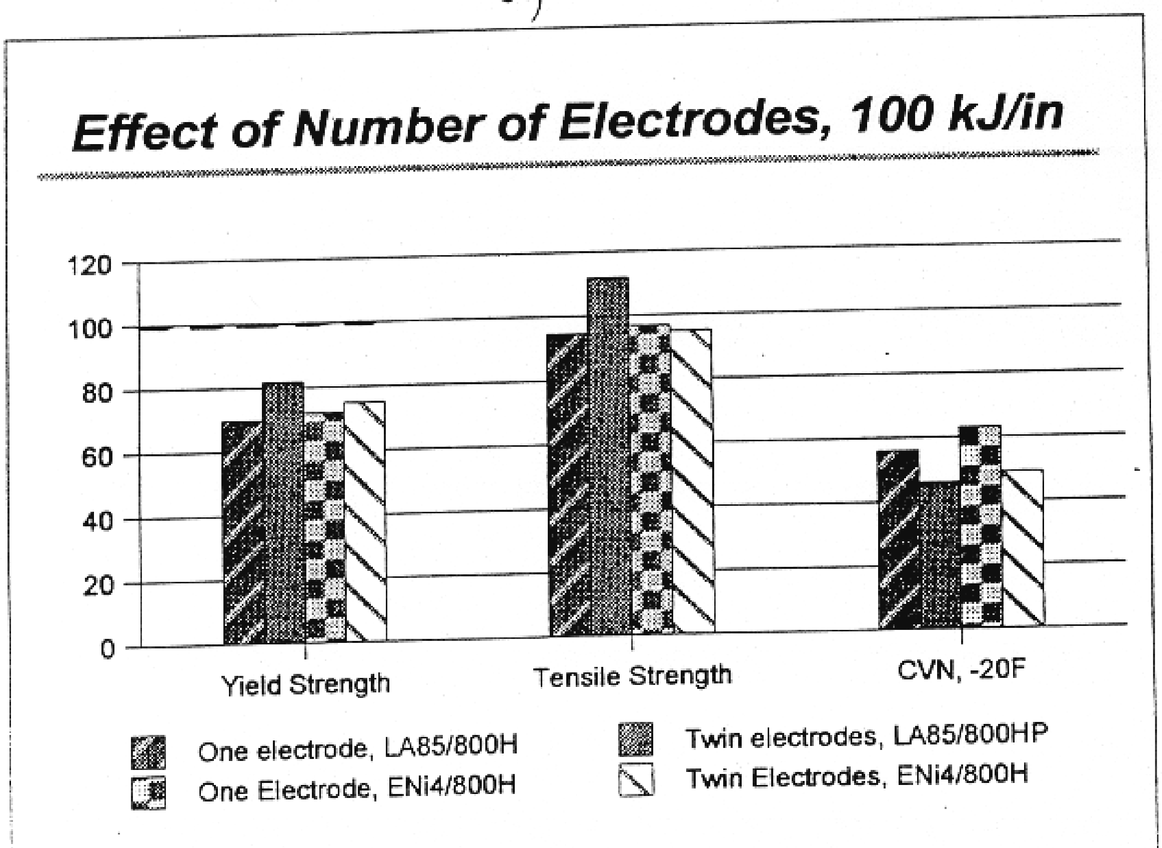
a)

Effect of Electrode Polarity, 100W, 40 kJ/in




Effect of Polarity, 100 W
SA 120+800H, 100 kJ/in
120
100
80
60
40
20
0
Yield Strength
Tensile Strength
CVN at -20F
DCEP
DCEN

a)


Effect of Number of Electrodes, 100 kJ/in
120
100
80
60
40
20
0
Yield Strength
Tensile Strength
CVN, -20F
One electrode, LA85/800H
One Electrode, ENi4/800H
Twin electrodes, LA85/800HP
Twin Electrodes, ENi4/800H

type. Therefore, depending on how conservative one wants to be, these high-strength weld deposits appear to mandate certain heat input and interpass temperature restrictions as compared to lower strength weld deposits.

4.2 Effect of Electrode Polarity

Direct Current Electrode Positive (DCEP) or Reverse Polarity (DCRP) is the most widely used connection in SAW multipass welding. The main reasons for this polarity choice are connected to the heat distribution in the electric arc. Higher electrode wire melting rates and hence higher depositions rates can be accomplished in DCEP. At the same time, the arc stability is good when using neutral fluxes, resulting in defect-free deposits. On the other hand, using Direct Current Electrode Negative (DCEN) has been known to produce better weld surface bead geometry in single-pass welds when using active fluxes. Because of the lower melting rate, more passes are needed to weld the same joint, therefore offering more control over the effective the heat input. In order to verify the above hypothesis, several DCEN welds were produced using equivalent arc energies with DCEP. The arc voltage and current had to be altered from the basic DCEP mode and the travel speed had to be changed to produce good multipass welds.

The main consequence of using DCEN was that it became very difficult to produce defect-free welds. Lack of fusion between passes and slag inclusions were the most frequently encountered weld discontinuities. Interestingly however, slight improvements were found in mechanical properties every time DCEN was used over DCEP (Figures 9a, 9b and 10a). The reason for this improvement was not evident, but it is believed that it was related to the microstructural refinement in the weld provided by the increased number of welding passes.

4.3 Effect of Number of Wire Electrodes

Using two wire electrodes instead of one appeared to have a positive effect on the weld metal strength but a negative effect on the weld toughness, for the same calculated arc energy (Figure 10b). The extremely long weld pool which resulted in twin-arc welding was more prone to hot cracking and was typically more difficult to make. Therefore, our results remain inconclusive in this area but show that at high heat inputs neither single- nor multiple-electrode welding will produce adequate weld strength. Overall, in case a fabricator has better practices for multipass welding and the total arc energy does not exceed the limits established in # 4.1, there is no reason why it shouldn't be used.

4.4 Effect of Wire Electrode and Flux Type

Two types of wire electrode (solid- and metal-core) and fluxes (neutral and alloyed) were used in the experiments. No significant differences in properties were found as the result of differences in chemical composition (Mn, Ni, Ti) and microstructures produced using these different types of consumables. All combinations were essentially adequate for the purpose and none of the consumable manufacturers claimed to have the "only answer" to finding the appropriate wire/flux combination for welding the HPS 100W.

4.5 Effect of Backing Bar Composition on Root Cracking

Half of the macro-etched specimens from the 70W target group were found having root cracks in the area of the backing bar (9 out of 18 welds). Although these cracks extending from 1 to 10 mm in length did not affect the test results because the tensile and Charpy specimens were removed from other locations (see sketch in Figure 11), the alarming number of these cracks warranted extra action. Magnetic Particle and Liquid Penetrant testing was performed on the end-pieces of suspect welds after machining off of the backing bar.

Most cracks initiated at the backing bar in the first few passes, varied in length between 5-50 mm (Liquid Penetrant testing after the backing bar was machined off). Transverse cross sections and ultrasonic testing revealed that the depth of the cracks extended between 1.6-12.7 mm and propagated at a 45 degree angle (Figure 5-A in Appendix V. Examination at higher magnification of these cracks showed that they were situated along solidification grain boundaries (Figure 1-A, 2-A), typical to solidification cracking. Indeed, the fracture surfaces retained the solidification structure, with liquated carbon and sulphur rich layers decorating the grain boundaries (Figure 3-A, 4-A). These features are typical to solidification ("hot") cracking caused by segregation due to constitutional supercooling. In ferrous alloys, formation of non-equilibrium FeS instead of MnS has been shown to cause cracking in the final stages of solidification. Changes in the weld bead shape (depth/width ratio) also can affect the driving force (transverse stresses) for opening these cracks. Finally, stress concentrators such as the backing bar/root interface can also enhance the chances for cracking. Apparently, all these conditions were present in these cases.

Because none of the HPS 100W deposits exhibited cracking, the investigation focused on all possible differences in welding procedure between the 70 and 100 W welds. It was found that because of shortage of 70W plate, an A 36 backing bar was used for all 70W welds, while a matching (HPS 100W) bar was used for the 100 W welds. Indeed, subsequent evaluation of the A 36 backing bar used for these particular welds revealed an unusually high (0.045% sulfur, as well as 0.17% carbon, minimill product), much higher than the base metal or consumables used.

It was concluded that these cracks resulted from the chemical admixture in the first passes because of high dilution with the improperly (accidentally) used A 36 backing bar. The extent of cracking was independent of the welding consumable or heat input used. Instead, the shape of the weld bead and the particular root geometry appeared to determine the extent of cracking.

