SERIAL NO. SSC-41

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PROGRESS REPORT

ON

EVALUATION OF IMPROVED MATERIALS AND METHODS OF FABRICATION FOR WELDED STEEL SHIPS

BY

F. R. BAYSINGER, R. G. KLINE, P. J. RIEPPEL
and C. B. VOLDRICH

BATTELLE MEMORIAL INSTITUTE
Under Bureau of Ships Contract NObs-48015

Transmitted through
NATIONAL RESEARCH COUNCIL'S

COMMITTEE ON SHIP STEEL
Advisory to

SHIP STRUCTURE COMMITTEE
under

Bureau of Ships, Navy Department
Contract NObs-50148

Division of Engineering and Industrial Research
National Research Council
Washington, D. C.
October 1, 1951

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2101 CONSTITUTION AVENUE, WASHINGTON 25, D. C.

COMMITTEE ON SHIP STEEL
OF THE
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

October 1, 1951

Chief, Bureau of Ships
Code 343
Navy Department
Washington 25, D. C.

Dear Sir:

Attached is Report Serial No. SSC-41 entitled "Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships." This report has been submitted by the contractor as a Progress Report of the work done on Research Project SR-100 under Contract Nobs-48015 (1773) between the Bureau of Ships, Navy Department and Battelle Memorial Institute.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Steel, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

R. F. Mehl, Chairman
Committee on Ship Steel

Advisory to the SHIP STRUCTURE COMMITTEE, *a committee representing the combined research activities of the member agencies - Bureau of Ships, Dept. of Navy; Military Sea Transportation Service, Dept. of Navy; United States Coast Guard, Treasury Dept.; Maritime Administration, Dept. of Commerce, American Bureau of Shipping.*

PREFACE

The Navy Department through the Bureau of Ships is distributing this report for the SHIP STRUCTURE COMMITTEE to those agencies and individuals who were actively associated with the research work. This report represents results of part of the research program conducted under the Ship Structure Committee's directive to "improve the hull structures of ships by an extension of knowledge pertaining to design, materials and methods of fabrication".

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REPORT

on

EVALUATION OF IMPROVED MATERIALS AND METHODS OF FABRICATION FOR WELDED STEEL SHIPS

to

BUREAU OF SHIPS,
NAVY DEPARTMENT

Describing Work Completing
Contract NObs-48015 (1773)
Index No. NS-011-067

by

F. R. Baysinger, R. G. Kline, P. J. Rieppel, and C. B. Voldrich

BATTELLE MEMORIAL INSTITUTE

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REPORT

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EVALUATION OF IMPROVED MATERIALS AND METHODS OF FABRICATION FOR WELDED STEEL SHIPS

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Describing Work Completing
Contract NObs-48015 (1773)
Index No. NS-011-067

ABSTRACT

This report covers work done from March 1, 1949, to October 15, 1950.

An investigation of the underbead cracking tendency of forty-one heats of ABS Classes "B" and "C" hull steels was conducted, using the Battelle underbead cracking test.

One of the steels studied was a peening-project steel received from the American Bureau of Shipping. It was not crack sensitive.

Eight ABS Class "B" steels received from David Taylor Model Basin were not crack sensitive.

Ten Class "B" steels and eight out of ten Class "C" steels received directly from steel company A were not crack sensitive. One Class "C" steel

gave 36 per cent underbead cracking, and another gave 16 per cent underbead cracking by the standard Battelle underbead cracking test.

Six Class "B" and five of six Class "C" steels purchased from steel company B were not crack sensitive. One Grade "C" steel from this supplier cracked 15 per cent in the underbead cracking test.

To study whether these crack-sensitive steels would give trouble in service, large tee-joints were prepared to simulate ship-welding conditions. Nine heats of Classes "B" and "C" steels in a total of thirty-five tee joints were tested, using various test conditions.

All of the tee-joints cracked except one joint made in 7/8-inch-thick Class "B" steel. The amount of tee-joint cracking appears to increase with underbead crack sensitivity. The tee-joint cracking was reduced by a 400 F preheat and by a homogenization treatment of the steel before welding. When a balanced welding sequence was used in welding tee-joints no cracking resulted.

Low-hydrogen lime-ferritic electrodes were used to weld tee-joints. When these electrodes were used, cracking in the tee-joints was increased, instead of reduced as was expected on the basis of experience with low-hydrogen electrodes and underbead cracking.

In an attempt to explain the tee-joint cracking, other studies were conducted. These included a study of the tensile properties normal to the plate surface in the "Z" direction, notched bar tests, and a study of banding. There was no correlation found between data obtained by these tests and the cracking of tee joint specimens.

Further study of tee-joint cracking is needed to provide information from which field control procedures can be written, and to furnish the fundamental information which is necessary to understand why this type of cracking occurs.

INTRODUCTION

This is the fifth progress report on the investigation entitled, "Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships", being conducted for the Ship Structure Committee (Project SR-100), under the Navy Department, Bureau of Ships, Contract NObs-48015 (1773), Index No. NS-011-067.

The first objective of this phase of the investigation was to determine the underbead cracking tendencies of forty-one heats of ABS Class "B" and "C" hull steels using the Battelle underbead cracking test. The second objective was to determine whether the more crack-sensitive heats would give trouble in service, as measured by large tee-joint specimens which simulated ship welding conditions.

This report describes the details of the crack-sensitivity studies, the tee-joint tests, and the supplemental studies which were conducted.

MATERIALS

Steels

One heat of ABS peening-project steel in plate thicknesses of 1/2 inch and 1 inch was received from the American Bureau of Shipping.

Eight heats of ABS Class "B" hull steels in plate thicknesses of 3/4 inch were received from the David Taylor Model Basin.

Twenty heats of Classes "B" and "C" hull steels were purchased directly from steel company A. Plate thicknesses were 1 inch for Class "B" steels and 1-1/8 inches to 1-1/4 inches for Class "C" steels.

Twelve heats of Classes "B" and "C" hull steels were purchased directly from another steel company B. Plate thicknesses varied from 13/16 inch to 1 inch for Class "B" steels and from 1-1/8 to 1-5/16 inches for Class "C" steels.

All steels from Companies A and B passed Navy inspection prior to being sent to Battelle. These were production steels and were picked at random. Some were selected because the carbon and manganese were considered to be on the high side of the ABS specifications and might give trouble in service. A control steel designated as Z-13, Heat Number 55P321, was used as a control throughout this investigation. This steel has been used in other investigations, and was known to be crack sensitive. In previous work, it cracked 11 to 24 per cent in the Battelle underbead-cracking test.

The heat numbers, mechanical properties, and chemical compositions of these steels are listed in Table 1.

TABLE 1. STRENGTH, CHEMICAL COMPOSITION, AND UNDERBEAD CRACKING DATA ON ABS CLASS B AND C HULL STEELS

ABS Class	Plate Thickness, In.	Heat Number	Source of Supply	Yield Strength, 1000 psi	Ultimate Tensile Strength, 1000 psi	Elongation, %	Chemical Composition, %(1)					Carbon Equivalent, $C + \frac{Mn}{4} + \frac{Si}{4}$	Average Underbead Cracking, %(2)
							C	Mn	Si	P	S		
B	1/2	512740	ABS Peening	38	64	31	0.19	0.73	0.040	0.012	0.032	0.39	1
B	1	512740	Project	38	63	29	0.19	0.73	0.040	0.012	0.032	0.39	1
Control	7/8		BMI Z-13	—	—	—	0.18	1.18	0.28	0.017	0.033	0.55	6
B	3/4	41T514-15	Model Basin	42-44	65-67	25-29	0.22	0.58	0.09	0.013	0.035	0.39	0
B	3/4	52V011F-15	Ditto	35-37	59-61	26-29	0.17	0.60	0.06	0.014	0.024	0.34	0
B	3/4	52V011C-6	"	35-37	59-61	24-30	0.18	0.61	0.06	0.011	0.027	0.36	1
B	3/4	56T549-15	"	35-39	58-62	28-31	0.19	0.46	0.07	0.015	0.038	0.32	1
B	3/4	50T533-15	"	37-42	64-66	27-30	0.26	0.50	0.06	0.014	0.035	0.40	1
B	3/4	60V025C-9	"	37-39	61-62	27-29	0.19	0.66	0.05	0.014	0.041	0.38	1
B	3/4	46T554C-15	"	42-44	67-68	25-28	0.21	0.93	0.07	0.012	0.046	0.46	2
B	3/4	46T554F-15	"	39-42	64-65	27-29	0.20	0.95	0.07	0.015	0.046	0.46	4
Control	7/8		BMI Z-13	—	—	—	0.18	1.18	0.28	0.017	0.033	0.55	8
B	1	67P239-1	Company	38	63	30	0.21	0.78	0.022	0.016	0.040	0.41	1
B	1	70P216-1		36	63	34	0.20	0.76	0.019	0.018	0.032	0.40	1
B	1	72P236-1	Ditto	37	65	31	0.23	0.76	0.021	0.034	0.046	0.43	1
B	1	71P235-1	"	39	66	30	0.24	0.77	0.038	0.012	0.035	0.44	3
B	1	69P259-1	"	37	66	30	0.21	0.78	0.033	0.026	0.038	0.41	4
B	1	73P229-1	"	37	66	29	0.22	0.77	0.036	0.024	0.037	0.42	4
B	1	66P245-1	"	37	66	27	0.21	0.90	0.031	0.016	0.040	0.44	5
B	1	73P221-1	"	36	64	32	0.21	0.83	0.022	0.017	0.035	0.42	5
B	1	66P243-1	"	39	66	31	0.22	0.84	0.027	0.016	0.033	0.44	6
B	1	24P266-1	"	37	67	28	0.22	0.74	0.028	0.018	0.035	0.41	7
C	1-1/8	71P200-1	"	39	65	32	0.17	0.80	0.21	0.028	0.031	0.42	0;0
C	1-1/8	71P207-1	"	40	68	29	0.18	0.90	0.22	0.036	0.034	0.46	1
C	1-1/8	69P232-1	"	37	62	27	0.18	0.84	0.24	0.036	0.031	0.45	2
C	1-1/8	66P046-1	"	42	68	29	0.20	0.90	0.20	0.030	0.039	0.48	2
C	1-1/8	21P176-1	"	43	71	30	0.20	0.87	0.23	0.034	0.030	0.47	3
C	1-1/4	66P192-1	"	41	67	33	0.19	0.85	0.21	0.034	0.031	0.46	1;2
C	1-1/4	72P194-1	"	43	68	28	0.17	0.76	0.19	0.022	0.029	0.41	2
C	1-1/4	19P180-1	"	40	70	26	0.18	0.78	0.21	0.030	0.036	0.43	2
C	1-1/4	21P169-1	"	42	73	27	0.18	0.96	0.24	0.020	0.030	0.48	16;20
C	1-1/4	66P193-1	"	38	72	30	0.20	0.96	0.24	0.030	0.034	0.50	36;39;46(3)
Control	7/8		BMI Z-13	—	—	—	0.18	1.18	0.28	0.017	0.033	0.55	1;5(4) 3;7

TABLE 1. (Continued)

ABS Class	Plate Thickness, In.	Heat Number	Source of Supply	Yield Strength, 1000 psi	Ultimate Tensile Strength, 1000 psi	Elongation, %	Chemical Composition, %(1) C	Mn	Si	P	S	Carbon Equivalent, $C + \frac{Mn}{4} + \frac{Si}{4}$	Average Underbead Cracking, %(2)
B	13/16	69Y609	**Company B**	38	62	27	0.16	0.68	0.05	0.010	0.026	0.34	1
B	7/8	61Y572	Ditto	35	61	28	0.17	0.71	0.05	0.016	0.027	0.36	0
B	7/8	66Y583	"	33	61	30	0.18	0.84	0.05	0.011	0.025	0.40	0
B	7/8	81Y586	"	36	61	31	0.16	0.75	0.05	0.012	0.026	0.36	0
B	15/16	58Y598	"	38	65	26	0.18	0.75	0.05	0.012	0.021	0.38	1
B	1	83Y578	"	34	63	28	0.17	0.70	0.05	0.011	0.030	0.36	1
C	1-1/8	73Y596	"	39	64	26	0.14	0.79	0.25	0.010	0.026	0.40	0;0
C	1-1/8	75Y592	"	39	70	26	0.20	0.88	0.21	0.013	0.020	0.47	11;19
C	1-1/8	71Y354	"	40	70	25	0.15	0.69	0.21	0.012	0.028	0.38	15;24
C	1-1/4	74Y590	"	35	62	29	0.14	0.67	0.18	0.010	0.028	0.35	0
C	1-1/4	71Y593	"	38	68	26	0.18	0.75	0.19	0.010	0.024	0.42	0
C	1-5/16	73Y486	"	39	65	27	0.15	0.75	0.25	0.013	0.026	0.40	0
Control	7/8		BMI Z-13	—	—	—	0.18	1.18	0.28	0.017	0.033	0.55	14;6

(1) Mill check analysis with the exception of the peening-project steel. This analysis is from ladle.

