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Report No. 25

Weld and Heat Affected Zone Crack Arrest Fracture Toughness of AAR TC128 Grade B Steel

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OF AAR TC128 GRADE B STEEL

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ABSTRACT

Weld and heat affected zone (HAZ) crack arrest fracture toughness tests was conducted on specimens from welded plates of normalized AAR TC128 grade B steel, currently used in appropriate tank cars that carry hazardous materials. The plates were joined under laboratory conditions and stress relieved using the recommended Association of American Railroads (AAR) welding procedures. In the calculation of the crack arrest fracture toughness, the yield strength at the test temperature is required in the appropriate equations. Hence weld metal tensile specimens were prepared from the joined plates and tested at temperatures ranging from -51 °C to -18 °C. Weld and HAZ crack arrest fracture toughness specimens were prepared and tested at -51 °C. Because of enhanced weld toughness, it was impossible to initiate a crack in any of the weld specimens tested, hence a crack arrest fracture toughness was not obtained. Crack arrest fracture toughness tests were conducted on similar specimens where the crack plane was within the HAZ. Crack arrest fracture toughness values were obtained for specimens tested at -51 °C and at -18 °C. Specimens tested at -29 °C were not valid since the final crack length could not be determined. Crack arrest fracture toughness results indicated that both the weld metal and the HAZ for the welded normalized and stress relieved AAR TC128 grade B steel were highly resistant to crack initiation and possessed the ability to arrest a propagating crack.

INTRODUCTION

The welds tested in this study joined steel plates that are currently used in appropriate tank cars that carry hazardous commodities. The traditional mechanical properties and fracture toughness determined for AAR TC128 grade B steel in both the normalized, and normalized and stress relieved conditions were presented in a paper entitled, "Mechanical Properties and Fracture Toughness of AAR TC128 grade B Steel in the Normalized, and Normalized and Stress Relieved Conditions" by Hicho and Harne. In that paper crack initiation and crack arrest fracture toughness, as a function of temperature, were determined for base plate material. To compliment this work, the crack arrest fracture toughness of the weld metal and heat affected zone were evaluated. This paper will show the ability of the weld metal and the associated heat affected zone to arrest a propagating crack.

MATERIAL AND WELDING PROCEDURE

Six plates, 1.4 cm (9/16 inch) in thickness by 28 cm (11 inches) in width, and 91 cm (36 inches) in length, of normalized AAR TC128 grade B steel were sent to Union Tank Car Company (UTC) to be welded and stress relieved by Mr. D. Untermeyer of UTC. The welding procedures followed by Mr. Untermeyer and the UTC staff are detailed in Appendices I and II. The plates were returned to the National Institute of Standards and Technology and test specimens were prepared.

TEST PROGRAM

Tensile specimens taken from the weld metal were prepared in order to evaluate the mechanical properties as a function of test temperature. Of primary importance is the yield strength since it is used in the determination of the crack arrest fracture toughness. American Society for Testing and Materials (ASTM) tensile specimens with a reduced diameter of 6.4 mm (0.25 inch) were machined from the centerline of the weld according to ASTM Method A 370-90. The tensile specimens were tested at -51 °C (-60 °F), -40 °C (-40 °F), -29 °C (-20 °F), and -18 °C (0 °F) in an environmental chamber where the temperature was held to ± 2 °C. Knoop hardness tests were conducted on the crack arrest specimens after testing. The specimens were sectioned, polished, etched, and Vickers hardness measurements taken. The Vickers measurements were then converted to Rockwell B hardness values. Metallographic examinations were also conducted on the etched microstructures and representative photomicrographs were taken. Crack arrest specimens were prepared and tested according to ASTM Method 1221-90. Two types of crack arrest specimens were prepared; one where the crack plane was entirely within weld metal, and the other where the crack plane was along the heat affected zone. Photomicrographs were used as an aid to locate the HAZ. Crack arrest testing was initiated at -51 °C (-60 °F) since this temperature corresponded to the lowest expected service test temperature to which this tank car steel would be exposed.