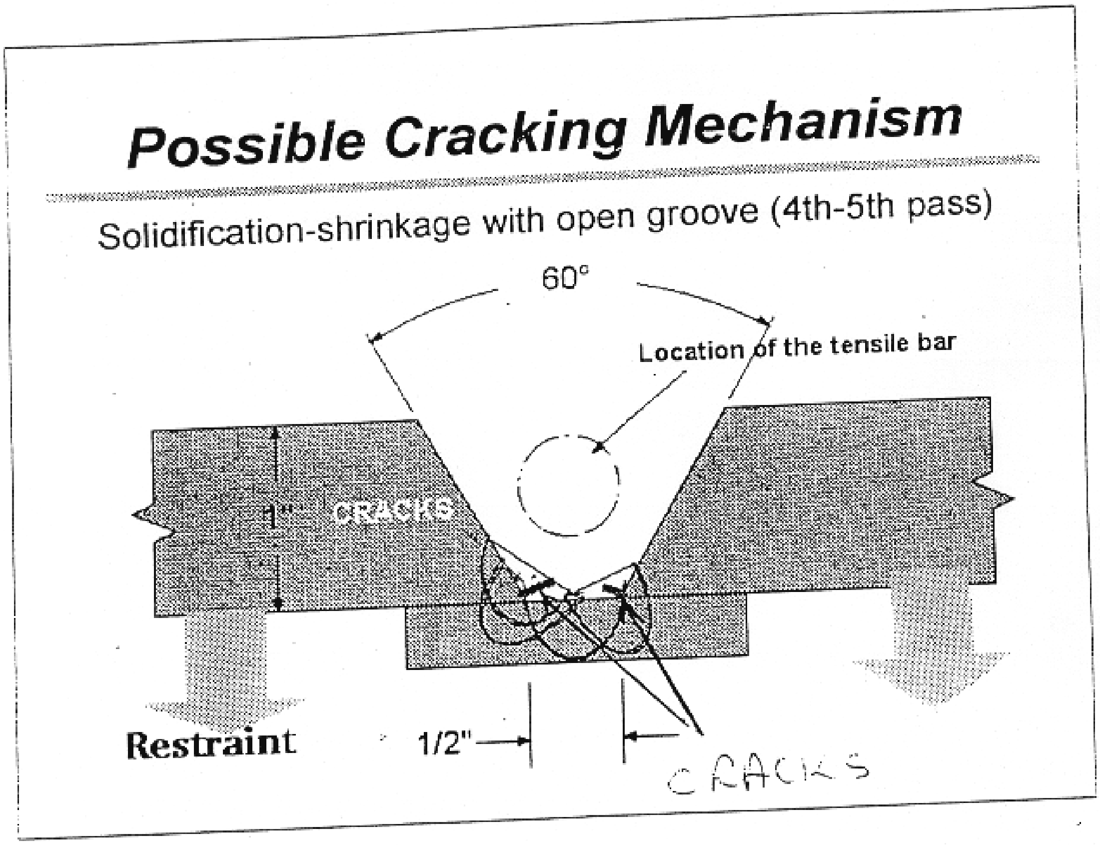


Figure 11. Schematic representation of the possible mechanism for cracking at the root of the weld when the A 36 backing bar was improperly used.

5.0 CONCLUSIONS

5.1 The mechanical properties of the weld deposits deteriorated with increasing heat input and interpass temperature, independent of consumable or welding process used.

Specifically, the E Ni4/800H and LA 85/800HP combinations met the 70 ksi minimum yield strength at heat inputs up to 100 kJ/in. The MC 120/80H and SA 120/800H combinations met the 100 ksi yield strength only up to 70 kJ/in.

5.2 The results correlated reasonably well with those reported by welding consumable manufacturer, Lincoln Electric and ESAB.

5.3 While welding using DCEN generally produced better mechanical properties, its impact at higher heat inputs it was not sufficient to change the overall trends found in DCEP.

5.4 More work is needed to establish the relationship between the results of the single-pass weldability tests and the properties of these multipass welds.

5.5 The solidification cracks found in some weld deposits were caused by the improper use of an A 36 backing bar.

6.0 ACKNOWLEDGMENTS

The author would like to thank all the dedicated students who performed welding and testing, namely Travis Olson, Nathan Nissley, Milton Coker, Dan Thiessen, Dwayne Mast and James Yancey.

7.0 REFERENCES

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5. Buchmayr, B., 1989. "HAZ-Calculator; A Software System for Welding Engineers", International Conference Proceedings, "Trends in Welding Research", Gatlinburg, TN, June 1989.

6. Evans, G.M., Rollason, E.C. -IIW Document 11A-217-68

7. Wong, R.J. "Weldability and Weld Procedure Development for HSLA-100 Steel Nonpressure Hull Structures", DTRC/SME-90/40, June 1986

APPENDIX I

veld Metal Test Sheet: Matrix: 100W - 40 KJ
B

Date: [illegible]

Tim, trans.
Jami

sumable and Base Metal

e	Spoolarc 120
:	Mil-800H
e Metal	100 w

Ambient Conditions:

Temperature	11:30 am 68° F
Relative Humidity	33 %

Notes: 12:30 - 30% 65° 1:40 28% 68° 2:30 26% 68° 3.30 24% 69°

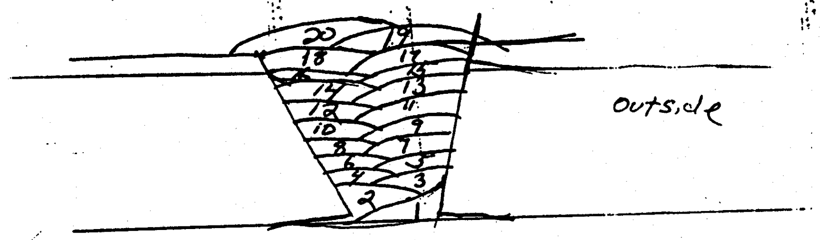
Can 2 - 1-8 passes
Can 1 - 8-20

lding Parameters

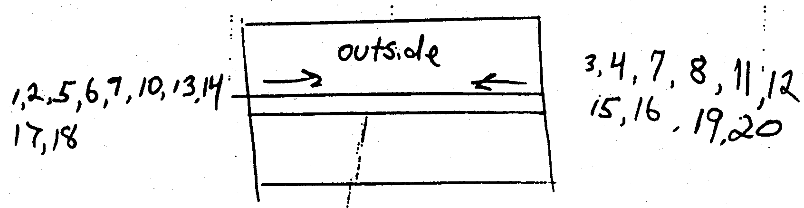
tage	29
perage (set by WFS)	600
re Feed Speed (WFS)	4●8
avel Speed	26.1 in/min
erpass Temperature	200 - 250° F

ctual Welding Parameters

	Time	WFS	Voltage	Amperage	Travel speed
ass 1	am 11:35	49.7	29.8	645	26.1
ass 2		49.3	29	625	26.2
ass 3	pm 12:10	49.6	29.2	635	26.2
ass 4		49.4	29	615	26.1
ass 5	12:34	48.9	30.5	620	26.1
ass 6		49.3	29	630	26.2
ass 7	1:04	49.5	29	635	26.0
ass 8		49.3	29	615	25.8
ass 9	1:40	47.5	29	635	26.0
ass 10		49.6	29.2	620	26.0
ass 11	2:05	49.4	29	610	26.1
ass 12		47.4	29	600	26.0
ass 13	2:27	47.6	29	620	26
ass 14		49.6	29	605	26
ass 15	2:51	49.4	29	610	26
ass 16		49.5	29	610	25.8
Pass 17	3:15	49.5	29	625	25.8
Pass 18		49.5	29	640	25.8
Pass 19	3:40	49.5	29	635	25.8
Pass 20		49.5	29	660	25.8
Pass 21					
Pass 22					



Welding Notes



Weld Metal Test Sheet: Matrix: 100 W - 130 ks A

Date: Operator: tim / travis

Recorder: Jami

Consumable and Base Metal

Weld Metal Test Sheet: Ma... OH can # 2 ... 120 ... W

Consumable and Base Metal

...e Linde 80... / Spoolarc

...se Metal 100 W

Welding Parameters

...ltage ...3

...perage (set by WFS) 600 ...50

Ambient Conditions:

Temperature	66°F · 9:00 am
[redacted]re Humidity Relative	39%

Notes: 9:30 - 32% 68° 10:30 - 34% 69° F

Actual Welding Parameters

		WFS	Voltage	Amperage	travel speed
Pass 1	am 8:54	48.7	29.8	530	8.05
Pass 2	9:15	48.6	29.5	560	8.05
Pass 3	9:33	48.7	29.5	540	8.1
Pass 4	9:52	48.7	29.5	545	8.4
Pass 5	10:10	48.2	29.8	550	8.05
Pass 6	10:28	48.6	29.5	550	8.05
Pass 7	10:50	48.7	29.8	570	8.05
Pass 8					
Pass 9					
Pass 10					
Pass 11					
Pass 12					
Pass 13					
Pass 14					
Pass 15					
Pass 16					
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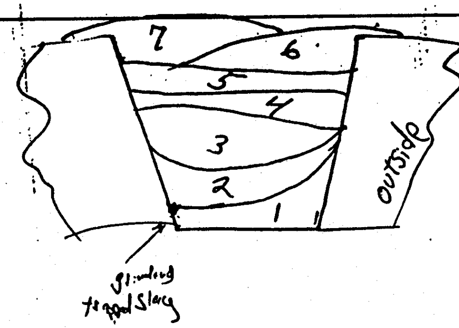
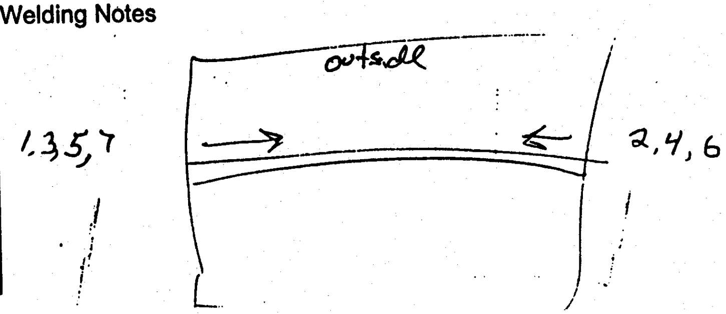
Pass 18					
Pass 19					
Pass 20					
Pass 21					
Pass 22					