(2) Duplicate values appearing in the column represent the average underbead cracking obtained in check tests.

(3) In initial tests, the average underbead cracking was 36 per cent. In check tests, one series of specimens had 1/16 inch machined from the plate surface before welding. The average underbead cracking for this series was 39 per cent. In a second series of check tests on this steel, five specimens were welded on one side of the plate surface and five were welded on the opposite surface. The average underbead cracking was 46 per cent.

(4) A series of specimens using low-hydrogen electrodes cracked 1 per cent. Another series, homogenized 5 hours at 2350 F and followed by normalizing at 1600 F, cracked 5 per cent.

Electrodes

Electrodes used in this investigation included 1/8- and 3/16-inch-diameter Class E6010 electrodes, and three brands of E7015 low-hydrogen electrodes. One of these brands conformed to Department of Defense Specification MIL-E-986 (Ships) for low-hydrogen electrodes.

TESTS WITH BATTELLE UNDERBEAD CRACKING SPECIMEN

A series of Battelle underbead cracking specimens was made for each of the forty-one heats of steel, and the control steel.

Specimen Preparation

Strips long enough to make ten specimens were flame cut from the plates. The 2- by 3-inch test specimens were saw cut from the strips with the direction of rolling parallel to the 3-inch dimension. Specimen surfaces were grit blasted prior to welding to remove mill scale, rust, or other contaminators.

Welding

Weld beads were deposited by automatic welding along the longitudinal centerline, as shown in Figure 1. The following welding schedule was used:

AWS electrode classification	E6010
Electrode diameter, inch	1/8
Amperes	96-100
Volts	24-26
Speed, inch/minute	10
Effective length of bead, inch	1-1/4
Weld time, seconds	9

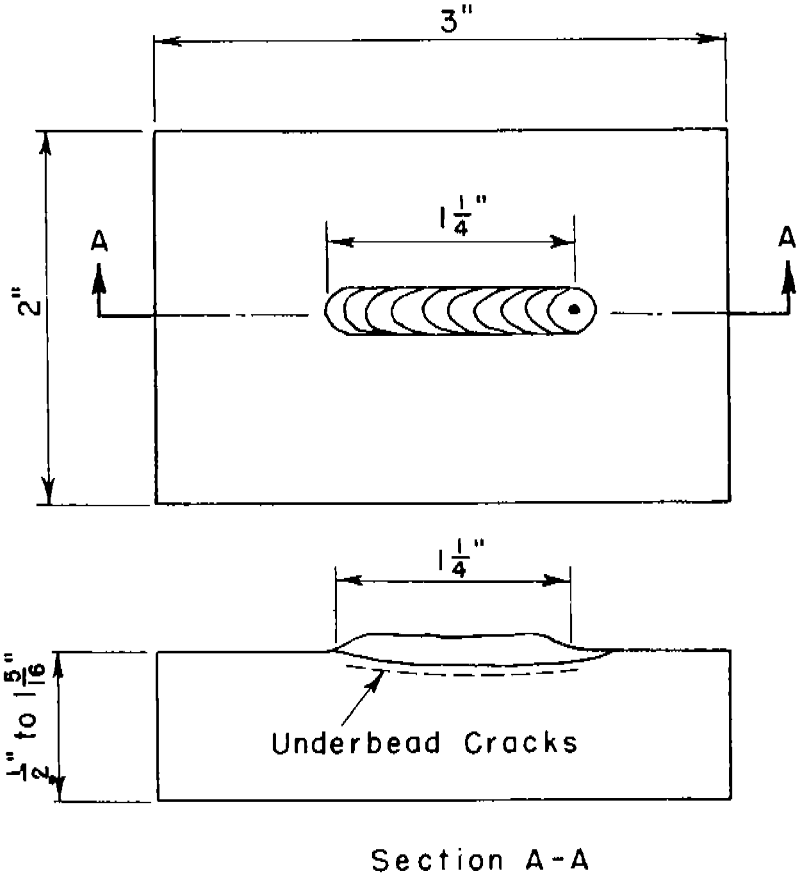


FIGURE 1. DETAILS OF BATTELLE UNDERBEAD-CRACKING TEST SPECIMEN

0-15047

During welding, all specimens were immersed to within 1/8 inch of the top surface in water at an initial temperature of 70 F. No more than a 4 F rise in water temperature was permitted.

Aging and Stress Relieving

Following welding, all specimens were aged at room temperature (75 F to 85 F) for twenty-four hours to permit cracks to develop. At the end of the 24-hour aging period, specimens were stress relieved to stop further underbead cracking so that the time element in cracking was held constant. Specimens 1 inch or less thick were stress relieved 1 hour at 1150 F; those over 1 inch thick were stress relieved for 1-1/2 hours at 1150 F. All specimens were furnace cooled overnight.

Cutting and Magnafluxing

Before sectioning, all specimens were scribed along the centerline of the weld. The saw cut was offset from the center so grinding would bring the surface to be examined to the scribed centerline of the weld bead. Grinding was carried through 600 grit. Specimens were etched with 5 per cent Nital to show the structure and fusion line. After etching, specimens were Magnafluxed, and washed in carbon tetrachloride to remove all excess oil.

Measuring Underbead Cracking

Strips of cellulose tape were pressed on the specimens to adhere to the Magnaflux crack indications. These tapes were then transferred to white record cards. The projected lengths of crack indications on each tape transfer were measured, using a low-power microscope. Only cracks from the start of the bead to the center of the crater were considered. The total length of crack indications was recorded for each of the ten specimens composing a test series. The per cent of underbead cracking for each heat was computed by dividing the total length of cracks by the total length of weld according to the following formula:

$$\text{Per cent cracking} = \frac{(1.00)\ (\text{Total crack length})}{(1.25)\ (\text{Number of specimens})}$$

Test Results

In Table 1, grouped according to source of supply, are listed the average per cent underbead cracking values for the forty-one heats of steel tested. Also included are the cracking values for the Z-13 control steel, which was tested with each group of hull steels.

Peening-Project Steels

The ABS peening-project steel showed very low cracking tendencies with 1 per cent cracking for tests made on both 1/2- and 1-inch plates.

David Taylor Model Basin Steels

The Class "B" David Taylor Model Basin steels showed very low underbead cracking. The per cent of cracking varied from 0 to 4 per cent for the eight heats tested.

Steel Company A

All Class "B" steels from company A had a low crack sensitivity, varying from 1 to 7 per cent. The Class "C" steels gave underbead cracking values of 0 to 3 per cent, except for two, Heat Number 21P169-1 and Heat Number 66P193-1, which gave 16 and 36 per cent cracking, respectively. These two steels had just slightly higher manganese contents, carbon equivalents, and tensile strengths than similar steels which were not crack sensitive. This agrees with results of previous investigations (1, 3) which indicate that chemical composition is not the only factor to be considered in judging a steel for susceptibility to underbead cracking.

Check tests were made on Steels 66P193-1 and 21P169-1, with high cracking, and Steels 71P200-1 and 66P192-1, with low cracking, to see if the original cracking values would be duplicated. The results from the crack-sensitivity check tests are given in Table 1.

Two series of check tests were made on Steel 66P193-1, which gave 36 per cent cracking in previous tests. It was believed that the weld beads on the original test specimens might have penetrated into a highly banded area of the steel, in which case a weld bead deposited in a different area might change the underbead cracking. For this reason, in the first series of tests, 1/16 inch was machined from the plate surface before welding the ten specimens, but the average underbead cracking for this series was nearly the same as previously obtained, 39 per cent.

In the second series of tests of this steel, the ten standard specimens were prepared, but five were welded on one side of the plate, and five were welded on the opposite surface. This was done as a further check on the possibility that in the original tests the weld had penetrated into a banded area from one side of the plate. There was; however, little difference in underbead cracking between the two groups of five specimens, and the average cracking for this series was 46 per cent.

In the check tests on Heats 21P169-1 (16 per cent cracking), 71P200-1 (0 per cent cracking), and 66P192-1 (1 per cent cracking), ten standard specimens were prepared and welded under standard conditions. The results from the check tests on Heats 21P169-1, 71P200-1, and 66P192-1 were 20, 0, and 2 per cent, respectively. These results agree with the original values well within the limits of expected variation.

Previous investigations (3) have linked manganese segregation with underbead cracking. As it was believed that the cracking in these steels might also be a result of manganese segregation, two additional underbead cracking tests were made on Heat 66P193-1, the 36 per cent cracking steel.

For the first test, one standard group of underbead cracking specimens was prepared, but welded with low-hydrogen Class E7015 electrodes instead of E6010 electrodes. This was done to reduce the hydrogen which would be absorbed by the weld metal. The average underbead cracking for this group was 1 per cent, as compared to the 36 per cent obtained with the E6010 electrodes.

The second test was made using standard welding procedures on homogenized specimens. The underbead cracking specimens were homogenized by heating for 5 hours at 2350 F in a controlled-atmosphere furnace, followed by air cooling. The specimens were normalized by reheating to 1600 F for 1 hour and air cooling. Homogeneity was checked by annealing a piece removed from homogenized specimen at 1650 F, polishing, etching, and examining the structure. A slot 1/16 inch deep and 1/2 inch wide was machined in the surface of each specimen to remove any surface decarburization where welded. Underbead cracking was reduced from 36 per cent to 5 per cent by the homogenizing treatment. The data for these two tests are shown in Table 1.

<u>Steel Company B</u>

Six Class "B" and four of the six Class "C" steels from company B cracked 1 per cent or less. Two Class "C" steels, Heats 75Y592 and 71Y354, cracked 11 and 15 per cent, respectively. Heat 75Y592 had slightly higher carbon and manganese than the other steels. However, the 15 per cent cracking for Heat 71Y354 was unexplainable on the basis of the 0.15 per cent carbon and 0.69 per cent manganese, as reported by the mill-check analysis.

To check these results, underbead cracking tests were repeated on

Heats 75Y592, 71Y354, and also on Heat 73Y596 which gave no cracking in the original test. Heats 75Y592 and 71Y354 cracked 11 and 15 per cent, respectively, on the original tests, and 19 and 24 per cent in the check tests. The results were in reasonable agreement for the two series.

In an effort to explain the cracking tendencies of Heat 71Y354, a check chemical analysis was made on the carbon and manganese content of this steel. The Battelle analysis gave 0.24 per cent carbon compared to 0.15 per cent, and 0.79 per cent manganese compared to 0.69 per cent reported by the mill-check analysis. The Battelle analysis compares well with the carbon and manganese content of Heat 75Y592, which cracked 11 per cent. It is believed the higher check analysis is a partial explanation for the cracking tendencies of this steel. Other factors must also be considered.