RESULTS

Tensile Tests

The results of the weld metal tensile tests are shown in Table 1 and figure 1. The yield strength was found to be essentially independent, 545 MPa (80 ksi), from -18 °C (0 °F) to -51 °C (-60 °F). The yield strength of the base plate was found to increase as the test temperature decreased and reach a value of about 450 MPa (65 ksi) at -51 °C (-60 °F). This improved yield strength for the weld material is beneficial. It has been shown that as the temperature decreases, as in the base plate, the yield strength decreases. This increase in yield strength is often accompanied by a decrease in material toughness. However as noted in the all weld metal mechanical property test results, the yield strength was essentially uniform over the comparable test temperatures. This leads to improved toughness properties where the weld is tougher, i.e., more resistant to crack initiation than the base plate. The toughness, in terms of the reduction in area and elongation, was comparable to base plate material.

Hardness

Vickers hardness measurements were taken in the welds and the heat affected zones of selected etched specimens. The results, and the corresponding hardness in Rockwell B units, are shown in Table 2. They indicate that the weld metal and base metal are within allowable limits. The hardness of the heat affected zone was also within acceptable limits; that is, there was no indication of hard, brittle zones which might lead to unstable cleavage fracture.

Crack Arrest Tests

In crack arrest testing, in order to obtain a valid crack arrest fracture toughness, one of the primary requirements for test validity is that a crack must initiate, propagate, and then arrest in the test specimen. Unlike other fracture toughness tests, a preexisting crack is not fatigued in these crack arrest specimens. Instead, a hard, brittle weld is deposited in the region where the crack is desired to initiate. On the application of a load, a crack is supposed to initiate in this hard, brittle zone and propagate into the weld metal and arrest. To enhance the initiation, the temperature is reduced to where the yield strength is increased and the toughness is reduced.

Tests were begun at -51 °C (-60 °F), and we were unable to initiate a crack in the all weld metal specimen. The test was repeated five more times, and on each occasion we were unable to initiate a crack in the specimen. Hence, we concluded that the weld metal was very resistant to crack initiation and had a higher crack initiation value than the base plate material. This further indicated that if a crack initiated in the base plate, it would not propagate in the weld metal since the weld metal was more resistant to both crack initiation and propagation.

Specimens were prepared to determine the crack arrest toughness of the heat affected zone. This is the zone adjacent to the weld and a photomicrograph of several heat affected zones are shown in figures 2 to 6. Crack arrest tests were also conducted at -51 °C (-60 °F) and arrest K_a's of 48 and 69 MPa*$M^{1/2}$ (44 and 63 Ksi*$in^{1/2}$) were obtained. The arrest K's were equivalent to the arrest K's obtained for the base metal. Similar tests were conducted at -29 °C (-20 °F) and it was not possible to obtain a crack arrest value since we believe that because of the variance in the microstructure of the HAZ, the propagating crack jumped out of the side groove. Hence we were not able to obtain a final crack length and a crack arrest value. At -18 °C (0 °F), a crack arrest value of 156 MPa*$M^{1/2}$ (172 Ksi*$in^{1/2}$) was obtained. Compared to other crack arrest values, this value is very high. All of these crack arrest results indicate that both the weld metal and HAZ possess the ability to arrest a propagating crack. Hence under these laboratory conditions, the results indicate that in the presence of a crack, both the weld metal and the HAZ would be highly resistant to catastrophic failure.

Metallographic Examinations

Photomicrographs of the crack arrest test specimens are shown in figures 2 to 6. The microstructures of all the welds were similar. At higher magnification coarse dendritic structure, characteristic of welded material, was observed. The stock molbydate etchant was composed of 100 ml water, 100 ml nitric acid, and 15 grams ammonium molybdate. When used, 1ml of ethyl alcohol was added to the stock solution.

Conclusions

The welds examined in this study were prepared using laboratory conditions. The results clearly indicate that the welds and the heat affected zone adjacent to these welds possessed fracture toughness properties that inhibited crack initiation and propagation.

ACKNOWLEDGEMENT

This work was supported by the Federal Railroad Administration and monitored by Ms. Claire Orth, Chief of the Safety Research Division. We would also like to thank Mr. M. Untermeyer and his staff of Union Tank Car Company for welding the test plates.

Table 1. Tensile Test Results for all Weld Metal Specimens.