Welding Notes



Weld Metal Test Sheet: Matrix: A36 - 130 k 70 ksi (B)

Date: [illegible]

Operators: Tim, Travis

Recording: Jami

nsumable and Base Metal

re	EN-4 5/32
ix	Mil-800H Con #3
se Metal	A-36

Ambient Conditions: 8:45 am

Temperature	66° F
Relative Humidity	40 %

Notes: Amperage lower than desired - WFS increased after Pass 2 + 4

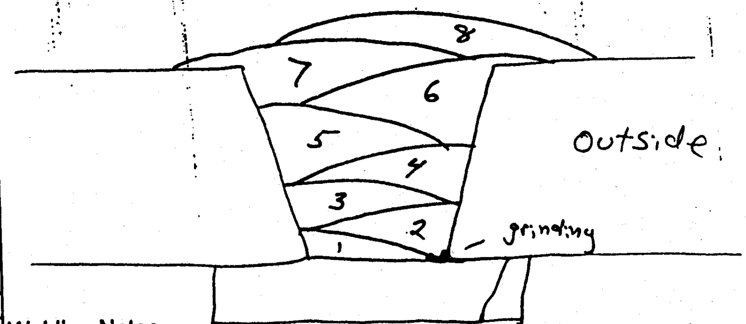
10:15 RH - 36.1 % 65°

elding Parameters

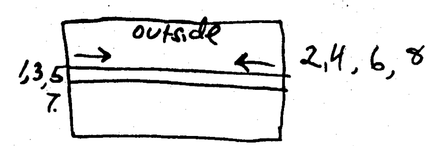
oltage	29
mperage (set by WFS)	600
/ire Feed Speed (WFS)	48
ravel Speed	8.03
nterpass Temperature	400 - 450° F

ctual Welding Parameters

		WFS	Voltage	Amperage	travel speed
Pass 1	9:00	49.4	29.2	550	8.05
Pass 2	9:35	49.1	29	540	8.05
Pass 3	9:53	50.1	29	540	8.2
Pass 4	10:13	50.2	30	540	8.1
Pass 5	10:30	51.2	30	555	8.2
Pass 6	10:46	51.2	30	560	8.05
Pass 7	11:05	51.3	30.2	580	8.1
Pass 8		51.2	30.2	575	8.1
Pass 9					
Pass 10					
Pass 11					
Pass 12					
Pass 13					
Pass 14					
Pass 15					
Pass 16					
Pass 17					
Pass 18					
Pass 19					
Pass 20					
Pass 21					
Pass 22					



Welding Notes



APPENDIX II

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON, TEXAS 77092 • TEL (713) 939-8690 • FAX (713) 939-0249

DATE : 01/08/98
REPORT NO: 232919.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: 3281
MATERIAL : 1" THK X 16 1/4" X 18" TEST PLATE
IDENT. : 70W-A40

CHEMICAL TEST RESULTS

1. C:.09 MN:.88 P:.008 S:.005 SI:.20 CR:.04 MO:.15

NI:1.76 CU:.16 CO:<.010 NB:<.005 V:.004 AL:.018 TI:<.001

B:<.0005 SN:.010 W:<.020 N:.0081

0.

O:.0317 "WELD"

Chemical results are reported in percent by weight.

WITNESSED BY: JAMES E. SIMS, 01/05/98.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON, TEXAS 77092 • TEL (713) 939-8690 • FAX (713) 939-0249

DATE : 01/08/98
REPORT NO: 232922.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: 3281
MATERIAL : 1" THK X 16 1/4" X 18" TEST PLATE
IDENT. : 70W-B130 130 kJ/in, 450F max interpass

TENSILE TEST RESULTS

NO	SIZE [IN]	YIELD [PSI]	TENSILE [PSI]	ELONG. [%]	R OF A [%]	HARDNESS
1	.500 AWM	66,700	89,000	27.20	68.90	

Unless otherwise stated, yield stress is .2% offset. Gage length is 2 in. for 1/2 in. bars or 1 in. for 1/4 in. bars.

CHARPY TEST RESULTS

TEMP	LOCATION	FOOT POUNDS	% SHEAR	MILS LAT EXP
-20°F	WELD CVN	63-54-71-75-67	60-50-60-60-60	45-40-55-57-51

Unless otherwise stated, Charpy Impact specimens are V-notch 10 by 10 mm.

CHEMICAL TEST RESULTS

1. C:.12 MN:.99 P:.010 S:.004 SI:.20 CR:.04 MO:.14
   NI:1.57 CU:.16 NB:<.005 V:.004 AL:.013 TI:<.001
   B:<.0005 SN:.010 W:<.020 N:.0080

Chemical results are reported in percent by weight.

Respectfully submitted,

BY: [signature]

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. · 4302 DAYCO STREET · HOUSTON, TEXAS 77092 · TEL (713) 939-8690 · FAX (713) 939-0249

DATE : 01/08/98
REPORT NO: 232922.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: 3281
MATERIAL : 1" THK X 16 1/4" X 18" TEST PLATE
IDENT. : 70W-B130

CHEMICAL TEST RESULTS

O.

O:.0178 "WELD"

Chemical results are reported in percent by weight.

WITNESSED BY: JAMES E. SIMS, 01/05/98.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ◆ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. - 4302 DAYCO STREET - HOUSTON, TEXAS 77092 - TEL (713) 939-8690 - FAX (713) 939-0249

DATE : 01/08/98
REPORT NO: 232921.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: 3281
MATERIAL : 1" THK X 16 1/4" X 18" TEST PLATE
IDENT. : 100W-B40 40 kJ/in, 250F interpass

TENSILE TEST RESULTS

NO	SIZE [IN]	YIELD [PSI]	TENSILE [PSI]	ELONG. [%]	R OF A [%]	HARDNESS
1	.501 AWM	103,000	119,000	20.70	60.50	

Unless otherwise stated, yield stress is .2% offset. Gage length is 2 in. for 1/2 in. bars or 1 in. for 1/4 in. bars.

CHARPY TEST RESULTS

TEMP	LOCATION	FOOT POUNDS	% SHEAR	MILS LAT EXP
-20°F	WELD CVN	79-66-88-72-85	70-60-80-70-80	50-40-54-45-54

Unless otherwise stated, Charpy Impact specimens are V-notch 10 by 10 mm.

CHEMICAL TEST RESULTS

1. C:.05 MN:1.49 P:.008 S:.005 SI:.27 CR:.33 MO:.52

NI:2.31 CU:.04 NB:.006 V:.008 AL:.009 TI:.003

B:<.0005 SN:<.005 W:<.020 N:.0057

Chemical results are reported in percent by weight.

Respectfully submitted,

BY: [signature]

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON, TEXAS 77092 • TEL (713) 939-8890 • FAX (713) 939-0249

DATE : 01/08/98
REPORT NO: 232921.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: 3281
MATERIAL : 1" THK X 16 1/4" X 18" TEST PLATE
IDENT. : 100W-B40

CHEMICAL TEST RESULTS

O.

O:.0366 "WELD"

Chemical results are reported in percent by weight.

WITNESSED BY: JAMES E. SIMS, 01/05/98.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ◆ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON. TEXAS 77092 • TEL (713) 939-8690 • FAX (713) 939-0249

DATE : 01/08/98
REPORT NO: 232920.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: 3281
MATERIAL : 1" THK X 16 1/4" X 18" TEST PLATE
IDENT. : 100W-A130 (130) 130 k/in

TENSILE TEST RESULTS

NO	SIZE [IN]	YIELD [PSI]	TENSILE [PSI]	ELONG. [%]	R OF A [%]	HARDNESS
1	.500 AWM	83,300	112,000	22.60	64.50	

Unless otherwise stated, yield stress is .2% offset. Gage length is 2 in. for 1/2 in. bars or 1 in. for 1/4 in. bars.

CHARPY TEST RESULTS

TEMP	LOCATION	FOOT POUNDS	% SHEAR	MILS LAT EXP
-20°F	WELD CVN	7 108-87-108-90-101	90-90-90-80-80	61-60-62-56-61

Unless otherwise stated, Charpy Impact specimens are V-notch 10 by 10 mm.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON, TEXAS 77092 • TEL (713) 939-8690 • FAX (713) 939-0249

DATE : 01/08/98
REPORT NO: 232920.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: 3281
MATERIAL : 1" THK X 16 1/4" X 18" TEST PLATE
IDENT. : 100W-AB0

CHEMICAL TEST RESULTS

1. C:.06 MN:1.59 P:.009 S:.004 SI:.27 CR:.36 MO:.51

NI:2.16 CU:.06 NB:.007 V:.012 AL:.006 TI:.003 B:.0005

SN:<.005 W:<.020 N:.0055 O:.0189

0.

"WELD"

Chemical results are reported in percent by weight.