Discussion of Results

Of the forty-two heats of steels tested for underbead crack sensitivity, four heats of Class "C" steel had underbead cracking values over 10 per cent. The chemistry and carbon equivalents for these heats were slightly higher than for many of the noncrack-sensitive heats of steel, but the difference does not explain the wide variations in cracking. Manganese segregations, which have been rolled out into bands parallel with the direction of rolling, are believed to be a factor in cracking. As these segregated areas of high-manganese alloy have slower transformation characteristics than other areas, as the temperature drops ferrite forms first in the remaining areas leaving carbon free to migrate to the yet untransformed austenitic manganese areas, with the resultant formation of pearlite bands in the manganese-rich areas.

These same areas, cooling from the heat of welding, transform last or remain in part as retained austenite, which can dissolve considerable hydrogen. When this retained austenite transforms at room temperature, the hydrogen, which has lesser solubility in the transformation products, is rejected and produces insoluble molecular hydrogen. This hydrogen can build up severe aerostatic pressures, which in addition to other stresses can cause cold cracking under the weld beads.

As demonstrated on Heat 66P193-1, lowering the hydrogen available to the weld by use of low-hydrogen electrodes practically eliminated the underbead cracking. Homogenization, which diffuses the segregated areas, also greatly reduced the cracking. However, to homogenize crack-sensitive heats of steel is impractical from a production standpoint.

At this point, it was not known whether a steel such as Heat 66P193-1 with 36 per cent underbead cracking would give trouble in service. It was decided to test some of the steels under simulated ship welding conditions in the form of tee-joint specimens.

TESTS WITH TEE-JOINT SPECIMEN

Originally, three steels were picked for tee-joint tests. These included company A Heats 66P193-1, 21P169-1, and 71P200-1 with 36, 16, and 0 per cent underbead cracking. Later, six other heats of steel were tested in tee-joints, for a total of nine steels. The additional steels were used to determine if tee-joint cracking could be produced in any Class "B" or "C" hull steel regardless of underbead crack sensitivity.

A series of tests using various brands of low-hydrogen electrodes were made on Heat 66P193-1. It was believed that excessive moisture in the coating might be causing cracking which occurred with the low-hydrogen electrodes(2). Tests were made with electrodes dried at 600 F, and electrodes which conformed to Department of Defense Specification MIL-E-986 (Ships), specifying 0.4 per cent maximum coating moisture content.

Other tests were made to determine the effect of preheat, homogenization, and balanced welding sequence on tee-joint cracking.

Specimen Preparation

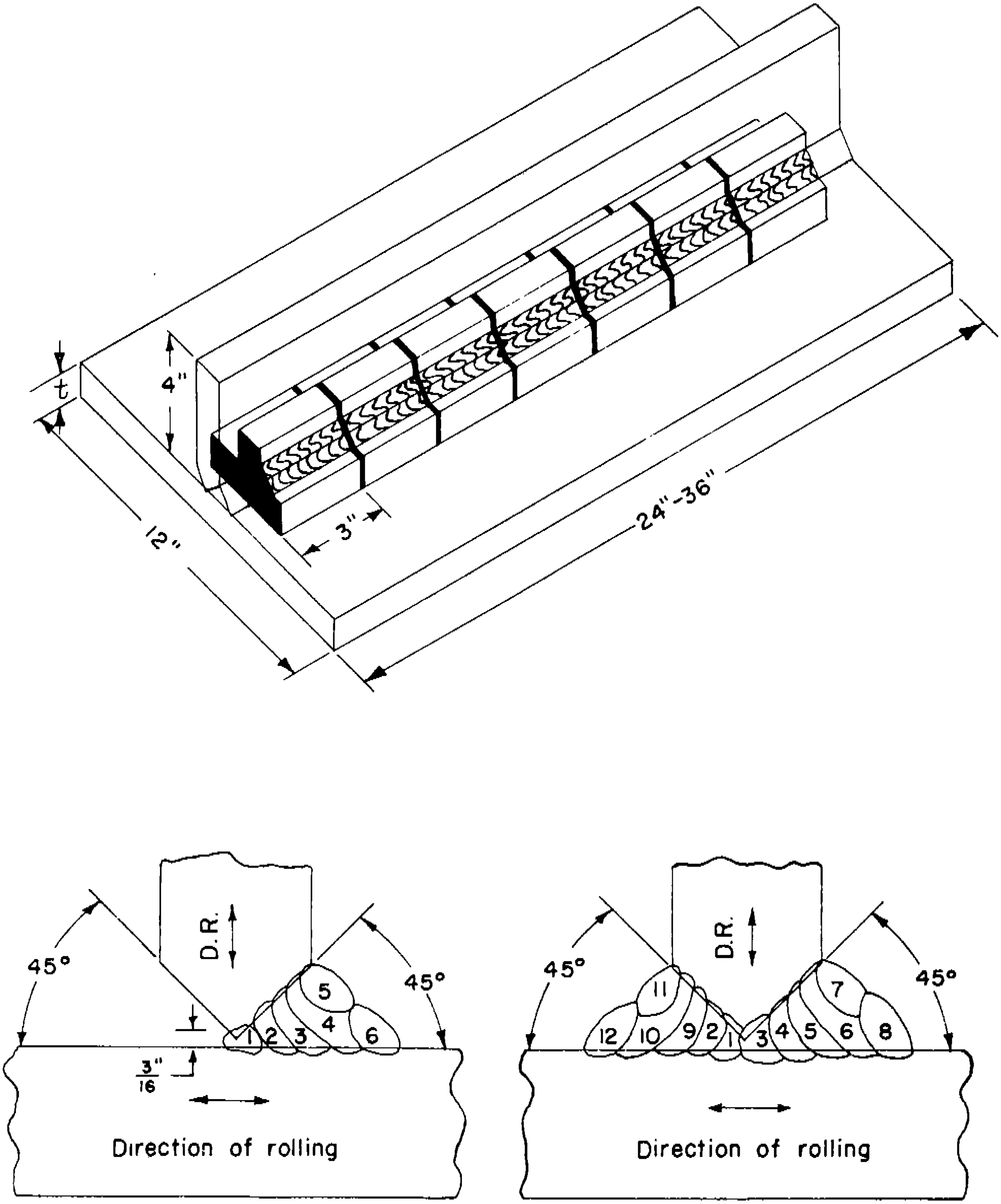
The original tee-joint specimens consisted of a base plate 12 inches wide and 36 inches long, to which was welded a 36- by 4-inch bar for the leg of the tee. In subsequent tests, the specimen length was reduced to 24 inches to conserve material. Figure 2 shows the joint design. The direction of rolling of the base plate was parallel to the 12-inch dimension and the direction of rolling of the tee-leg was parallel to the 4-inch dimension. Root openings of 0, 1/16, and 3/16 inch were tried, and the 3/16 inch root gap was found necessary to obtain full penetration in the root weld pass. Scale on base plate and tee-leg was removed by grinding before welding.

Standard Welding Procedure

Prior to welding, the base plate and leg of the tee were tacked at the ends and center. The joint was welded manually in the flat position at room temperature, and the specimen was cooled to room temperature between successive passes. The welding schedule used was as follows:

Class of electrode	E6010	E7015
Size of electrode, inch	3/16	3/16
Root pass: Amperes	160	160
Volts	25	25
Other passes: Amperes	180	200
Volts	27	27
Speed, average inch/minute	6	7
Number of passes	6	9

Figure 2 shows the standard welding sequence. The last pass was deposited at the toe of the weld to develop any possible toe cracking that might occur in the base plate. It was not necessary to complete the weld, as the side of the joint which was welded first cracked, while the second side did not crack.



Standard Welding Sequence

Balanced Welding Sequence

Typical Transverse Sections

FIGURE 2. DETAILS OF TEE-JOINT SPECIMENS SHOWING LOCATION OF SECTIONS

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Modified Welding Procedures

In several tee-joint specimens, the welding procedure was modified from the original conditions established.

E7015 Electrodes

Three brands of E7015 electrodes were used in welding tee-joints as follows:

Brand	Coating Moisture, Per Cent*	Condition
(A) Murex HTS	1.03	Stored at 30 per cent relative humidity
(A) Murex HTS	0.18	Dried 600 F for 8 hours
(B) Fleetweld LH-70	0.27	As received
(C) P&H-12	0.40	Conforms to MIL-E-986 (Ships)

* See Reference 2

The low-hydrogen electrodes cannot be weaved, hence it was necessary to deposit the weld metal in 9 string beads. In Figure 2, passes 3 and 4 of standard sequence, would require 2 string beads each, and passes 5 and 6 would require 3 string beads each.

Preheat

Tee-joint specimens were welded, similar to the standard procedure, except that a 400 F preheat and interpass temperature was used.

Homogenization

A 12- by 12-inch plate of steel from Heat 66P193-1 (36 per cent cracking) was homogenized using the same procedure as described previously for homogenizing underbead cracking specimens. This plate was welded to another 12- by 12-inch plate to form a 12- by 24-inch base plate. Several tee-joints were made on this composite plate. Welds were interrupted at the weld seam in the base plate to prevent cracking through from the as-received to the homogenized side of the specimen.

Balanced Weld Sequence

Figure 2 shows the weld sequence used in balanced weld specimens. Any root cracking was chipped to solid metal and checked by Magnafluxing between passes 2 and 3. The remainder of the procedure was similar to standard.

Cutting, Grinding, and Inspection

The tee-joint specimen was reduced in size by flame cutting. Three-inch sections were saw cut as shown in Figure 2, allowing an inch for end discard. One face of each section was ground through 600 grit, etched, Magnafluxed, and cellulose-tape transfers made in the same manner as for the underbead cracking specimens, described previously.

Maximum crack depth was measured as the projected transverse crack depth, excluding weld overlap. Average crack depth was calculated as the sum of crack depths of the sections in the joint divided by the total number of sections in the joint.

Test Results and Discussion

Appendix Table A-1 gives the complete data for all tee-joint tests, grouped according to heat numbers. Figure 3 is a condensed summary of the same test data, presented graphically for easier comparison. All of the tee-joints cracked, except for one joint welded in 7/8-inch-thick steel, and those tee-joints welded with a balanced welding sequence. The differences in the amount of cracking as influenced by various test conditions are discussed in the following sections.

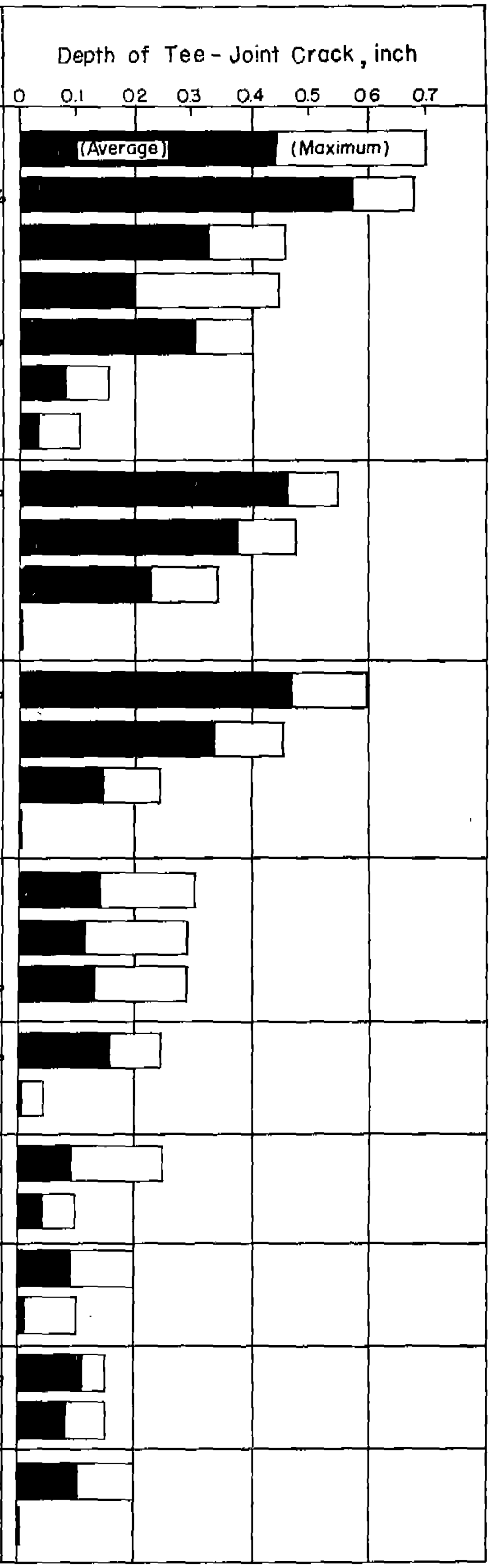
Effect of Underbead Crack Sensitivity

Steels with a high sensitivity to underbead cracking cracked more in the tee-joint test than steels with low underbead crack sensitivity. Figure 4 shows the relation of underbead crack sensitivity to tee-joint cracking for joints welded with E6010 electrodes. Figure 5 is a similar comparison for joints welded with E7015 electrodes.