Specimen Number	Test Temp. °C	(°F)	UTS MPa	(ksi)	Ys (0.2%) MPa	(ksi)	R_A %	Elongation, % 25 mm (1 inch)
W1	-51	-60	694.5	100.8	556.0	80.7	59.2	29.7
W2	-51	-60	689.7	100.1	546.4	79.3	63.1	24.4
W3	-40	-40	697.9	101.3	555.3	80.6	64.5	30.7
W4	-29	-20	684.9	99.4	550.5	79.9	64.0	28.9
W5	-18	0	673.2	97.7	541.6	78.6	64.8	31.4

Table 2. Knoop and Corresponding Rockwell B (HRB) Hardness Results for Base Metal, Heat Affected Zones, and Weld Metal

Specimen Code	Base[1] Metal	(HRB)	Heat Affected Zone	(HRB)	Weld Metal	(HRB)
1/2 A	159.7	83	168.3	86	203	90.5
1/2 B	156.3	82	173.3	87	206.3	94.0
1/2 C	160.0	83	169.0	86	192.0	91.5
1/2 D	163.3	84	167.6	85.5	195.6	92.0
1/2 E	159.3	83	176.6	88.0	202.6	93.0

1 Average of three values

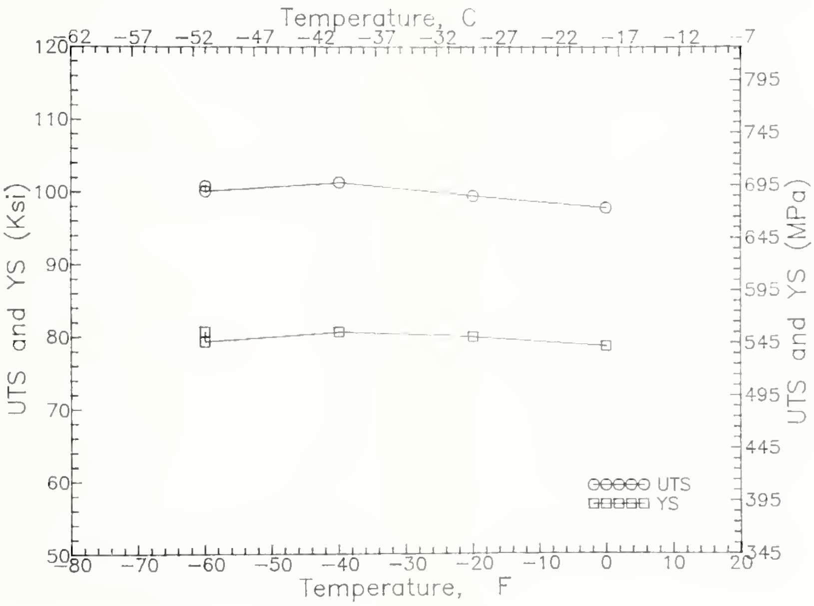
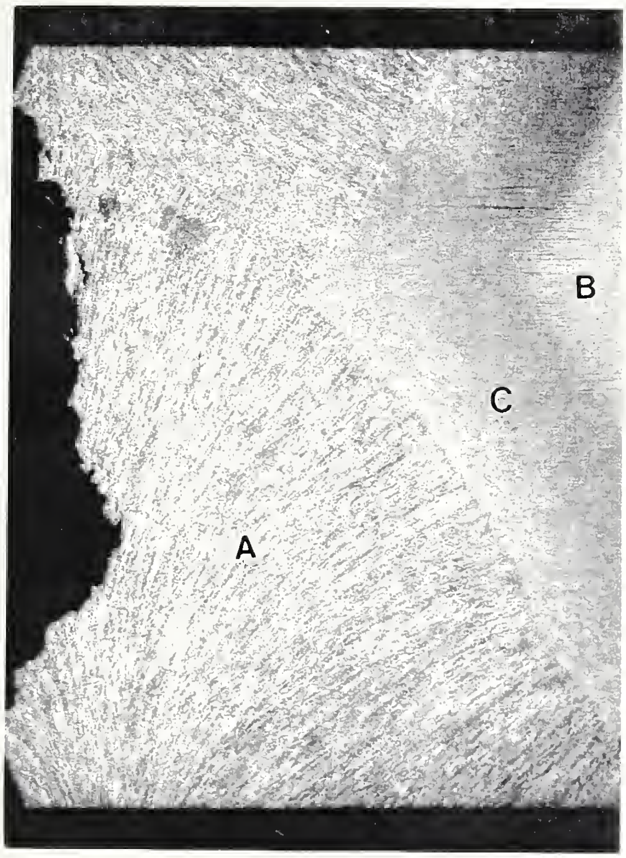


Figure 1. Tensile test results for all weld specimens.