WITNESSED BY: JAMES E. SIMS, 01/05/98.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

CB&I Constructors, Inc.
8900 Fairbanks North Houston Road (77064)
P.O.Box 41146
Houston, Texas 77241-1146

713 466 7581
FAX: 713 466 1259

AWS A4.3-93 WELD METAL DIFFUSIBLE H2 DATA

NAME	Le Tourneau				
CONTRACT	05109752				
WORK ORDER NO.	AN				
WELDING PROCESS	SAW				
ELECTRODE I.D.		LA85	LA85	LA85	LA85
FLUX OR SHIELDING GAS		800HP	800HP	800HP	800HP
FLUX MOISTURE	unk				
AMPERAGE		450	420	415	415
VOLTAGE		29	29	29	29
TRAVEL SPEED (IPM)		17.5	17.5	17.0	17.0
WELDING HEAT INPUT (KJ/IN)		44.7	41.8	42.5	42.5
ELECTRODE STICKOUT		1-1/4"	1-1/4"	1-1/4"	1-1/4"
ELECTRODE CONDITIONING	N/A				
FLUX CONDITIONING	unk				
DATE WELDED	12-Aug-98				
HYDROGEN EVOLUTION TIME	85 HOURS				

====================================

HYDROGEN EVOLUTION DATA

BAROMETRIC PRESSURE (MM) 763 AMBIENT TEMP (C) 25.5

SPECIMEN NO.	AN1	AN2	AN3	AN4
MEASURED VOLUME H2 (ML)	.54	.52	.53	.54
MERCURY HEAD (MM)	253	265	270	252
H2 VOL. CORRECTED TO STP (ML)	0.33	0.31	0.31	0.33
WEIGHT OF WELD METAL (GM)	16.69	15.81	16.22	15.76
H2 PER WT. (ML/100GM)	2.0	2.0	1.9	2.1

AVERAGE H2 PER WEIGHT OF WELD (ML/100GM) **2.0**

====================================

Test by CHICAGO BRIDGE & IRON COMPANY
HOUSTON, TEXAS

SIGNED: Lewis N May
L. N. May

DATE: 17-Aug-98

CB&I Constructors, Inc.
8900 Fairbanks North Houston Road (77064)
P.O.Box 41146
Houston, Texas 77241-1146

713 466 7581
FAX: 713 466 1259

AWS A4.3-93 WELD METAL DIFFUSIBLE H2 DATA

NAME	Le Tourneau				
CONTRACT	05109752				
WORK ORDER NO.	AM				
WELDING PROCESS	SAW				
ELECTRODE I.D.		ENi4	ENi4	ENi4	ENi4
FLUX OR SHIELDING GAS		800H	800H	800H	800H
FLUX MOISTURE	unk				
AMPERAGE		440	435	435	440
VOLTAGE		29	29	29	29
TRAVEL SPEED (IPM)		17.5	17.3	17.3	17.3
WELDING HEAT INPUT (KJ/IN)		43.7	43.7	43.7	44.3
ELECTRODE STICKOUT		1-1/4"	1-1/4"	1-1/4"	1-1/4"
ELECTRODE CONDITIONING	N/A				
FLUX CONDITIONING	unk				
DATE WELDED	12-Aug-98				
HYDROGEN EVOLUTION TIME	85 HOURS				

====================================

HYDROGEN EVOLUTION DATA

BAROMETRIC PRESSURE (MM) 763 AMBIENT TEMP (C) 25.5

SPECIMEN NO.	AM1	AM2	AM3	AM4
MEASURED VOLUME H2 (ML)	.88	.99	1.12	1.06
MERCURY HEAD (MM)	280	269	260	269
H2 VOL. CORRECTED TO STP (ML)	0.51	0.59	0.68	0.63
WEIGHT OF WELD METAL (GM)	17.25	17.72	19.33	17.06
H2 PER WT. (ML/100GM)	3.0	3.3	3.5	3.7

AVERAGE H2 PER WEIGHT OF WELD (ML/100GM) 3.4

====================================

Test by CHICAGO BRIDGE & IRON COMPANY
HOUSTON, TEXAS

SIGNED: Lewis N. May
L. N. May
DATE: 17-Aug-98

CB&I Constructors, Inc.
8900 Fairbanks North Houston Road (77064)
P.O.Box 41146
Houston, Texas 77241-1146

713 466 7581
FAX: 713 466 1259

AWS A4.3-93 WELD METAL DIFFUSIBLE H2 DATA

NAME	Le Tourneau				
CONTRACT	05109752				
WORK ORDER NO.	AL				
WELDING PROCESS	SAW				
ELECTRODE I.D.		SA120	SA120	SA120	SA120
FLUX OR SHIELDING GAS		800H	800H	800H	800H
FLUX MOISTURE	unk				
AMPERAGE		435	420	420	425
VOLTAGE		29	29	29	29
TRAVEL SPEED (IPM)		17.5	17.3	17.5	17.3
WELDING HEAT INPUT (KJ/IN)		43.2	42.2	41.8	42.7
ELECTRODE STICKOUT		1-1/4"	1-1/4"	1-1/4"	1-1/4"
ELECTRODE CONDITIONING	N/A				
FLUX CONDITIONING	unk				
DATE WELDED	12-Aug-98				
HYDROGEN EVOLUTION TIME	85 HOURS				

==================================

HYDROGEN EVOLUTION DATA

BAROMETRIC PRESSURE (MM) 763 AMBIENT TEMP (C) 25.5

SPECIMEN NO.	AL1	AL2	AL3	AL4
MEASURED VOLUME H2 (ML)	1.63	1.02	1.62	1.44
MERCURY HEAD (MM)	244	281	239	256
H2 VOL. CORRECTED TO STP (ML)	1.02	0.59	1.02	0.88
WEIGHT OF WELD METAL (GM)	17.33	15.43	17.63	15.12
H2 PER WT. (ML/100GM)	5.9	3.8	5.8	5.8

AVERAGE H2 PER WEIGHT OF WELD (ML/100GM) 5.3

==================================

Test by CHICAGO BRIDGE & IRON COMPANY
HOUSTON, TEXAS

SIGNED: Lewis N May
L. N. May

DATE: 17-Aug-98

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON, TEXAS 77092 • TEL (713) 939-8690 • FAX (713) 939-0249

DATE : 08/26/98
REPORT NO: 245125.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: NC 4375
MATERIAL : 1" THK X 18" WELD PLATE
IDENT. : 70W-L

TENSILE TEST RESULTS

NO	SIZE [IN]	YIELD [PSI]	TENSILE [PSI]	ELONG. [%]	R OF A [%]	HARDNESS
1	.250 AWM	71,900	96,800	28.70	58.50	

Unless otherwise stated, yield stress is .2% offset. Gage length is 2 in. for 1/2 in. bars or 1 in. for 1/4 in. bars.

CHARPY TEST RESULTS

TEMP	LOCATION	FOOT POUNDS	% SHEAR	MILS LAT EXP
-20°F	WELD	61-58-63-78-64	30-30-30-40-30	49-43-46-59-49

Unless otherwise stated, Charpy Impact specimens are V-notch 10 by 10 mm.

CHEMICAL TEST RESULTS

1. C:.17 MN:.84 P:.010 S:.009 SI:.18 CR:.03 MO:.15
NI:1.48 CU:.19 NB:<.005 V:.002 AL:.015 TI:<.01
B: <.0005 O: .0188 N: .0041

Chemical results are reported in percent by weight.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON, TEXAS 77092 • TEL (713) 939-8690 • FAX (713) 939-0249

DATE : 08/26/98
REPORT NO: 245125.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: NC 4375
MATERIAL : 1" THK X 18" WELD PLATE
IDENT. : 70W-L

TENSILE TEST RESULTS

NO	SIZE [IN]	YIELD [PSI]	TENSILE [PSI]	ELONG. [%]	R OF A [%]	HARDNESS
1	.250 AWM	71,900	96,800	28.70	58.50	

Unless otherwise stated, yield stress is .2% offset. Gage length is 2 in. for 1/2 in. bars or 1 in. for 1/4 in. bars.

CHARPY TEST RESULTS

TEMP	LOCATION	FOOT POUNDS	% SHEAR	MILS LAT EXP
-20°F	WELD	61-58-63-78-64	30-30-30-40-30	49-43-46-59-49

Unless otherwise stated, Charpy Impact specimens are V-notch 10 by 10 mm.