Two things can be observed from these graphs. First, an increase in the underbead crack sensitivity of the steels is accompanied by increases in the amount of tee-joint cracking. This is supporting evidence that the same mechanism which causes underbead or cold cracking may be influencing tee-joint cracking.

On the other hand, the second observation which can be made is that steels having no underbead cracking may still crack in the tee-joint. This would suggest that some factor other than crack sensitivity might

Heat No.	Test No.	Electrode Class	Length of Tee, inches	Varied Test Condition
66P-193-1 (36%)(1) Class "C"	AC-214	E6010	36	Standard test
	AC-251	E7015	24	Brand B, moisture 0.27%
	AC-250	E6010	24	Standard test
	AC-252	E7015	24	Brand A, dried to 0.18 % moisture
	AC-233	E7015	24	Brand A, moisture, 1.03%
	AC-253	E6010	24	400 F preheat
	AC-250H	E6010	24	Homogenized
21P169-1 (16%)(1) Class "C"	AC-271	E7015(2)	24	Brand C, moisture <0.4%
	AC-257	E6010	36	Standard test
	AC-263	E6010	24	Standard test
	AC-274 AC-276	E6010	24	Balanced weld sequence
71Y354 (15%)(1) Class "C"	AC-272	E7015(2)	24	Brand C, moisture <0.4%
	AC-247	E6010	36	Standard test
	AC-284	E6010	24	Standard test
	AC-275 AC-277	E6010	24	Balanced weld sequence
71P200-1 (0%)(1) Class "C"	AC-256	E6010	36	Standard test
	AC-262	E6010	24	Standard test
	AC-270	E7015(2)	24	Brand C, moisture <0.4%
71Y593 (0%)(1) Class "C"	AC-273	E7015(2)	24	Brand C, moisture <0.4%
	AC-265	E6010	24	Standard test
24P266-1 (7%)(1) Class "B"	AC-267	E7015(2)	24	Brand C, moisture <0.4%
	AC-259	E6010	24	Standard test
72P236-1 (1%)(1) Class "B"	AC-266	E7015(2)	24	Brand C, moisture <0.4%
	AC-258	E6010	24	Standard test
83Y578 (1%)(1) Class "B"	AC-269	E7015(2)	24	Brand C, moisture <0.4%
	AC-261	E6010	24	Standard test
66Y583 (0%)(1) Class "B"	AC-268	E7015(2)	24	Brand C, moisture <0.4%
	AC-260	E6010	24	Standard test



(1) Underbead cracking
(2) Electrodes meet Department of Defense Specification MIL-E-986 (Ships)

FIGURE 3. SUMMARY OF TEE-JOINT TEST DATA, SHOWING HOW VARIATION IN TEST CONDITIONS AFFECTS DEPTH OF CRACKING IN TEE-JOINT SPECIMENS

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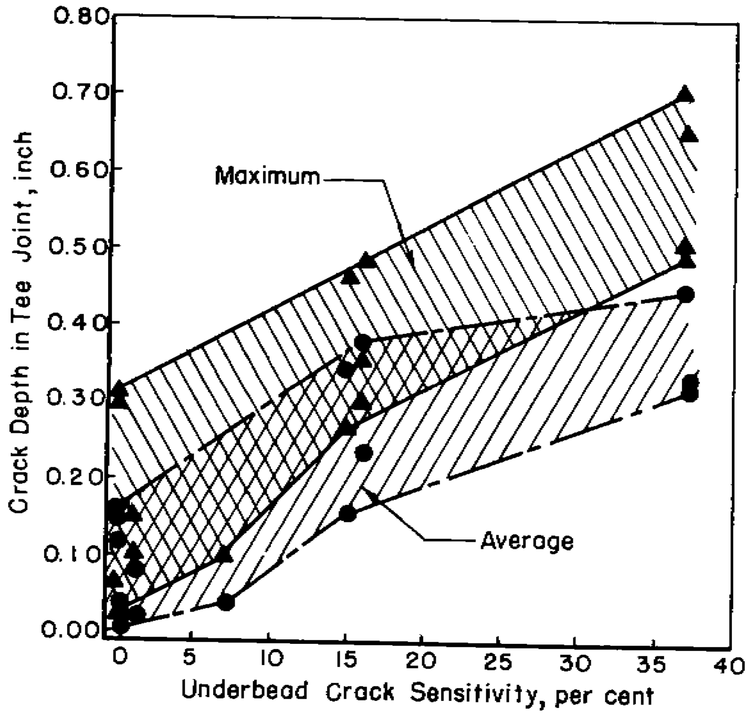

FIGURE 4. RELATION OF UNDERBEAD CRACK SENSITIVITY TO CRACKING IN TEE-JOINT SPECIMENS OF CLASSES "B" AND "C" HULL STEELS WELDED WITH E6010 ELECTRODES

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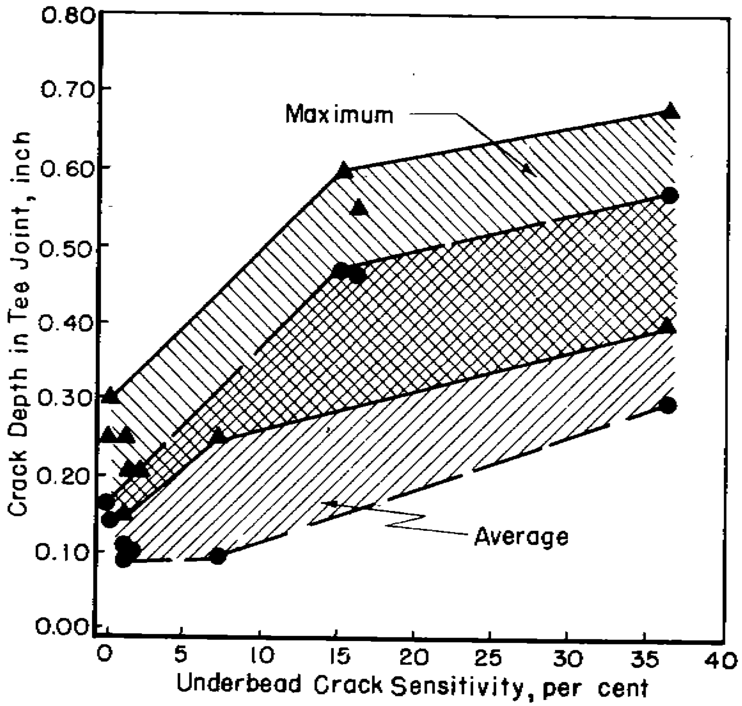

FIGURE 5 RELATION OF UNDERBEAD CRACK SENSITIVITY TO CRACKING IN TEE-JOINT SPECIMENS OF CLASSES "B" AND "C" HULL STEELS WELDED WITH E7015 ELECTRODES

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contribute to tee-joint cracking. It has been suggested that these cracks might be hot cracks.

However, without the knowledge of when these cracks form and how they propagate, trying to attribute the cracking to some cause is premature. The fact to be emphasized is that throughout this work, some of the observed facts point to crack sensitivity, while others do not.

Effect of Different Electrodes

As low-hydrogen electrodes had reduced underbead cracking on Heat 66P193-1 from 36 to 1 per cent, it was decided to see if they would also reduce tee-joint cracking. However, it was found that tee-joint cracking was increased somewhat by use of the low-hydrogen electrodes. A comparison of average cracking in tee-joints welded with E6010 and E7015 electrodes is made in Figure 6. Similarly, maximum cracking for the same tee-joints is compared in Figure 7. A possible explanation for this increase in tee-joint cracking could be the additional number of passes required with the low-hydrogen electrodes, resulting in higher stresses at the root of the joint.

With the E7015 electrodes with different coating moisture content used on Heat 66P193-1, there was no relation between amount of moisture and cracking. Brand "A" electrodes, with 1.03 per cent moisture, gave 0.40 inch maximum crack depth, while Brand "B", with but 0.27 per cent moisture, gave 0.68-inch maximum crack depth. The latter was the deepest crack observed in the 24-inch-long tee-joint specimens.

These results would also tend to confirm the assumption that tee-joint cracking may not be related to or caused by the same mechanism as underbead cracking. If the moisture content of the coating has no influence on cracking, then the role of hydrogen as a cause of tee-joint cracking may drop out.

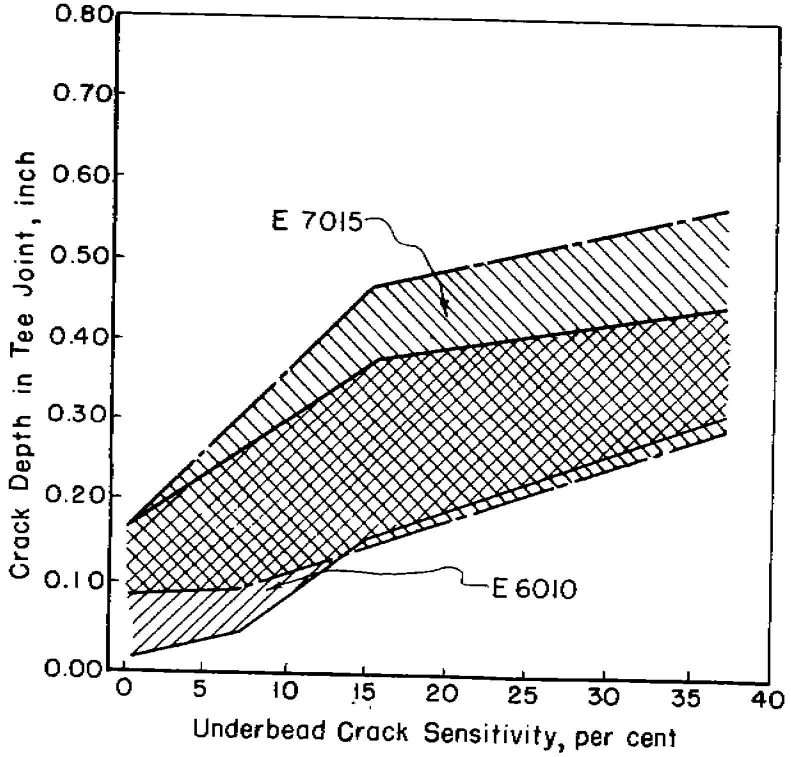

FIGURE 6. COMPARISON OF AVERAGE CRACK DEPTH OF TEE-JOINT SPECIMENS OF CLASSES "B" AND "C" HULL STEELS WELDED WITH E6010 AND E7015 ELECTRODES