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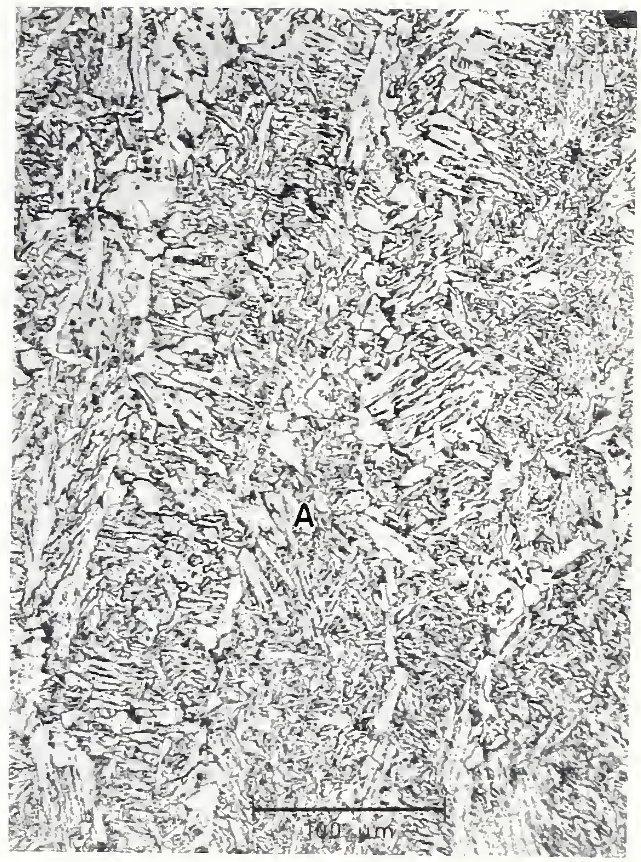
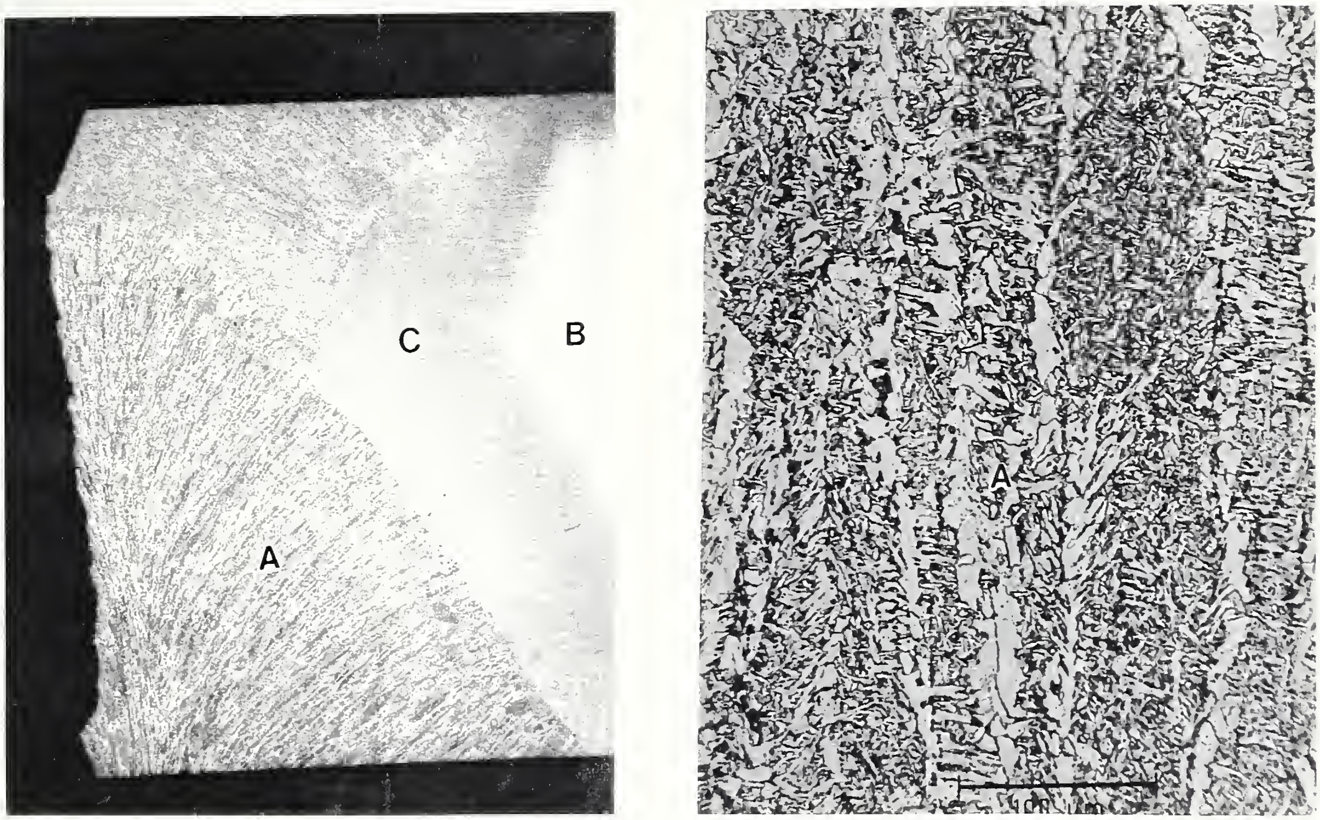