CHEMICAL TEST RESULTS

1. C:.17 MN:.84 P:.010 S:.009 SI:.18 CR:.03 MO:.15

NI:1.48 CU:.19 NB:<.005 V:.002 AL:.015 TI:<.01

B: <.0005 O: .0188 N: .0041

Chemical results are reported in percent by weight.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ♦ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. · 4302 DAYCO STREET · HOUSTON, TEXAS 77092 · TEL (713) 939-8690 · FAX (713) 939-0249

DATE : 08/26/98
REPORT NO: 245125.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: NC 4375
MATERIAL : 1" THK X 18" WELD PLATE
IDENT. : 70W-L

X-RAY EXAMINATION PER AWS D1.1: FAILED

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ◆ OMNI LABORATORY
METAL TECHNOLOGY
BODYCOTE OMNITEST INC. • 4302 DAYCO STREET • HOUSTON, TEXAS 77092 • TEL (713) 939-8690 • FAX (713) 939-0249

DATE : 08/26/98
REPORT NO: 245128.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: NC 4375
MATERIAL : 1" THK X 18" LG WELD PLATE
IDENT. : 100W-N

X-RAY EXAMINATION PER AWS D1.1: FAILED

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

Bodycote MATERIALS TESTING ◆ OMNI LABORATORY

METAL TECHNOLOGY

BODYCOTE OMNITEST INC. · 4302 DAYCO STREET · HOUSTON, TEXAS 77092 · TEL (713) 939-8690 · FAX (713) 939-0249

DATE : 08/26/98
REPORT NO: 245128.0
CUST ACCT: 4718

TO: LE TOURNEAU UNIVERSITY
P.O. BOX 7001
LONGVIEW, TX 75607

MECHANICAL TEST REPORT

CUSTOMER JOB: NC 4375
MATERIAL : 1" THK X 18" LG WELD PLATE
IDENT. : 100W-N

TENSILE TEST RESULTS

NO	SIZE [IN]	YIELD [PSI]	TENSILE [PSI]	ELONG. [%]	R OF A [%]	HARDNESS
1	.249 AWM	88,100	120,000	24.20	64.70	

Unless otherwise stated, yield stress is .2% offset. Gage length is 2 in. for 1/2 in. bars or 1 in. for 1/4 in. bars.

CHARPY TEST RESULTS

TEMP	LOCATION	FOOT POUNDS	% SHEAR	MILS LAT EXP
-20°F	WELD	80-83-84-84-76	50-50-50-50-50	54-51-53-52-50

Unless otherwise stated, Charpy Impact specimens are V-notch 10 by 10 mm.

CHEMICAL TEST RESULTS

1. C:.08 MN:1.45 P:.008 S:.007 SI:.25 CR:.34 MO:.47
NI:2.16 CU:.05 NB:.007 V:.007 AL:.006 TI:<.01
B: <.0005 O: .0239 N: .0066

Chemical results are reported in percent by weight.

Respectfully submitted,

BY:

Bodycote Omnitest Inc.

APPENDIX III

All Weld Metal Parameters / All Weld Metal Mechanical Results

Input I/in)	Individual #	Lab No.	Wire	Flux	Polarity	Preheat (°F)	Interpass (°F)	WFS (in/min)	Amperage (A)	Voltage (V)	Travel Spd. (in/min)	Yield (ksi)	Tensile (ksi)	% Elong.	R of A (%)	Charpy @ -20°F (ft-lb)	% shear	Lat Exp (mils)	Avg. Hardness
0	100W-B	232921	SA 120	800H	DCEP	200	200-250	48	600	29	26.1	103.0	119.0	20.7	60.5	79, 66, 88, 72, 65	70, 60, 80, 70, 80	50, 40, 54, 45, 54	290.8
70	100W-C	234551	SA 120	800H	DCEP	200	200-250	50	600	29	14.9	94.8	116.0	22.4	65.2	92, 109, 87, 96, 102	70, 70, 70, 70, 70	58, 71, 54, 64, 60	299.8
00	100W-D	234550	SA 120	800H	DCEP	400	400-450	50	600	29	10.4	81.4	117.0	23.3	64.9	68, 64, 74, 68, 75	40, 40, 40, 40, 40	44, 44, 50, 46, 50	314
30	100W-A	232920	SA 120	800H	DCEP	400	400-450	48.5	600	29	8.03	83.3	112.0	22.6	64.5	108, 87, 108, 90, 101	90, 90, 90, 80, 80	61, 60, 62, 56, 61	311.2
40	100W-E	237660	SA 120	800H	DCEN	200	200-250	66	500	30	22.5	114.0	129.0	19.7	62.9	110, 109, 103, 101, 92	90, 90, 90, 90, 90	64, 67, 63, 67, 56	
100	100W-N	245128	SA120	800H	DCEN	400	400-450	130	600	32	11.5	88.1	120	24.2	64.7	80,83,84,84,76	50,50,50,50,50	54,51,53,52,50	
40	100W-J	241039	MC-120S	800H	DCEP	200	200-250	127	600	29	26.1	107	120	20.7	59.3	67,70,82,72,73	70,75,85,75,75	50,47,45,51,52	
70	100W-K	241041	MC-120S	800H	DCEP	200	200-250	127	600	29	14.9	103	117	21.6	61.9	80,77,79,82,78	90,85,85,90,90	57,52,53,57,52	
100	100W-I	241042	MC-120S	800H	DCEP	400	400-450	127	600	29	10.4	88.1	114	22.1	66.6	79,91,80,67,76	75,85,75,70,70	57,61,56,47,53	
130	100W-H	241040	MC-120S	800H	DCEP	400	400-450	127	600	28.9	8.03	81.7	116	22.5	63.9	45,55,69,61,64	50,60,65,65,65	34,39,48,39,40	
40	100W-L	241043	MC-120S	800H	DCEN	200	200-250	140	600	31.5	28.8	110	126	9	26.9	79,79,82,79,76	80,80,80,80,80	56,59,59,56,51	
100	100W-G	Not Tested	MC-120S	800H	DCEN	400	400-450	166	600	32	11.5	[redacted]							
100	100W-M	Failed X-Ray	MC-120S	800H	DCEN	400	400-450	129	500	32	9.6								
130	100W-F	Not Tested	MC-120S	800H	DCEN	400	400-450	166	600	32	8.9								
70W																			
40	70W-A	232919	ENi4	800H	DCEP	200	200-250	47	600	29	26.1	81.9	96.1	25.3	69.0	116, 119, 104, 120, 88	80, 80, 80, 80, 70	81, 82, 70, 77, 62	307
70	70W-D	234548	ENi4	800H	DCEP	200	200-250	50	600	29	14.9	79.9	95.1	26.6	61.6	110, 118, 120, 108, 112	70, 70, 80, 70, 70	79, 75, 81, 73, 76	282
100	70W-C	234549	ENi4	800H	DCEP	400	400-450	50	600	29	10.4	71.2	91.4	27.3	67.8	55, 66, 58, 76, 63	40, 50, 40, 50, 40	46, 54, 48, 60, 50	282
130	70W-B	232922	ENi4	800H	DCEP	400	400-450	48	600	29	8.03	66.7	89.0	27.2	68.9	63, 54, 71, 75, 76	60, 50, 60, 60, 60	45, 40, 55, 57, 51	268
40	70W-I	237658	ENi4	800H	DCEN	200	200-250	52	400	30	18.5	[redacted]							
100	70W-L	245125	ENi4	800H	DCEN	400	400-450	128	600	32	11.5	71.9	96.8	28.7	58.5	61,58,63,78,64	30,30,30,40,30	49,43,46,59,49	
40	70W-E	237252	LA 85	800HP	DCEP	200	200-250	52	600	29	26.1	83.5	97.9	23.0	66.0	92, 99, 114, 96, 102	90, 90, 95, 90, 90	70, 78, 82, 70, 73	263
70	70W-F	237253	LA 85	800HP	DCEP	200	200-250	50	600	29	14.9	81.8	97.3	25.5	67.4	122, 126, 128, 122, 114	90, 90, 90, 90, 80	78, 83, 88, 83, 79	262
100	70W-H	237250	LA 85	800HP	DCEP	400	400-450	51	600	29	10.4	71.1	90.1	26.8	70.5	119, 114, 122, 126, 121	90, 80, 90, 90, 90	87, 78, 78, 84, 85	253
130	70W-G	237251	LA 85	800HP	DCEP	400	400-450	50	600	29	8.1	69.8	94.6	26.6	68.8	60, 58, 52, 58, 59	60, 60, 50, 60, 60	50, 44, 35, 48, 46	262
40	70W-J	237659	LA 85	800HP	DCEN	200	200-250	66	500	30	22.5	87.9	108.0	20.8	59.1	107, 133, 110, 122, 138	90, 100, 90, 100, 100	73, 87, 78, 83, 91	
100	70W-K	245127.1	LA 85	800HP	DCEN	400	400-450	128	600	32	11.5	78.9	96.6	24.8	66.1	89,120,88,100,106	100,100,100,100,100	65,84,66,71,82	
100	70W-M	247014	ENi4 Twin	800H	DCEP	400	400-450	70	900	31	16.7	75	94.9	26.9	64	82,60,49,46,40	40,40,40,40,40	70,55,48,45,37	
130	70W-N	247015	ENi4 Twin	800H	DCEP	400	400-450	67	800	34	13	73.8	101	24.6	59.8	39,39,40,46,61	30,30,30,30,30	32,36,33,41,48	
130	70W-P	Not Complete	LA 85 Twin	800HP	DCEP	400	400-450	[redacted]											
100	70W-Q	247016	LA 85 Twin	800HP	DCEP	400	400-450	69	800	33	15.8	81.6	112	19	41.9	40,40,46,48,48	40,40,40,40,40	35,37,369,41,47	