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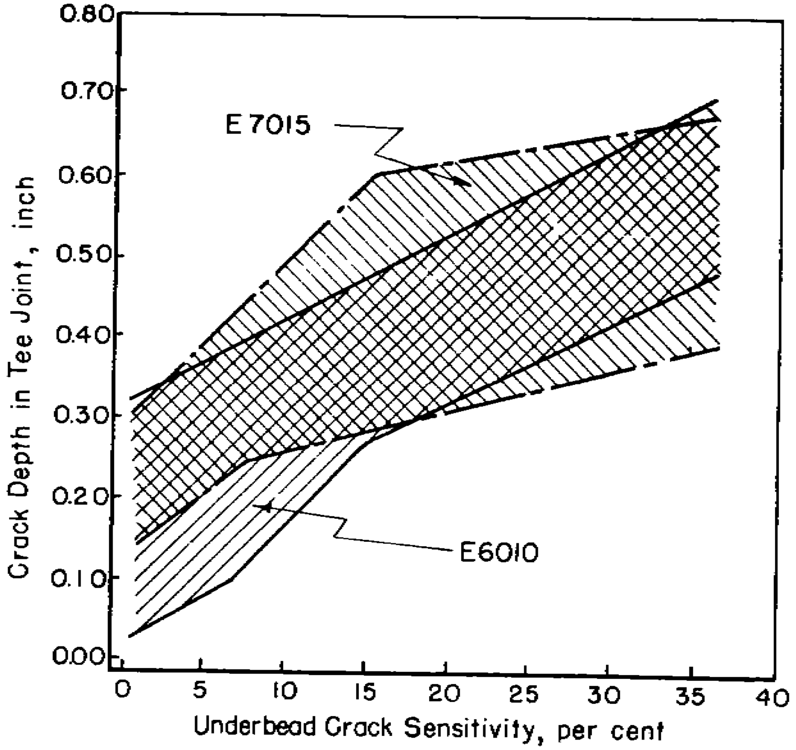

FIGURE 7. COMPARISON OF MAXIMUM CRACK DEPTH OF TEE-JOINT SPECIMENS OF CLASSES "B" AND "C" HULL STEELS WELDED WITH E6010 AND E7015 ELECTRODES

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Effect of Preheat

A preheat and interpass temperature of 400 F reduced the maximum depth of tee-joint cracking in Heat 66P193-1 from 0.46 to 0.16 inch, and the average cracking from 0.33 inch to 0.08 inch.

Effect of Homogenization

A homogenizing heat treatment reduced the maximum tee-joint crack depth in Heat 66P193-1 from 0.46 inch to 0.11 inch, and the average tee-joint crack depth from 0.33 inch to 0.03 inch. These results compare with the reduction in underbead crack sensitivity of this heat from 36 per cent for as-received specimens to 5 per cent for homogenized specimens. That homogenization reduces both tee-joint and underbead cracking is strong evidence toward the assumption that the two may be affected or caused by segregation.

Effect of Balanced Welding Sequence.

Tee-joints using a balanced welding sequence were made with Heats 21P169-1 and 71Y354, having 16 and 15 per cent underbead cracking, respectively. Check tests were made, also. No cracking was found in any of the four tee-joints made. Although this seems to be an easy way of eliminating tee-joint cracking, it is doubtful that sufficient control could be exercised over yard welding practices to preclude the possibility of an unbalanced joint from getting built into a ship. Stress undoubtedly plays an important part in tee-joint cracking, but other factors are also involved.

OTHER TESTS AND STUDIES

Additional studies were made in an effort to explain the differences in cracking between steels. It was thought that some weakness in the "Z" direction might be the cause of this cracking. Standard tensile specimens were made to test several steels in the "Z" direction normal to the plate surfaces. Keyhole Charpy bars were also made and tested. Metallographic studies of the cracks, banding, and inclusions were made. These tests and results are described in the following sections.

Z-Direction Tensile Tests

Specimen Preparation and Testing

Five steels were selected for testing. These included Heats 66P193-1 (36 per cent underbead cracking), 21P169-1 (16 per cent), and 71P200-1 (0 per cent), which had been tested in tee joints. In addition, Heats 21P176-1 (3 per cent) and 66P046-1 (2 per cent) were included because they had chemistry and carbon equivalents similar to Heats 66P193-1 and 21P169-1, the two crack-sensitive heats.

Blocks of the test steels 3 by 6 inches were flame cut. To these test blocks were welded tee-legs of manganese-molybdenum steel. Manganend 2M electrodes were used with a 400 F preheat and balanced welding sequence.

The specimen design and location of the standard 0.505-inch tensile specimen is shown in Figure 8. Both before and after machining, all specimens were Magnafluxed for cracks. No cracks were observed, even in the 36 per cent cracking steel.

The tensile specimens were tested at 80 F using a crosshead speed of 0.02 inch per minute. Yield point was determined by dividers, and elongations were measured for a 2-inch gauge length.

Test Results and Discussion

In Appendix Table 2, the complete test data are given for the Z-direction tensile tests.

The following table gives the average results:

Heat Number	Underbead Cracking, %	Tee-Joint Cracking, in.	Reduction of Area, %	Yield Strength, psi	Ultimate Strength, psi
66P193-1	36	0.70	6	48,700	60,000
21P169-1	16	0.55	12	49,200	67,200
21P176-1	3	--	9	50,900	62,200
66P046-1	2	--	6	48,000	57,000
71P200-1	0	0.30	8	49,400	59,500

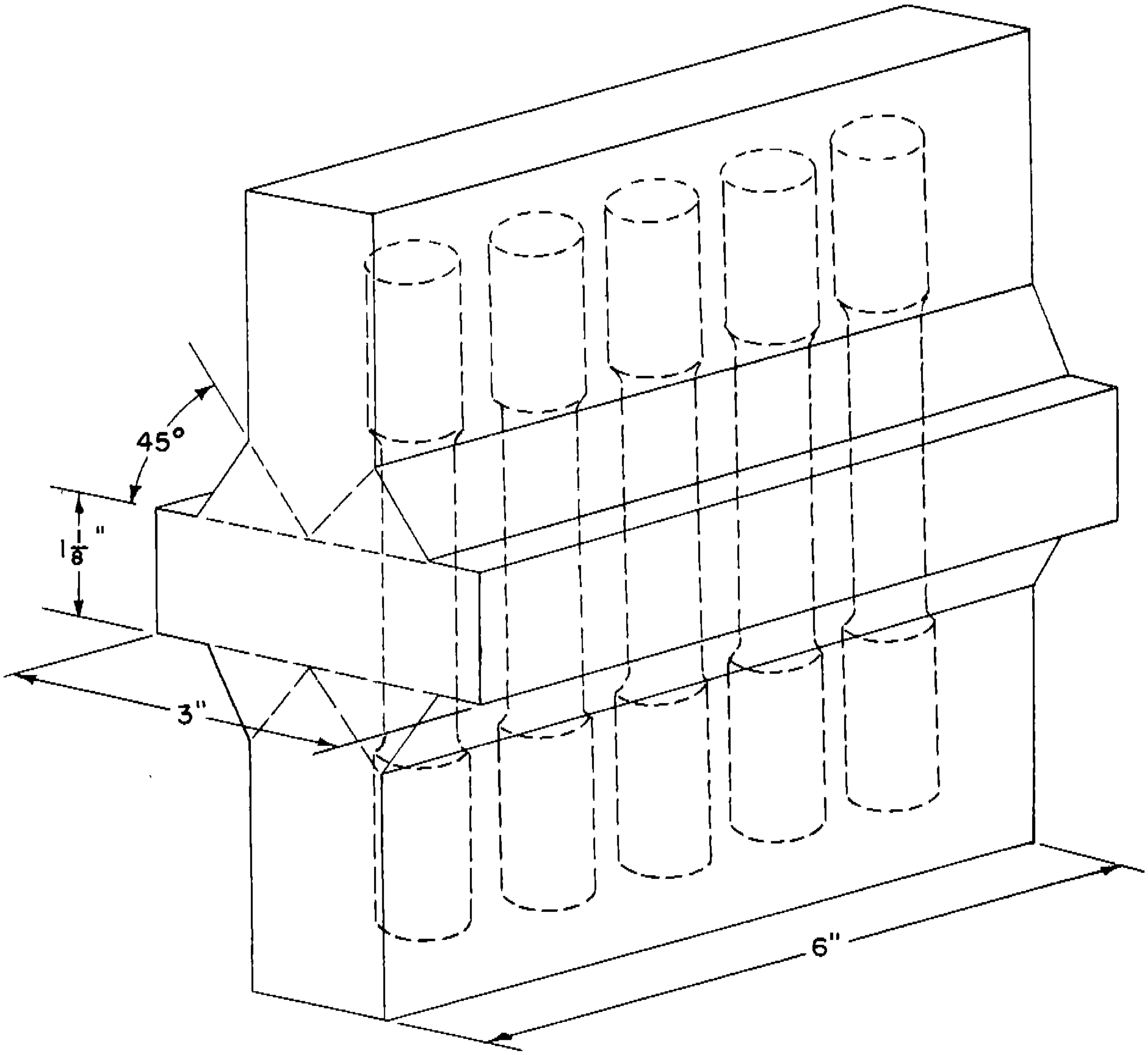


FIGURE 8. SPECIMEN USED TO TEST PROPERTIES NORMAL TO PLATE SURFACE DOTTED LINES SHOW LOCATION OF STANDARD 0.505-INCH TENSILE SPECIMENS

These tests established the fact that no Z-direction weakness existed. There was no particular relation between underbead cracking, tee-joint cracking, and Z-direction tensile strength.

This led to the idea that perhaps the cracking in these steels might be due to notch sensitivity in the Z-plane.

Keyhole Charpy-Bar Tests

Keyhole Charpy bars were prepared to test the notch sensitivity of Heats 66P193-1, 21P169-1, and 71P200-1 (36, 16, and 0 per cent underbead cracking) in the same direction as the crack which occurs in the tee-joints. Six bars were prepared from each heat, as shown in Figure 9. Test results were as follows:

Test Temperature, F	Energy Absorbed, Ft-Lb		
	66P193-1 36 Per Cent Underbead Cracking	21P169-1 16 Per Cent Underbead Cracking	71P200-1 0 Per Cent Underbead Cracking
75	46	47	45
0	28	28	36
-40	27	26	30
-80	17	17	20
-100	3, 19	3, 21	8.4

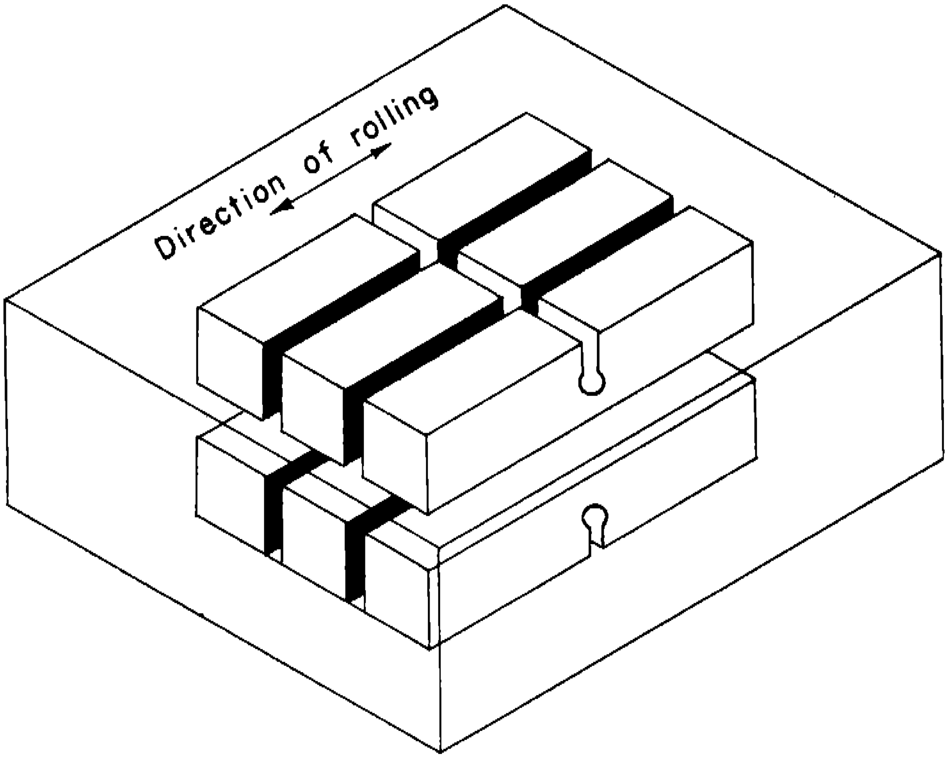


FIGURE 9. SKETCH SHOWING LOCATION OF STANDARD KEYHOLE CHARPY SPECIMENS WITH RESPECT TO PLATE SURFACES AND THE DIRECTION OF ROLLING