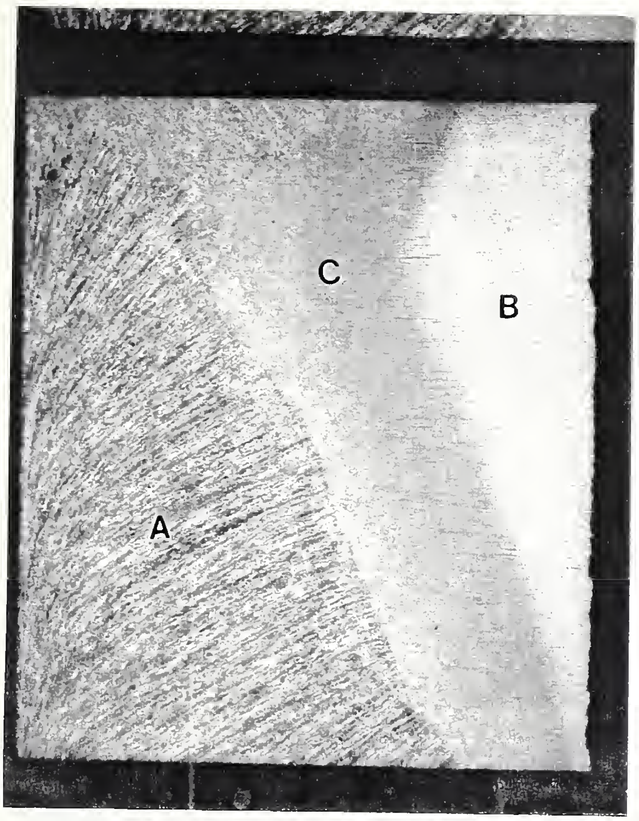
(b)

Figure 2. Photomicrographs showing the microstructure of the weld metal in specimen 1/2 A. The microstructure consists of ferrite and pearlite. The weld metal is A, base metal, B; and the HAZ C.
Mag: a) X6.5, b) X250 Etchant: Molybdate



(a) (b)

Figure 3. Photomicrographs showing the microstructure of the weld metal in specimen 1/2 B. The microstructure consists of ferrite and pearlite. The weld metal is A, base metal, B; and the HAZ C.
Mag: a) X6.5, b) X250 Etchant: Molybdate