AWM Chemistries

Input (J/In)	Individual #	C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cr (%)	Mo (%)	Ni (%)	Cu (%)	Co (%)	Nb (%)	V (%)	Al (%)	Ti (%)	B (%)	Sn (%)	W (%)	N (%)	O (%)
40	100W-B	0.05	1.49	0.008	0.005	0.27	0.33	0.52	2.31	0.04		0.006	0.008	0.009	0.003	<0.0005	<0.005	<0.02	0.0057	
70	100W-C	0.06	1.53	0.010	0.008	0.26	0.35	0.51	2.07	0.07		0.006	0.012	0.011	0.004				0.0058	0.020
100	100W-D	0.06	1.51	0.010	0.008	0.27	0.36	0.51	2.02	0.08		0.006	0.013	0.011	0.004				0.0057	0.029
130	100W-A	0.06	1.59	0.009	0.004	0.27	0.36	0.51	2.16	0.06		0.007	0.012	0.006	0.003	0.0005	<0.005	<0.02	0.0055	0.0189
40	100W-E	0.10	1.47	0.009	0.008	0.26	0.29	0.50	2.30	0.03		<0.005	0.006	<0.002	0.006	<0.0005			0.0051	0.0122
100	100W-N	0.08	1.45	0.008	0.007	0.25	0.34	0.47	2.16	0.05		0.007	0.007	0.006	<.01	<0.0005			0.0066	0.0239
40	100W-J	0.04	2.1	0.004	0.008	0.39	0.08	0.38	1.62	0.06		0.006	0.008	0.009	0.023	0.001			0.0045	0.039
70	100W-K	0.05	2.09	0.005	0.007	0.32	0.12	0.4	1.6	0.08		0.006	0.011	0.006	0.014	0.001			0.0046	0.036
100	100W-I	0.05	2.06	0.006	0.007	0.36	0.14	0.41	1.55	0.09		0.006	0.013	0.007	0.017	0.001			0.0046	0.031
130	100W-H	0.06	2.02	0.006	0.007	0.36	0.17	0.41	1.51	0.1		0.006	0.014	0.009	0.017	0.001			0.005	0.026
40	100W-L	0.07	2.11	0.004	0.008	0.36	0.07	0.4	1.68	0.05		0.006	0.008	0.006	0.017	0.001			0.0043	0.028
100	100W-G	not tested																		
100	100W-M	Failed X-Ray																		
130	100W-F	not tested																		

40	70W-A	0.09	0.88	0.008	0.005	0.2	0.04	0.15	1.76	0.16	<0.010	<0.005	0.004	0.018	<0.001	<0.0005	0.01	<0.02	0.0081	0.0317
70	70W-D	0.11	0.96	0.009	0.008	0.18	0.03	0.15	1.73	0.17		<0.005	0.005	0.017	<0.001				0.0094	0.013
100	70W-C	0.11	1.00	0.011	0.008	0.20	0.03	0.15	1.65	0.16		<0.005	0.005	0.018	<0.001				0.0085	0.021
130	70W-B	0.12	0.99	0.010	0.004	0.20	0.04	0.14	1.57	0.16		<0.005	0.004	0.013	<0.001	<0.0005	0.01	<0.02	0.008	
40	70W-I	not tested																		
100	70W-L	0.17	0.84	0.01	0.009	0.18	0.03	0.15	1.48	0.19		<.005	0.002	0.015	<.01	<.0005			0.0188	0.0188
40	70W-E	0.10	1.35	0.013	0.007	0.19	0.04	0.13	1.27	0.08	<0.010	<0.005	0.021	0.012	<0.001	0.0007	<0.005	<0.020	0.0039	0.0321
70	70W-F	0.10	1.35	0.013	0.008	0.19	0.04	0.12	1.07	0.12	<0.010	<0.005	0.017	0.014	<0.001	0.0007	<0.005	<0.020	0.0047	0.0282
100	70W-H	0.08	1.49	0.012	0.006	0.16	0.04	0.14	1.41	0.08	<0.010	<0.005	0.027	0.011	<0.001	0.0008	<0.005	<0.020	0.0038	0.0245
130	70W-G	0.10	1.42	0.015	0.008	0.21	0.04	0.11	1.10	0.10	<0.010	<0.005	0.020	0.014	<0.001	0.0007	<0.005	<0.020	0.0065	0.0175
40	70W-J	0.13	1.40	0.010	0.009	0.18	0.03	0.18	1.52	0.09		<0.005	0.021	<0.002	<0.001	<0.0005			0.0030	0.142
100	70W-K	0.13	1.43	0.014	0.007	0.18	0.03	0.15	1.28	0.11		<0.005	0.02	0.003	<0.001	<0.0005			0.0032	0.0162
100	70W-M	0.13	0.8	0.014	0.035	0.15	0.11	0.02	0.14	0.56	0.009	<0.005	<.001	0.008	0.004	0.0006	0.015	<.020	0.0133	0.0088
130	70W-N	0.17	1.03	0.01	0.006	0.3	0.08	0.15	1.35	0.19	0.015	<.005	0.008	0.023	0.005	0.0006	0.008	<.020	0.0061	0.0179
130	70W-P																			
100	70W-Q	0.14	0.8	0.015	0.035	0.15	0.11	0.02	0.14	0.57	0.009	<.005	<.001	0.008	0.004	0.0006	0.016	<.020	0.0128	0.0083

APPENDIX IV

SOURCE – LINCOLN ELECTRIC CO

	All Weld Metal				Transverse	
	Tensile (ksi)	Yield (ksi)	% Elongation	CVN (ft-lbs)	Tensile (ksi)	Side-bends
HPS70W Undermatching (LA75 800HP)						
100 kJ/in	87.3	67.0	31	68	85.5	Passed
40 kJ/in	93.6	83.4	28	166	100.0	Passed
Requirement		*63.0*	*17 min*	*25 @ -25° F*		
HPS70W Matching (LA85 800HP)						
100 kJ/in	96.4 / 83	72.4 / 90	28	73	90.5 /	Passed
40 kJ/in	102.0 / 71	94.3 / 97	24	124	104.0 / 102	Passed
Requirement	*88-114*	*70 min.*	*17 min*	*25 @ -25° F*		

Table 1. Mechanical testing results.

	C	S	Mn	Si	P	Cu	Ni	Mo	V	Nb	Ti
HPS70W Undermatching (LA75 800HP)											
100 kJ/in	0.072	<0.003	1.28	0.48	0.009	0.109	1.15	0.01	0.033	<0.002	0.002
40 kJ/in	0.093	<0.003	1.22	0.49	0.006	0.048	1.37	0.01	0.021	<0.002	0.003
Requirement							*1 min.*				
HPS70W Matching (LA85 800HP)											
100 kJ/in	0.077	0.003	1.49	0.24	0.012	0.164	1.18	0.14	0.035	<0.002	0.002
40 kJ/in	0.080	0.004	1.41	0.19	0.009	0.113	1.42	0.19	0.019	<0.002	0.002
Requirement							*1 min*				
LA-75 chemistry	0.075	0.005	1.06	0.60	0.007	0.004	0.94	<0.00	<0.000	0.003	0.002
LA-85 chemistry	0.095	0.006	1.42	0.20	0.010	0.010	1.04	0.18	<0.000	0.005	0.001
HPS70W Baseplate	0.100	<0.003	0.88	0.30	0.015	0.352	0.87	0.47	0.039	0.004	0.031

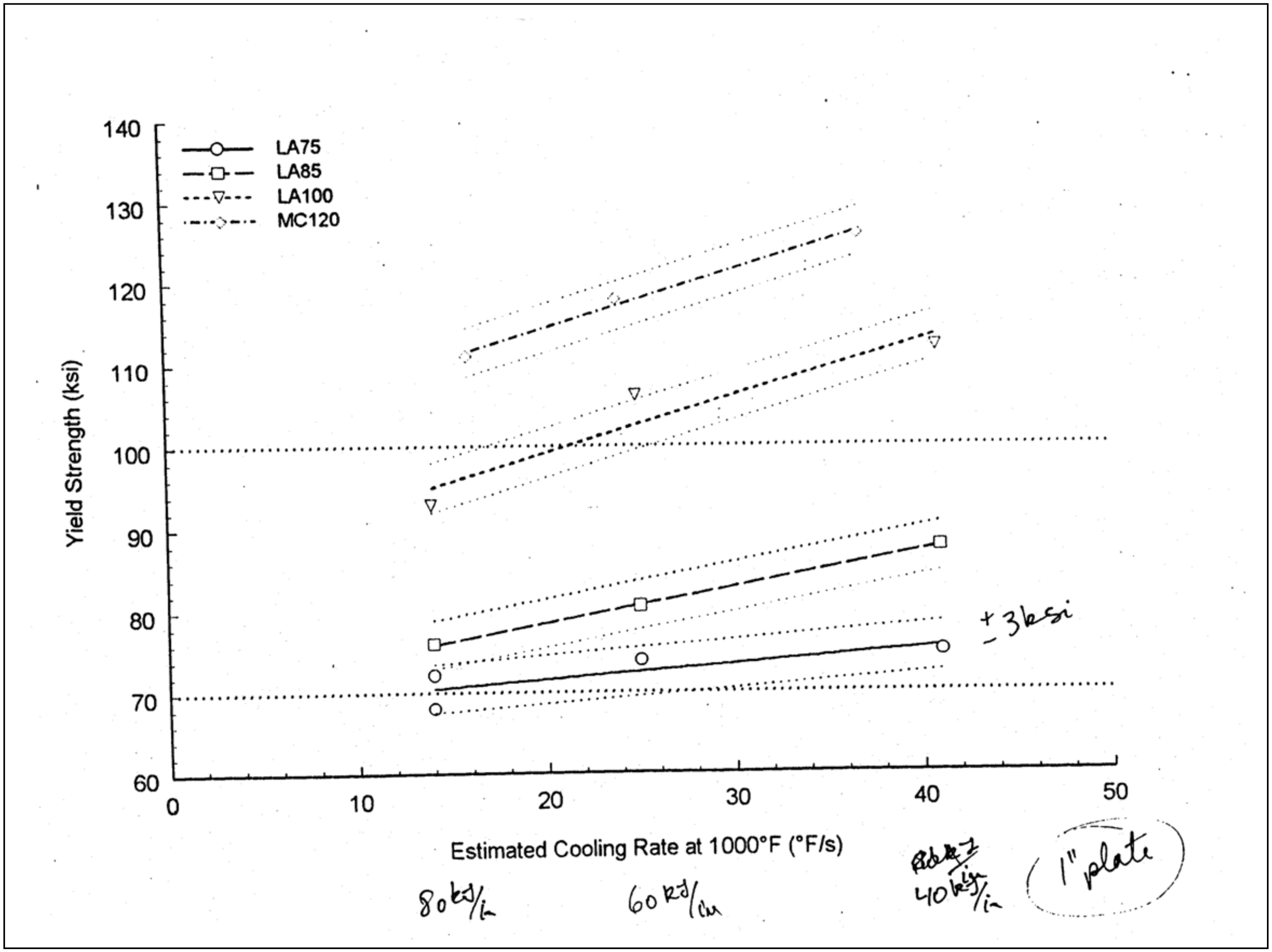
Table 2. Electrode, baseplate, and deposit chemistry.