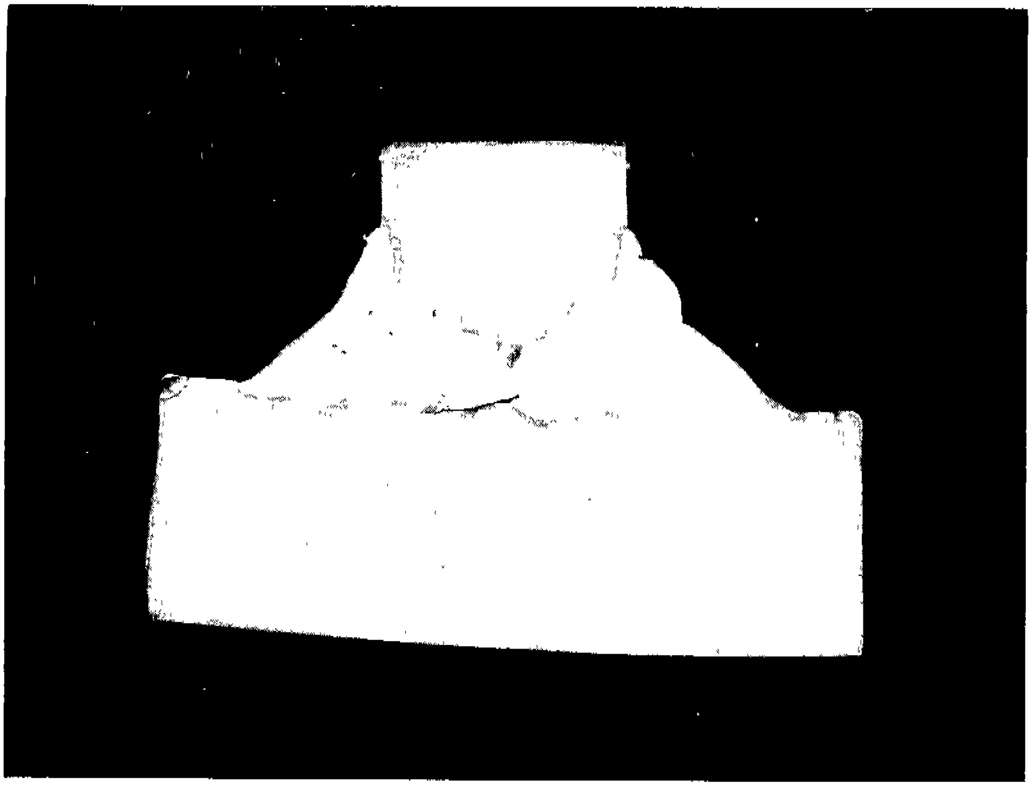
There was no significant difference between the steels in notch-bar properties. These data would indicate that there is more to consider in tee-joint cracking than the simple resistance of the material to a stress at the root of the notch. As both the Z-direction tests and Charpy-tests gave similar values between steels, it is reasonable to expect that the amount of the tee-joint cracking due to stress set up by welding should be equal for each of the steels. It does not explain why there is a difference in amount of tee-joint cracking between steels.

Metallographic Studies

Several metallographic studies were made in an attempt to find an explanation of why the tee-joints cracked. These studies included microscopic examination of the cracks, study of banding in the steels, and a brief study of inclusions. These studies are discussed in the following sections.

Study of Tee-joint Cracks

In the early part of the investigation, it had been observed that only one side of the tee-joint cracked. See Figure 10. The first side of the tee-joint welded always cracked, but the second side welded did not. Hence, it was necessary to weld but one side to produce cracking. Root chipping was stopped because it destroyed any evidence of the crack origin.



1X 67528

FIGURE 10. TYPICAL CRACK FOUND IN TEE-JOINTS. SPECIMEN AC-214 IN HEAT 66P193-1, (36% UNDERBEAD CRACKING), USING E6010 ELECTRODES

Figure 11 is a macrograph of a typical tee-joint crack. The crack origin is at the end of the weld overlap where the weld fuses with the base plate. From its origin it goes in the heat-affected zone just below the fusion line. This crack exhibits a step-like appearance, which is typical of all of the cracks. Inclusions are parallel with the crack, but in Figure 11, inclusions can be observed which the crack cuts vertically. Figure 12 is a view of a typical tee-joint section which has been broken open to expose the crack. The crack surface was oxidized when the specimen was stress relieved.

When the crack forms, and how it propagates are not known. Several welders have made the observation that more angular rotation of the tee-leg occurs during welding the cover passes than occurs during the welding of the filler passes. No measurements other than with a rule were made, however. It is believed that the angular rotation of the tee-joint might be connected with the amount of cracking. However, to demonstrate the growth of the crack, it would be necessary to run a series of tee-joints of the same steel, in which each successive tee-joint had an additional pass. Comparison of the crack depths of these joints would perhaps show when and how the crack formed. Similar tests for different steels might disclose some differences in crack propagation.

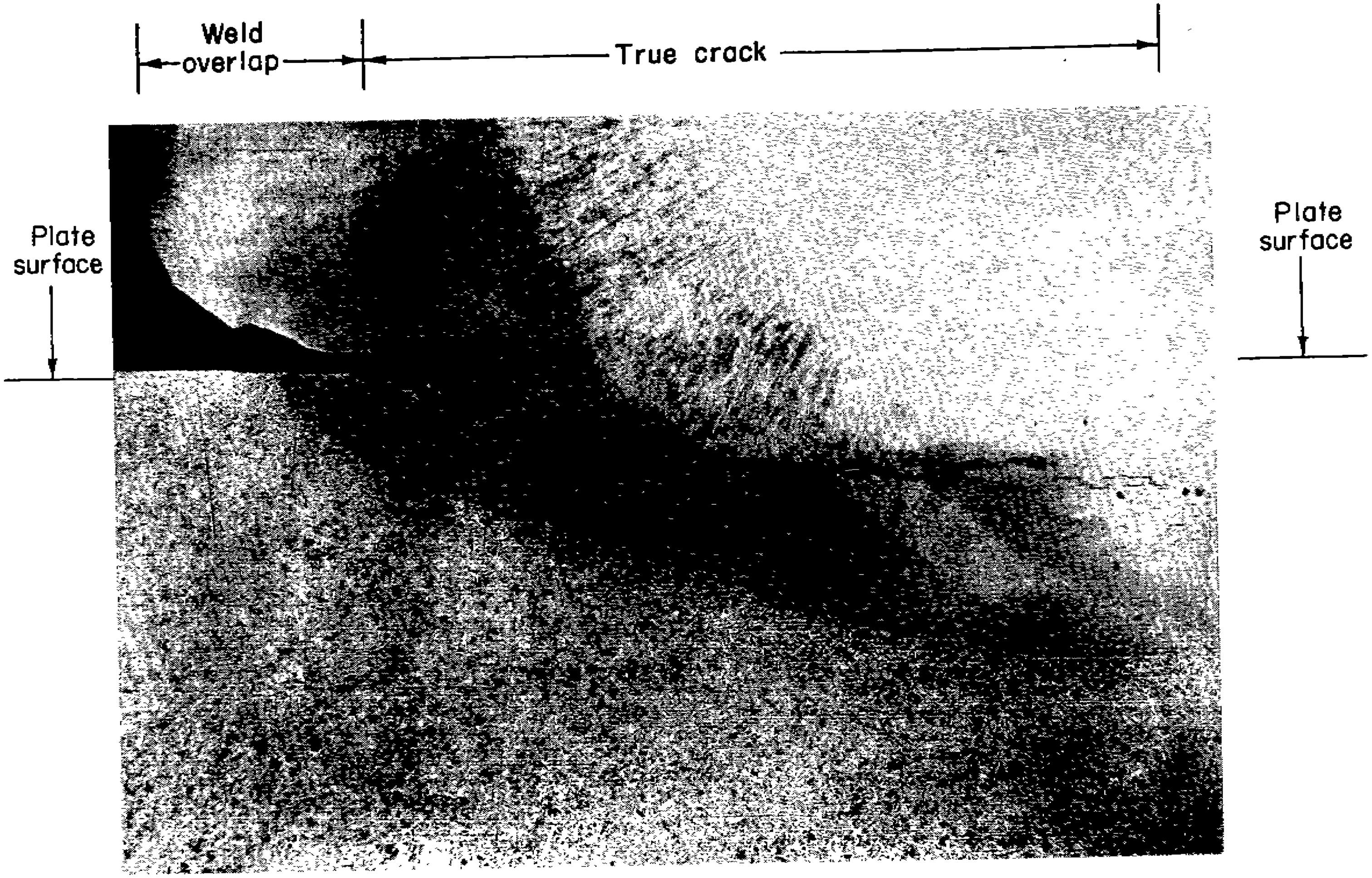
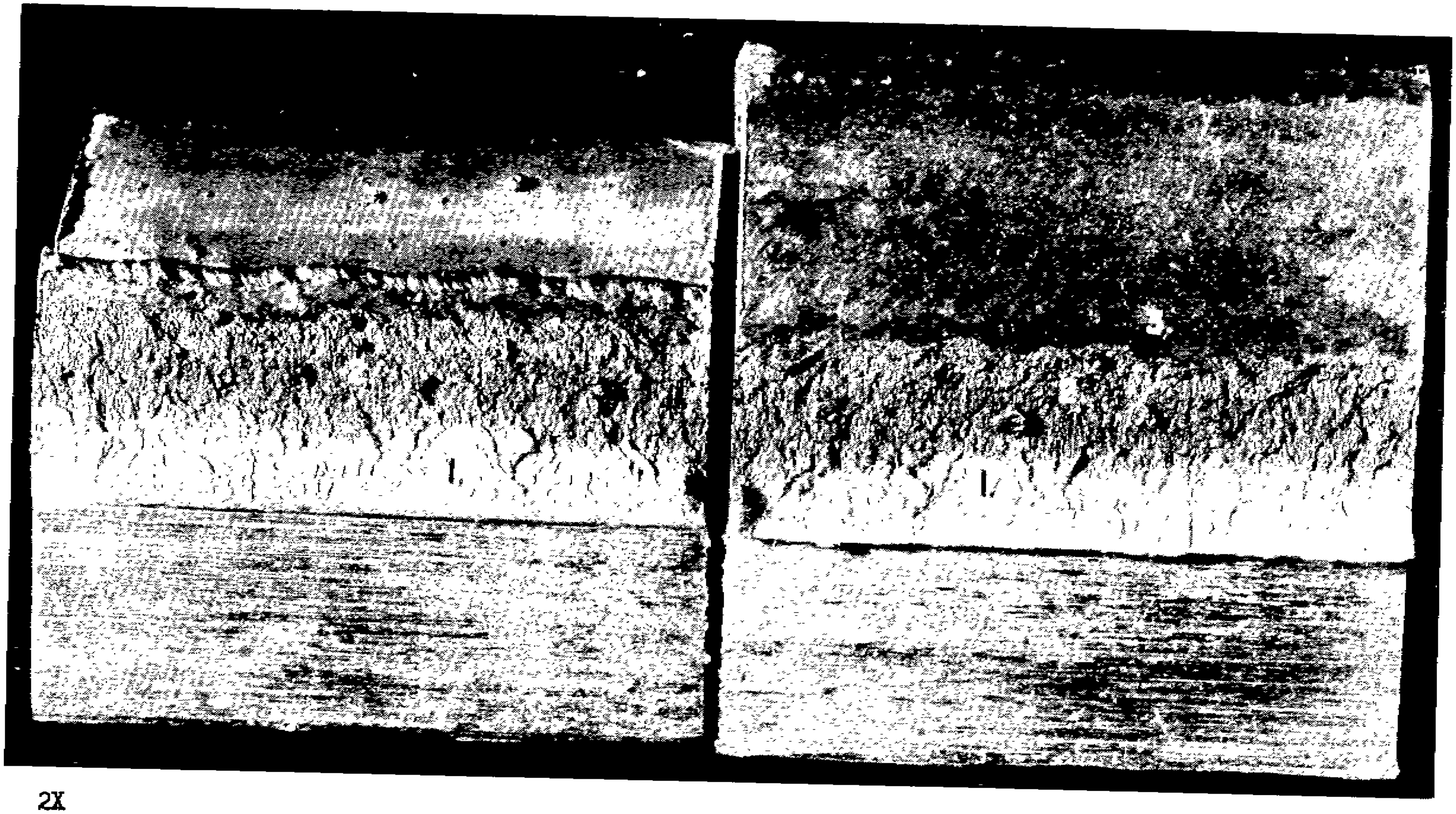