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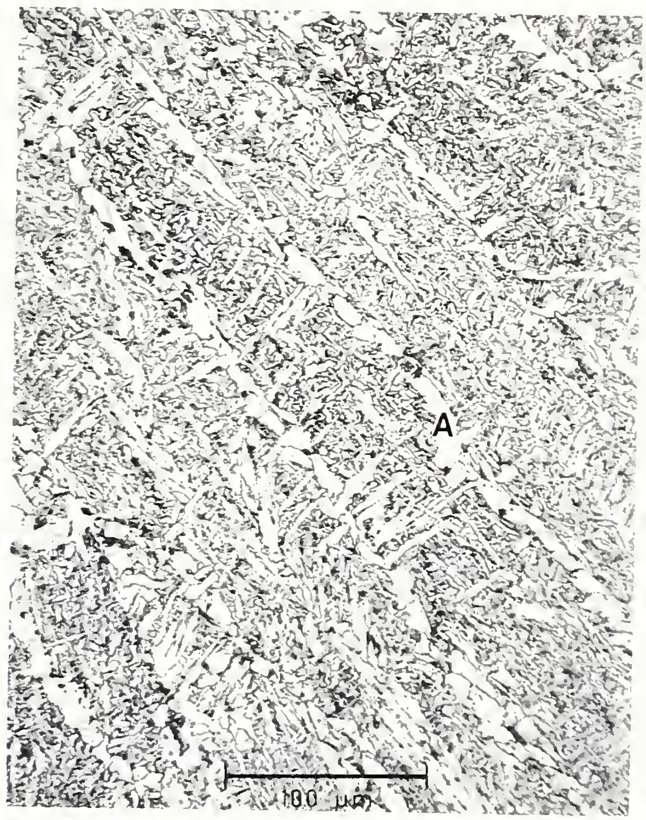
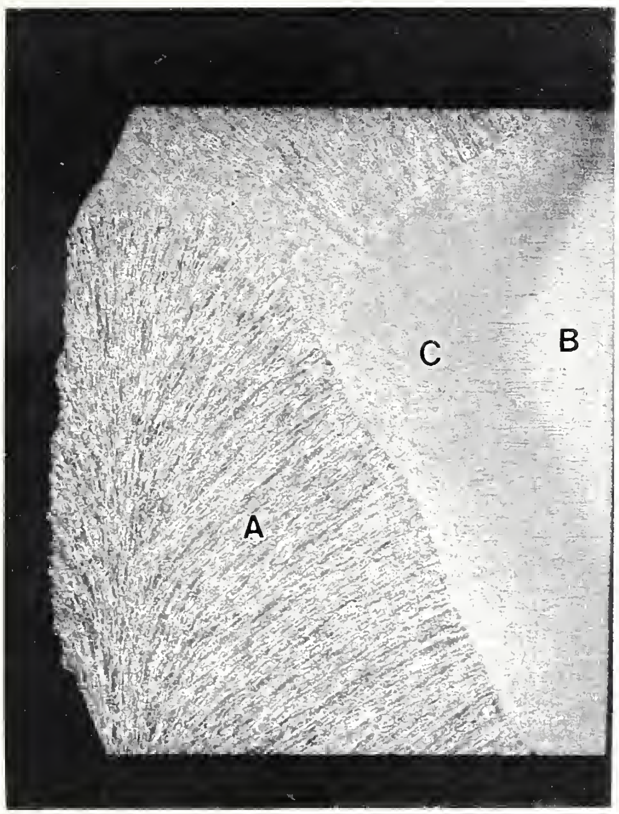


(b)