HIGH PERFORMANCE STEEL WELDABILITY PROJECT – LINCOLN ELECTRIC

Submerged Arc Welding Consumables for HPS70W and HPS100W

Electrode	Flux	HI (kJ/in)	Tensile Test Results UTS (ksi)	YS (ksi)	EL (%)	Charpy V-notch Energy -25°F (ft-lbf)	-40°F (ft-lbf)	Chemical Test Results C	S	Mn	Si	P	Ni	Mo	V
LA75	MIL800-H modified 1% Ni	80	87.3	72.1	29	112 Avg.		0.086	0.003	1.28	0.44	0.010	1.15	0.01	0.024
		80	85.1	68.0	32	158 Avg.		0.095	0.003	1.24	0.43	0.009	1.09	0.01	0.021
		58	87.5	73.8	30	145 Avg.		0.095	0.004	1.25	0.44	0.008	1.17	0.01	0.022
		40	88.8	74.8	31	145 Avg.				1.26	0.45	0.009	1.26	0.01	0.024
LA85	MIL800-H modified	80	91.1	76.0	28		133 Avg.	0.098	0.003	1.44	0.19	0.011	1.14	0.14	0.021
		58	93.1	80.5	27		134 Avg.			1.48	0.19	0.011	1.30	0.15	0.024
		40	97.3	87.6	26		112 Avg.			1.53	0.18	0.012	1.52	0.17	0.027
LA100	MIL800-H modified	80	111.0	92.9	25		110 Avg.	0.075	0.003	1.67	0.36	0.009	1.85	0.34	0.024
		58	116.0	106.0	22		71 Avg.			1.70	0.43	0.010	2.02	0.34	0.025
		40	121.0	112.0	21		91 Avg.			1.77	0.43	0.011	2.22	0.47	0.028
MC120S-55	MIL800H	80	119.0	111.0	24		74 Avg.			2.29	0.39	0.007	2.05	0.44	0.008
		58	126.0	126.0	20		61 Avg.			2.40	0.41	0.007	2.03	0.44	0.008
		40	130.0	126.0	20		61 Avg.			2.43	0.41	0.008	2.09	0.45	0.009

M. A. Quintana
17 February 1998



140
130
120
110
100
90
80
70
60
Yield Strength (ksi)
LA75
LA85
LA100
MC120
0
10
20
30
40
50
Estimated Cooling Rate at 1000°F (°F/s)
± 3ksi
80 kJ/in
60 kJ/in
40 kJ/in
1" plate

APPENDIX V

All Weld Metal Crack Investigation of HP 70W and HP 100W Steel

FINAL REPORT

December 8, 1998

by

Travis Olson

LeTourneau University, Longview, TX

1.0 Background

For approximately two years, the LeTourneau University Welding Research Team has been performing contract work for the Federal Highway Administration. This work includes mechanical properties and weldability tests performed on 70 and 100 ksi minimum yield strength, high performance, weathering steels. While evaluating cross-sections of completed All Weld Metal (AWM) test plates, cracks were observed in some of the joints. These cracks were located in and/or near the first two passes of the joint. Although AWS A5.23 does not specifically address the issue of cracks near the root passes of a test plate, it was determined that the frequency, approximate size and cause of the cracks should be investigated. The task was assigned as an independent research project to be completed within the Fall of '98 semester by a research assistant.

1.0 Objectives

The objectives of this project were to characterize the type, size, location and morphology of located cracks.

2.0 Procedure

All existing scraps from the test plates were located and transverse cross sections of the joint were mounted and polished. The cross sections were visually examined and all visible cracks were measured. The cracks were also inspected under an optical microscope.

All cross sections containing cracks of sufficient size were then broken out of the plastic mount. The samples were broken along the crack in order to view the crack surface and were viewed using a SEM to determine the crack morphology.

When a sufficient length of scrap was available, the backing bar was removed and the sample was examined for distribution, length, and depth of cracks using non-destructive methods. Liquid dye penetrant, magnetic particle, and ultrasonic testing were used.

3.0 Results and Dicsussion

Table 1 contains a summary of all cracks and cross sections found. None of the 100 ksi samples showed any indications of cracking. However, nearly all of the 70 ksi samples exhibited at least one crack in and/or near the first two passes of the joint.

Table 1.

L. U. #	Bodycote #	Base Metal	Heat Input (KJ/in)	Wire	Flux	Polarity	Travel Spd. (in/min)	Crack Length (mm)
100W-B	232921	100W	40	SA 120	800H	DCEP	26.1	0
100W-C	234551	100W	70	SA 120	800H	DCEP	14.9	0
100W-D	234550	100W	100	SA 120	800H	DCEP	10.4	0
100W-A	232920	100W	130	SA 120	800H	DCEP	8.03	0
100W-N	245128	100W	100	SA120	800H	DCEN	11.5	0
70W-A	232919	70W	40	ENi4	800H	DCEP	26.1	0
70W-D	234548	70W	70	ENi4	800H	DCEP	14.9	1.6
70W-C	234549	70W	100	ENi4	800H	DCEP	10.4	2.4
70W-B	232922	70W	130	ENi4	800H	DCEP	8.03	2, 2.4
70W-L	245125	70W	100	ENi4	800H	DCEN	11.5	9.5, 4
70W-E	237252	70W	40	LA 85	800HP	DCEP	26.1	1.6
70W-H	237250	70W	100	LA 85	800HP	DCEP	10.4	0
70W-G	237251	70W	130	LA 85	800HP	DCEP	8.1	7.1, 3.2
70W-K	245127.1	70W	100	LA 85	800HP	DCEN	11.5	12.7
70W-M	247014	70W	100	ENi4 Twin	800H	DCEP	16.7	4.8
70W-N	247015	70W	130	ENi4 Twin	800H	DCEP	13	2.4
70W-Q	247016	70W	100	LA 85 Twin	800HP	DCEP	15.8	5.6

4.1 Micro-photographs

Micro-photographs of a typical crack are shown in Figures 1 and 2. The cracks exhibit an intergranular propagation pattern, typical of solidification cracking (Ref. 1). The solidification pattern is also evident, showing coarse, columnar grains of different orientations merging at the crack. This indicates that the crack initiated at the final stages of solidification in the middle of the fusion zone, which is also indicative of solidification cracking (Ref. 2 & 3).

4.2 Fractography

SEM fractography exposed very smooth crack surfaces and also revealed a columnar dendritic solidification morphology (Figures 3 & 4). This is also typical of solidification cracking (Ref. 3). When examined with an EDS x-ray line scan immediately upon breaking, some samples exhibited non-homogenities across dendrite boundaries.

Relative concentration differences of carbon, sulfur, and phosphorus were found between dendrites and at different locations on a particular dendrite, indicating substantial segregation occurred during solidification.

4.3 Non-destructive Evaluation

Most cracks were relatively short and exhibited very little depth. The cracks tended to be located near the beginning and end of the weld. However, the plates welded with twin arc exhibited longer cracks. The weld pool associated with the twin arc was much longer and narrower than in the single arc tests, which makes the twin arc more susceptible to solidification cracking (Ref. 2).

4.4 Chemistries

Since only the 70 ksi material was observed to be cracking, the welding materials and procedures were analyzed to try to find a practical difference between the 70 ksi and the 100 ksi AWM tests. The backing bars used for the 100 ksi tests were made of the same material as the test plates. However, the 70 ksi tests used an A36 backing bar. Chemistries of the A36 backing bar and the 70 ksi base material are summarized in Table 2.

Table 2.