FIGURE 11. MACROGRAPH OF TYPICAL CRACK FOUND IN TEE JOINT. CRACK IS 0.45 INCH LONG. SPECIMEN AC-247-6, IN HEAT 71Y354, (15% UNDERBEAD CRACKING) USING E6010 ELECTRODES



2X

73511

Top, looking into weld and tee-leg

Bottom, looking into base plate

1. Area fractured when specimen was broken open.
2. Tee-joint crack. Surface was oxidized during 1100 F stress relieving.
3. Overlap of root pass on base plate.

FIGURE 12. VIEW OF A SECTION OF TEE-JOINT WHICH HAS BEEN BROKEN OPEN TO SHOW THE CRACK

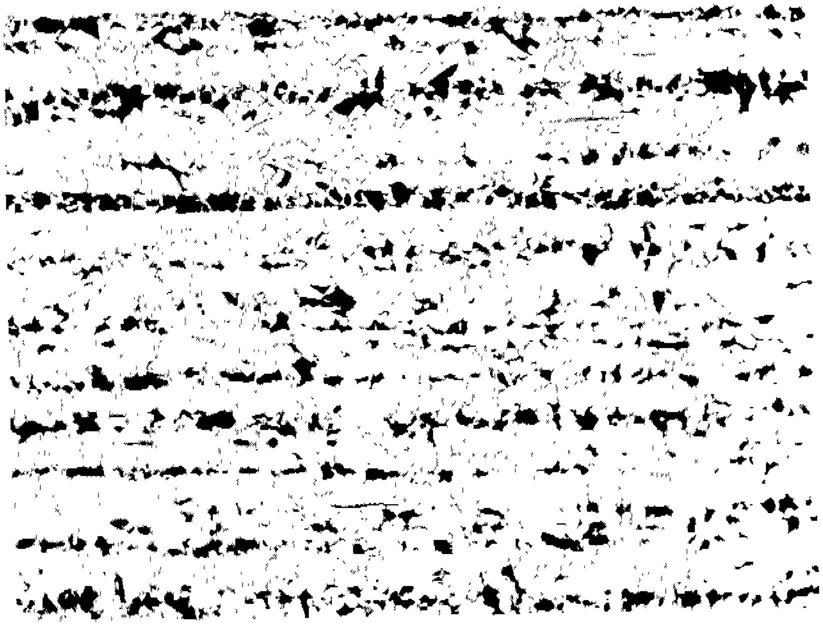
Study of Banding

In an effort to further understand the cracking tendencies of the steels, a study of banding was made in Heats 66P193-1, 21P169-1, and 71P200-1, which had been used in the other supplementary tests.

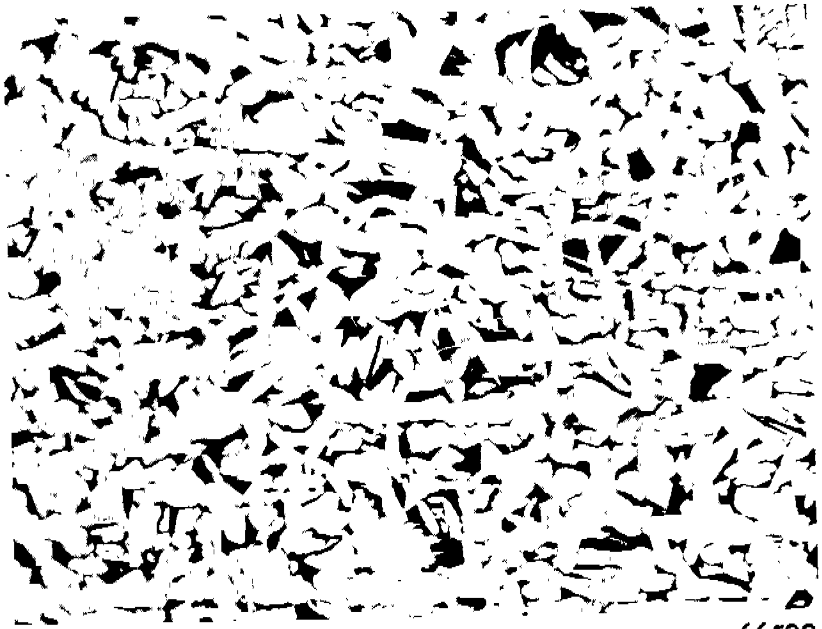
A sample of each steel was obtained in the as-rolled condition. A second sample of each steel was annealed at 1650 F to develop banding, and then studied. Figures 13, 14, and 15 show the photomicrographs of each of the three steels in the as-rolled condition and in the annealed condition. Comparison of Figure 13 with 14 and 15 shows that steel 71P200-1 had the least tendency toward visible banding of the three. Steels 21P169-1 and 66P193-1 showed severe banding tendencies, as shown in Figures 14 and 15. There is no visible reason to explain why Steel 66P193-1 should crack more than Steel 21P169-1.

The difference in the amount of pearlite in the bands of Steels 71P200-1 and 66P193-1 appeared greater than the difference in the carbon content of these two steels, as shown by the mill-check analyses. The mill-check analyses and Battelle analyses follow:

Heat Number		Composition, Per Cent				
		C	Mn	Si	P	S
66P193-1	(Mill)	0.20	0.96	0.24	0.030	0.034
	(BMI)	0.23	0.99	0.23	0.020	0.030
71P200-1	(Mill)	0.17	0.80	0.21	0.028	0.031
	(BMI)	0.18	0.71	0.20	0.019	0.033

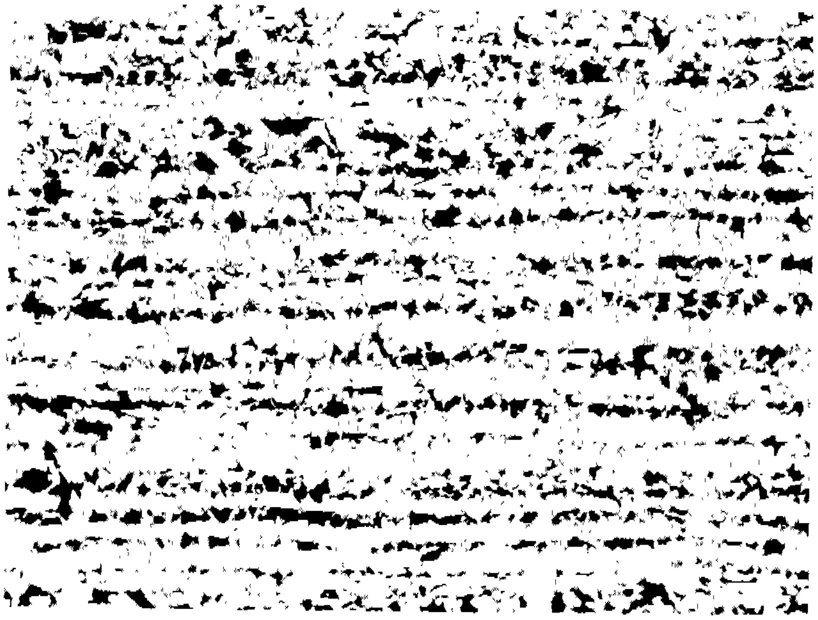


100X Annealed 66517



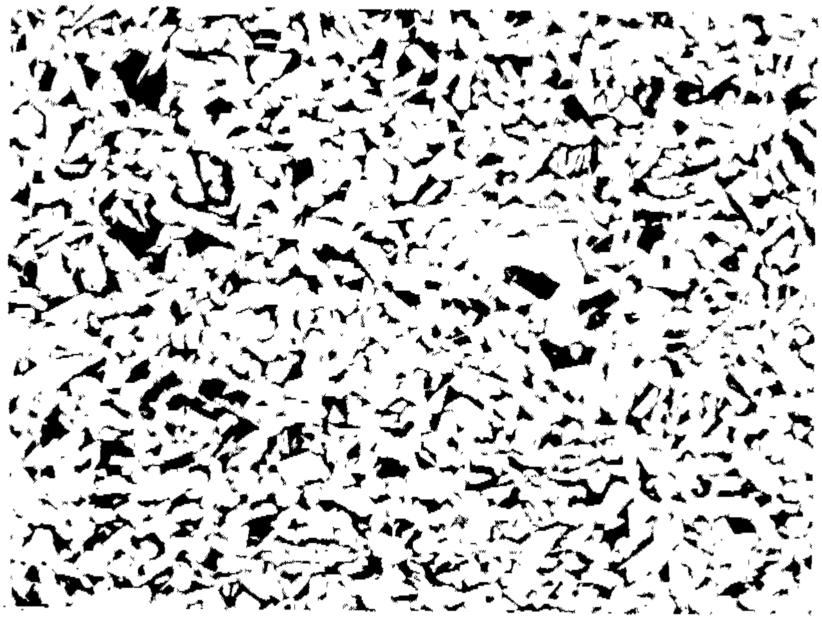
100X As rolled 66520

FIGURE 13. BANDING TENDENCIES OF COMPANY A STEEL HEAT NUMBER 71P200-1 WHICH CRACKED 0 PER CENT IN STANDARD TESTS



100X 66516

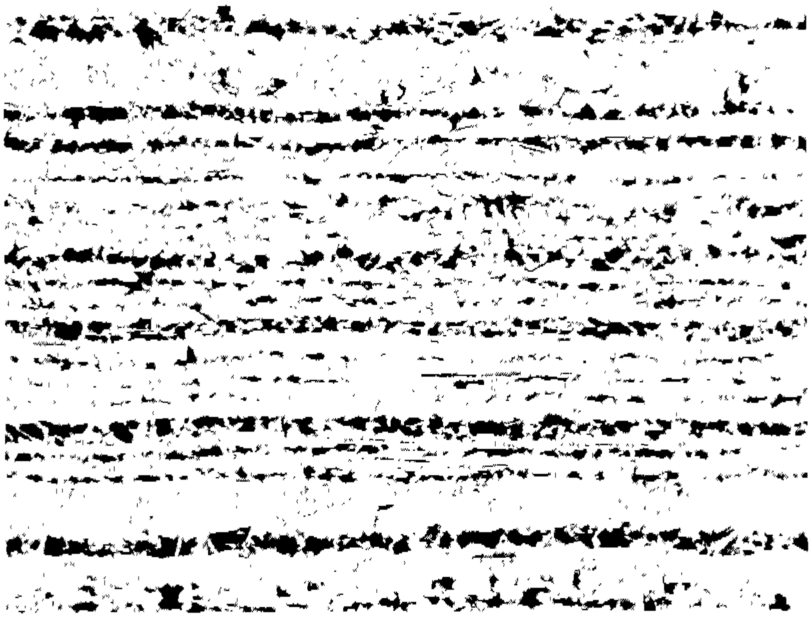
Annealed



100X 66519

As rolled

FIGURE 14. BANDING TENDENCIES OF COMPANY A STEEL HEAT NUMBER 21P169-1 WHICH CRACKED 16 TO 20 PER CENT IN STANDARD TESTS


100X 66515

Annealed


100X 66518

As rolled

FIGURE 15. BANDING TENDENCIES OF COMPANY A STEEL HEAT NUMBER 66P193-1 WHICH CRACKED 36 TO 46 PER CENT IN STANDARD TESTS

Steel 66P193-1, with the greater amount of pearlite, had 5 points more carbon and 28 points more manganese than the other steel, 71P200-1. The higher chemistry and greater banding would appear to correlate with the greater amount of underbead cracking. However, when the banding of 66P193-1 and 21P169-1 are compared, there is no visible correlation with underbead cracking. These same observations have been made for other steels in previous investigations(3).