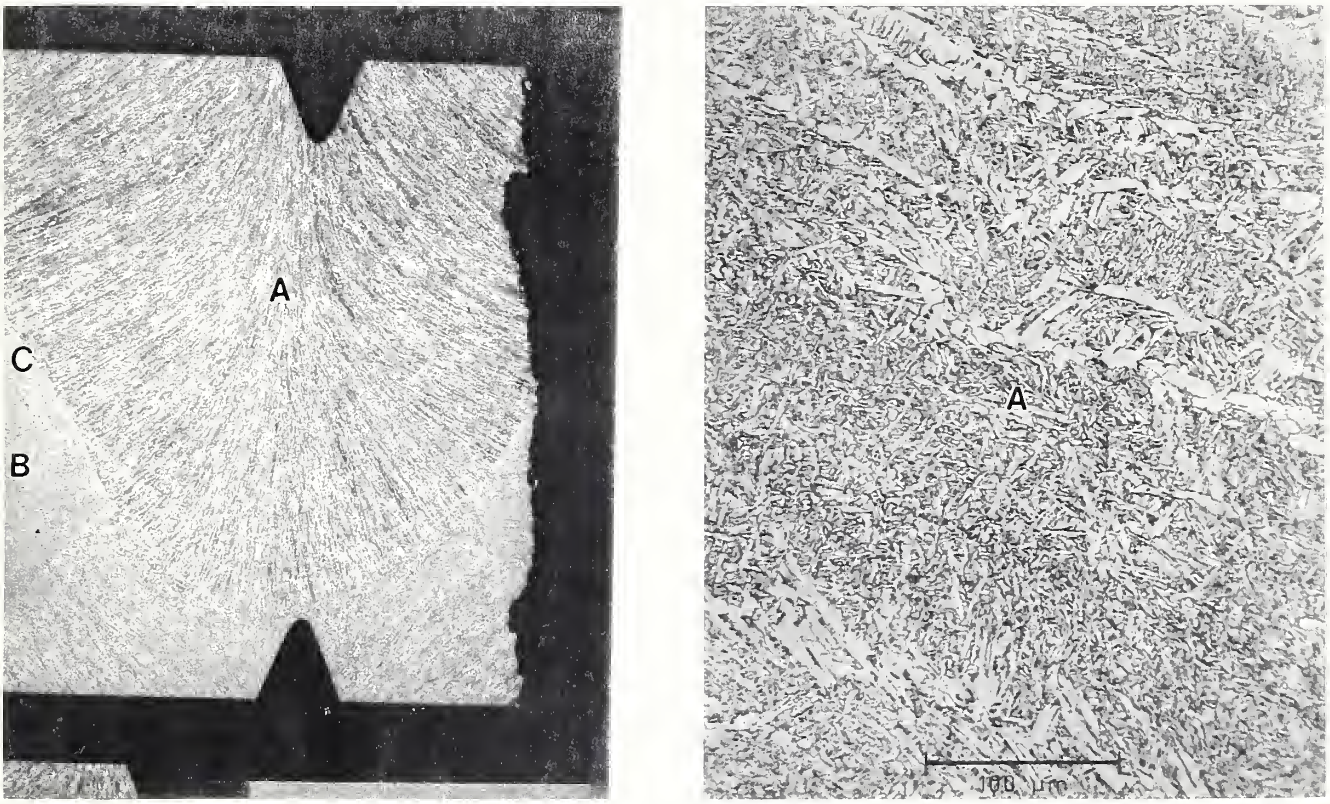
Figure 4. Photomicrographs showing the microstructure of the weld metal in specimen 1/2 C. The microstructure consists of ferrite and pearlite. The weld metal is A, base metal, B; and the HAZ C.
Mag: a) X6.5, b) X250 Etchant: Molybdate



(a)

(b)

Figure 5. Photomicrographs showing the microstructure of the weld metal in specimen 1/2 D. The microstructure consists of ferrite and pearlite. The weld metal is A, base metal, B; and the HAZ C.
Mag: a) X6.5, b) X250 Etchant: Molybdate



(a) (b)

Figure 6. Photomicrographs showing the microstructure of the weld metal in specimen 1/2 E. The microstructure consists of ferrite and pearlite. The weld metal is A, base metal, B; and the HAZ C.
Mag: a) X6.5, b) X250 Etchant: Molybdate

APPENDIX I

WELDING PROCEDURE SPECIFICATION

ORIGINAL DATE: 5/21/90
REVISION DATE: 6/22/90

WPS#: 1.T.2.8 Revision 1

Qualified by PQR#: 1.T.2.8, 1.T.2.8A

Material Specification: AAR TC128 GRB TO SAME or P1 TO P1

Welding Process: SUBMERGED ARC WELDING (TANDEM)

Manual or Machine: MACHINE

Position of Welding: FLAT (1G)

Filler Metal Specification: SFA 5.17

Filler Metal Classification: LINCOLN LS3 (S3M)

F No.: 6 A No.: 1

Flux: LINCOLN 882

*Weld Metal Grade: F8P3EG

Type of Backing: FLUX (LINCOLN 780)

Shielding Gas: N/A Flow Rate (CFH): N/A

Single or Multiple Pass: MULTIPLE

Single or Multiple Arc: MULTIPLE

Welding Current: LEAD ELECTRODE (DC) TRAIL ELECTRODE (AC)

Polarity: LEAD ELECTRODE (REVERSE) TRAIL ELECTRODE (N/A)

Electrical Stickout: 1-1/8" +/- 1/8"

Welding Progression: N/A

Root Treatment: REMOVE SLAG WITH SCALING HAMMER

Preheat: 50°F Interpass Temperature: 300°F

Postweld Heat Treatment: 1200°F / 1 HOUR

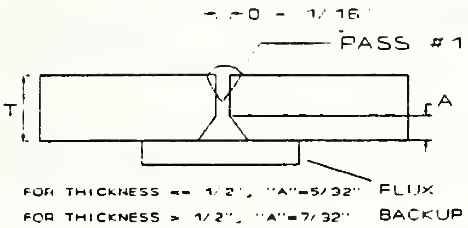
Impact Requirements: 15 ft/lbs. @ -30°F

* Applicable only when filler metal has no AWS specification.