	C	Mn	P	S	Cu	Ni	Cr
A36 backing bar	0.170	0.875	0.012	0.045	0.463	0.165	0.123
70 ksi base metal	0.1	1.2	0.01	0.003	0.3	0.35	0.52

Carbon and sulfur are shown to be significantly higher and the manganese lower in the backing bar than in the base metal. This will lead to an increase in C and S and a decrease in Mn in the fusion zone due to the dilution contribution of the backing bar. There is then an increase in the solidification cracking tendencies due to fact that C and S are the principle elements that promote solidification cracking. The decrease in Mn also contributes to the problem. S will combine with both Fe and Mn, but has a higher affinity for Mn. FeS is much more detrimental to the weld than MnS. If less Mn is available to combine with S, more FeS is formed, increasing the solidification susceptibility (Ref. 3 & 4).

4.5 Welding Parameters

During welding, amperage variations and changes in bead shape and location were observed within the same pass during the welding of test plates. This was especially true during the root passes which is where the cracks are located (Figure 5). A change in amperage could alter the pool shape, solidification rate, and temperature gradient, thus altering the solidification morphology (Ref. 5). Changes in bead shape can affect the amount and concentration of stress in the bead (Ref. 2 & 3).

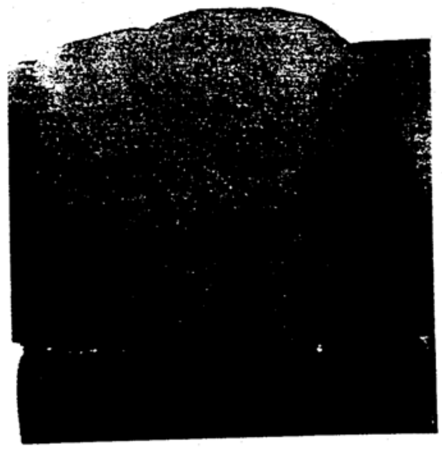


Figure 5 - Typ. Macro - LU# 70W-Q

5A

4.0 Conclusions & Recommendations

The observed cracks have been identified as solidification cracks resulting from the high C and S content and the low Mn content of the A36 backing bar. Weld pool shape, solidification morphology, and grain orientation have also been indentified as factors involved in the solidification cracking susceptibility. Areas in the first two passes not exhibiting cracking most likely experienced a different weld pool shape or welding parameters than areas with cracking.

Using a backing bar of similar material to the base metal will reduce the amount of solidification cracking. However, further testing is needed using these similar backing bars to determine if the consumables will deposite allowable amounts of C, S, P, and Mn in the weld metal. Limits on welding parameters may also be necessary to obtain proper pool shape and solidification morphology. It is recommended that the dissimilar welding of HP70W and HP100W be avoided until further research is conducted to determine allowable dissimilar base metal composition limits and dillution effects.

5.0 References

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3. Linnert, G., 1994. *Welding Metallurgy, Volume I,* GML Publications, pg. 507.
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5. Kou, S., 1987. *Welding Metallurgy,* John Wiley & Sons, pgs. 129-137.

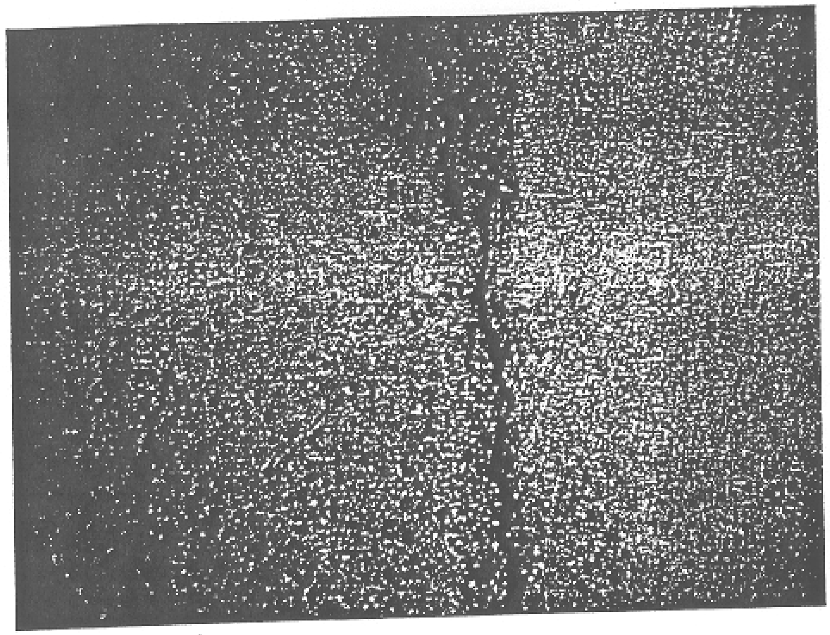

Figure 1-A
LU #70W-Q – 50X

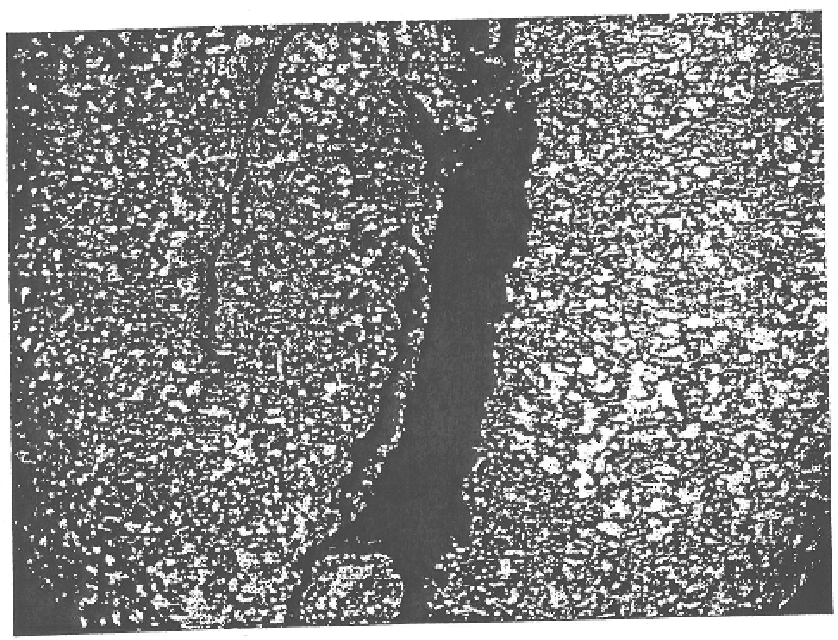

Figure 2-A
LU #70W-Q – 400X

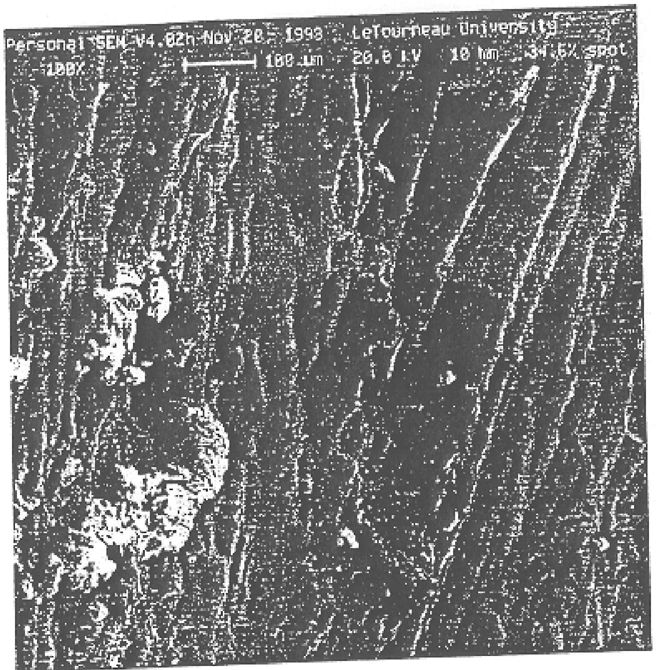

Figure 3-A
LU #70W-C – 100X – SE

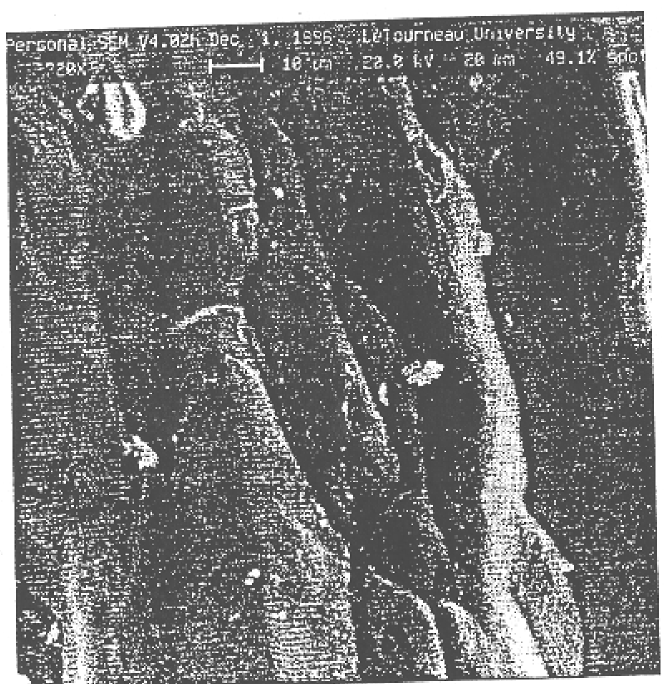

Figure 4-A
LU #70W-C – 720X – SE