As previously discussed, manganese segregation plus hydrogen is attributed to be the cause of underbead cracking. The difficulty with a microstudy of banding is that the bands do not give any clue as to what the composition gradients are. This very important fundamental work must be done before the variation in cracking between steels can be thoroughly explained.

SUMMARY

Crack Sensitivity

1. Forty-one heats of ABS Classes "B" and "C" hull steel were tested with the Battelle underbead cracking test.
    a. A peening-project steel received from the American Bureau of Shipping was not crack sensitive.
    b. Eight ABS Class "B" steels received from David Taylor Model Basin were not crack sensitive.
    c. Ten Class "B" steels and eight of ten Class "C" steels received from company A were not crack sensitive. The two crack-sensitive heats gave 16 and 36 per cent underbead cracking.
    d. Six Class "B" and five of six Class "C" company B steels were not crack sensitive. One Class "C" steel cracked 15 per cent in the underbead cracking test.
2. Only one of the forty-one heats cracked seriously in this test.

Tee-Joint Tests

1. Nine heats of steel were tested in thirty-five tee-joints simulating ship welding conditions. All of the tee-joints cracked, whether welded with E6010 or E7015 electrodes, except one joint of 7/8-inch plate.
2. Preheat of 400 F, and homogenization at 2350 F, each reduced cracking in the tee-joints, but did not eliminate it.
3. A balanced welding sequence eliminated tee-joint cracking. This suggests weld shrinkage as the source of the stresses which produce cracking. The technique is thought to be too complicated for commercial welding.
4. The amount of tee-joint cracking increased with underbead crack sensitivity of the steel used in the joint. This was true for tee-joints welded with either E6010 or E7015 electrodes.

Other Tests

1. No conclusive results were obtained from tension tests of several crack-sensitive and noncrack-sensitive heats tested in the direction normal to the plate surfaces. No steel tested had a Z-direction weakness.
2. Keyhole Charpy tests of three heats indicated a transition range below -80 F. These results did not correlate with the tee-joint tests.
3. Severe pearlite banding was observed in two of three heats studied. This banding is believed to be the result of manganese segregation. Banding did not correlate with cracking in tee-joints.

CONCLUSIONS

This study has confirmed the belief that steels which crack severely in the underbead cracking test would likewise tend strongly to crack in ship welding when the same electrode is used. Such steels should not be used for important or critical components unless the well-known remedial measures are adopted.

Without further testing, the causes for tee-joint cracking can not be definitely stated. The amount of tee-joint cracking increases with the underbead crack sensitivity of the steels, and homogenization reduces both kinds of cracking; these indicate that the same mechanism could cause both types. On the other hand, tee-joints cracked in steels having no underbead crack sensitivity and increasing or decreasing the available hydrogen had no effect on the amount of tee-joint cracking. These data would indicate that the tee-joint crack does not altogether depend on the presence of hydrogen or retained austenite. Also, stress alone cannot be the cause, for stresses were present in the homogenized tee-joint, which cracked very little. Thus, it must be concluded the causes of tee-joint cracking are still unknown.

It is also pertinent that low-hydrogen electrodes do not appear, from this investigation, as a cure of tee-joint cracking.

FUTURE WORK

All testing has been completed. No further work will be done on the present contract.

Data given in this report are recorded in Battelle Laboratory Book No. 3856, pp. 58-59, 80-85, 94-99; Book No. 4698, pp. 1-18, 41-42, 72-89, 98-99; and Book No. 5390, pp. 1-5.

FRB:RGK:PJR:CBV/mt
December 14, 1950

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2. Mallet, N. W., and P. J. Rieppel, "Arc Atmospheres and Underbead Cracking", Welding Journal, Vol. 25, No. 11, November, 1946, pp. 748s-759s.

3. Voldrich, C. B., "Cold Cracking in the Heat-Affected Zone", Welding Journal, Vol. 26, No. 3, March, 1947, pp. 153s-169s.

APPENDIX A

TABLE A-1. TEST DATA FOR TEE-JOINTS OF ABS CLASSES "B" AND "C" HULL STEEL

Heat Number	ABS Class	Thickness, Inches	Underbead Cracking, Per Cent	Specimen Number	Electrodes		Specimen Length, Inches	Varied Test Condition	Crack Frequency		Crack Depth	
					AWS Class	Brand			Sections Examined	Sections With No Cracks	Maximum, Inch	Average, Inch
66P193-1	C	1-1/4	36	AC-197	E6010	GE W-22	36	No root gap	10	0	0.65	0.50
				AC-201	E6010	GE W-22	36	1/16-inch root gap	11	1	0.50	0.31
				AC-214	E6010	GE W-22	36	3/16-inch root gap, standard test	10	0	0.70	0.44
				AC-233	E7015	Murex HTS	36	Electrode coating moisture, 1.03%	11	1	0.40	0.30
				AC-250	E6010	GE W-22	24	Standard test	6	0	0.46	0.33
				AC-250-H	E6010	GE W-22	24	Homogenized 2350 F, normalized 1600 F	5	3	0.11	0.03
				AC-251	E7015	Fleetweld LH-70	24	Electrode coating moisture, 0.27%	5	0	0.68	0.57
				AC-252	E7015	Murex HTS	24	Electrode dried 600 F; 0.18% moisture	6	0	0.45	0.20
				AC-253	E6010	GE W-22	24	400 F preheat and interpass temperature	5	0	0.16	0.08
				AC-254	E6010	GE W-22	24	Root bead only deposited	5	2	0.02	0.01
21P169-1	C	1-1/4	16	AC-196	E6010	GE W-22	36	No root gap	11	8	0.30	0.10
				AC-257	E6010	GE W-22	36	Standard test	12	0	0.48	0.38
				AC-263	E6010	GE W-22	24	Standard test	7	0	0.35	0.23
				AC-271	E7015	P&H-12	24	Electrode coating moisture, <0.4%	7	0	0.55	0.46
				AC-274	E6010	GE W-22	24	Balanced welding sequence	8	8	0.00	0.00
				AC-276	E6010	GE W-22	24	Balanced welding sequence	8	8	0.00	0.00
71Y354	C	1-1/4	15	AC-247	E6010	GE W-22	36	Standard test	12	0	0.46	0.34
				AC-264	E6010	GE W-22	24	Standard test	7	0	0.25	0.15
				AC-272	E7015	P&H-12	24	Electrode coating moisture, <0.4%	7	0	0.60	0.47
				AC-275	E6010	GE W-22	24	Balanced welding sequence	8	8	0.00	0.00
				AC-277	E6010	GE W-22	24	Balanced welding sequence	8	8	0.00	0.00
71P200-1	C	1-1/8	0	AC-198	E6010	GE W-22	36	No root gap	11	4	0.05	0.03
				AC-256	E6010	GE W-22	36	Standard test	11	0	0.31	0.15
				AC-262	E6010	GE W-22	24	Standard test	7	1	0.30	0.12
				AC-270	E7015	P&H-12	24	Electrode coating moisture, <0.4%	6	1	0.30	0.14
71Y593	C	1-1/4	0	AC-265	E6010	GE W-22	24	Standard test	7	5	0.05	0.01
				AC-273	E7015	P&H-12	24	Electrode coating moisture, <0.4%	7	2	0.25	0.16

TABLE A-1. (Continued)

Heat Number	ABS Class	Thickness, Inches	Underbead Cracking, Per Cent	Specimen Number	Electrodes		Specimen Length, Inches	Varied Test Condition	Crack Frequency		Crack Depth	
					AWS Class	Brand			Sections Examined	Sections With No Cracks	Maximum, Inch	Average, Inch
24P266-1	B	1	7	AC-259	E6010	GE W-22	24	Standard test	7	3	0.10	0.04
				AC-267	E7015	P&H-12	24	Electrode coating moisture, <0.4%	7	3	0.25	0.09
72P236-1	B	1	7	AC-258	E6010	GE W-22	24	Standard test	7	6	0.10	0.01
				AC-266	E7015	P&H-12	24	Electrode coating moisture, <0.4%	7	2	0.20	0.09
83Y578	B	1	1	AC-261	E6010	GE W-22	24	Standard test	7	0	0.15	0.08
				AC-269	E7015	P&H-12	24	Electrode coating moisture, <0.4%	7	1	0.15	0.11
66Y583	B	7/8	0	AC-260	E6010	GE W-22	24	Standard test	7	7	0.00	0.00
				AC-268	E7015	P&H-12	24	Electrode coating moisture, <0.4%	7	1	0.20	0.10

TABLE A-2. TENSION-TEST DATA FOR STEELS TESTED IN "Z" DIRECTION, NORMAL TO THE PLATE SURFACE, WITH STANDARD 0.505 TENSILE SPECIMENS

Specimen Number	Heat Number	Underbead Cracking, Per Cent	Elongation, Per Cent	Reduction of Area, Per Cent	Yield Strength, psi	Ultimate Strength, psi
AC-239-1	66P193-1	36	2.5	6.0	43,500	61,400
AC-239-2(1)	66P193-1	36	2.5	4.5	46,300	58,600
AC-239-3	66P193-1	36	2.0	5.4	53,100	60,100
AC-239-4	66P193-1	36	2.0	7.0	49,500	58,200
AC-239-5(1)	66P193-1	—	1.5	6.1	54,300	58,600
AC-240-1(1)	21P169-1	16	4.3	6.0	49,300	66,000
AC-240-2(1)	21P169-1	16	7.0	6.1	49,700	67,200
AC-240-3	21P169-1	16	7.0	8.0	50,500	67,600
AC-240-4	21P169-1	16	5.0	14.8	50,100	67,600
AC-240-5	21P169-1	16	6.0	13.0	47,000	66,600
AC-241-1	21P176-1	3	2.5	9.0	50,000	63,200
AC-241-2	21P176-1	3	4.0	11.0	46,900	64,200
AC-241-3	21P176-1	3	3.0	7.8	50,000	61,600
AC-241-4	21P176-1	3	1.5	7.8	57,500	59,700
AC-241-5	21P176-1	3	2.0	8.6	50,500	62,600
AC-242-1	71P200-1	0	3.0	11.0	43,100	55,500
AC-242-2	71P200-1	0	4.0	8.0	46,500	58,400
AC-242-3	71P200-1	0	3.0	8.0	50,100	57,200
AC-242-4	71P200-1	0	3.0	6.1	50,000	57,300
AC-242-5	71P200-1	0	1.5	6.1	51,000	55,500
AC-243-1	66P046-1	2	2.0	5.5	48,600	55,500
AC-243-2	66P046-1	2	1.8	5.4	46,900	56,700
AC-243-3	66P046-1	2	3.0	6.1	51,700	60,500
AC-243-4	66P046-1	2	1.5	7.8	45,700	55,200
AC-243-5	66P046-1	2	1.5	6.0	51,700	57,500

(1) Specimens failed in weld metal. These data were not used when average results were calculated.