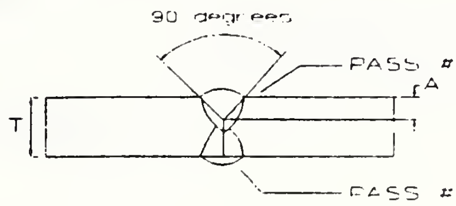
APPENDIX II

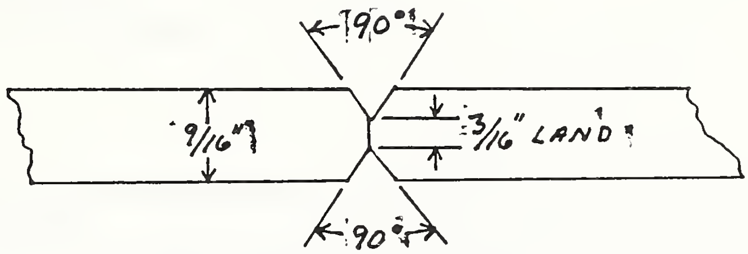
UNION TANK CAR COMPANY
WPS# 1.T.2.8
MAY 21, 1990
PAGE 2

DETAIL 1A



DETAIL 1B





LINCOLN LS-3 ELECTRODE / 882 FLUX

DETAIL	THICK-NESS	PASS NO.	POS.	DIA.	AMPS	VOLTS	TRAVEL SPEED	REMARKS
1A	7/16"	1	1G	5/32"	600-650	30	34-36	DC
1A	7/16"	1	1G	5/32"	600	37	34-36	AC
1B	7/16"	2	1G	5/32"	850	32-33	34-36	DC
1B	7/16"	2	1G	5/32"	600	37	34-36	AC
1A	5/8"	1	1G	5/32"	625-675	31	32	DC
1A	5/8"	1	1G	5/32"	600	37	32	AC
1B	5/8"	2	1G	5/32"	900	34	32	DC
1B	5/8"	2	1G	5/32"	600	37	32	AC
1A	9/16"	1	1G	5/32"	625-675	31	34-36	DC
1A	9/16"	1	1G	5/32"	600	37	34-36	AC
1B	9/16"	2	1G	5/32"	900	34	36	DC
1B	9/16"	2	1G	5/32"	600	37	36	AC

NOTE- Two (2) passes are required on inside shell to head seams on thicknesses greater than 1/2".

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George E. Hicho
Donald E. Harne

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N/A

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Weld and heat affected zone (HAZ) crack arrest fracture toughness were determined for welded plates of normalized AAR TC128 grade B steel, currently used in appropriate tank cars that carry hazardous materials. The plates were joined under laboratory conditions and stress relieved using the recommended Association of American Railroads (AAR) welding procedures. In the calculation of the crack arrest fracture toughness, the yield strength at the test temperature is required in the appropriate equations. Hence weld metal tensile specimens were prepared from the joined plates and tested at temperatures ranging from -51°C to -18°C. Weld and HAZ crack arrest fracture toughness specimens were prepared and tested at -51°C. Because of enhanced weld toughness, it was impossible to initiate a crack in any of the weld specimens tested, hence a crack arrest fracture toughness was not obtained. Crack arrest fracture toughness tests were conducted on similar specimens where the crack plane was within the HAZ. Crack arrest fracture toughness values were obtained for specimens tested at -51°C and at -18°C. Specimens tested at -29°C were not valid since the final crack length could not be determined. Crack arrest fracture toughness results indicated that both the weld metal and the HAZ for the welded normalized and stress relieved AAR TC128 grade B steel were highly resistant to crack initiation and possessed the ability to arrest a propagating crack.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

Crack arrest; Base metal; Fracture toughness; heat affected zone; steel; tank car; welds

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