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SUMMARY REPORT

on

METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

by

C. E. SIMS, H. M. BANTA AND A. L. WALTERS
BATTELLE MEMORIAL INSTITUTE
Under Navy Contract NObs-31219

NRC 37

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Advisory to

BUREAU OF SHIPS, NAVY DEPARTMENT
Under Contract NObs-34231

Serial No. SSC-11

Copy No. 20

May 5, 1947

PREFACE

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals that were actively associated with this research program. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels".

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May 5, 1947

Chief, Bureau of Ships
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Dear Sir:

Attached is Report Serial No. SSC-11, entitled "Metallurgical Quality of Steel used for Hull Construction". This report has been submitted by the contractor as a summary report of the work done on Research Project SR-87 under Contract NObs-31219 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 Construction, 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,

Frederick M. Feiker

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on

NAVY RESEARCH PROJECT NObs-31219

METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

by

C. E. Sims, H. M. Banta, and A. L. Walters

BATTELLE MEMORIAL INSTITUTE

February 25, 1947

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SUMMARY REPORT

on

NAVY RESEARCH PROJECT NObs 31219

METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

February 25, 1947

From:
Battelle Memorial Institute

Report Prepared By:
H. M. Banta
A. L. Walters

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C. E. Sims, Supervisor

ABSTRACT

This report discusses some of the pertinent factors, especially banding and homogenization, which influence the susceptibility of HTS hull steel to underbead weld cracking. The use of laboratory heats for evaluating various chemical compositions and deoxidation practices is considered. The specific items covered are as follows:

(1) The influence of time and temperature upon the homogenization of both average and high chemical composition HTS steels.

(2) The effect of various degrees of homogenization upon underbead cracking and tensile properties.

(3) The effect of hot reduction upon the response to homogenizing treatments.

(4) A demonstration of the mechanism of banding in HTS hull steels.

(5) A study of the underbead cracking characteristics of quenched and drawn HTS having a yield strength above 75,000 p.s.i.

(6) A comparison of the underbead cracking characteristics and mechanical properties of laboratory and commercial HTS hull steels.

SUMMARY

A study of the effect of various homogenizing cycles on HTS hull steel heats that were weld-crack sensitive revealed that one-half hour at 2350°F. or one hour at 2250°F. was effective in reducing the underbead cracking in heats of average chemical analysis. In the case of abnormally high chemical composition, a longer homogenizing time was required.

Metallographic examination showed that relatively long homogenizing cycles, in the neighborhood of two hours at 2350°F. or four hours at 2250°F., were required to completely eliminate the banding. In view of the results from the weld crack-sensitivity tests, it appears that only the peaks of the alloy segregation need be reduced to make a marked improvement in welding characteristics.

The tensile strength of the homogenized-normalized steels was comparable to the hot-rolled strength, while the yield strength was somewhat higher, being similar to that of hot-rolled and normalized steel. In the case of some heats, the ductility was improved, but in others there was no appreciable change.

In order to illustrate the mechanism by which banding is produced in the medium-manganese steels, a macroscopically banded composite steel was made in the laboratory by hot-rolling together sheets of alternately high- and low-manganese steels, both of which had the same carbon content. Metallographic study of this composite steel showed that carbon segregation, or banding, found in the commercial hull steels is caused by manganese segregation as previously postulated.

The time required for homogenizing was found to decrease rapidly with increased reduction of the steel by hot-rolling, 11 hours at 2350°F. being required to homogenize the cast structure of a 6" x 6" laboratory ingot as compared with 7 hours after 12.5 per cent reduction, while 50 per cent reduction reduced the time to less than one hour.

An investigation of the mechanical properties and weld crack sensitivity of three commercial heats in various heat-treated conditions, such as quenched and drawn, normalized, homogenized, and annealed, showed that high tensile properties did not necessarily cause underbead cracking, but that microsegregation was an important factor.

In order to obtain the same level of crack sensitivity and mechanical properties from laboratory heats as found in commercial steels, it was necessary to increase the carbon and manganese contents slightly above that of the commercial steel. It appears that the low residual alloy content and the small-scale segregation in the laboratory ingots account for these differences.

Steel plate made from the laboratory ingots was found to be lacking in the directional characteristics found in the commercial steel. The small degree of hot reduction seems to account for this difference.

The notched-bar impact properties of the laboratory heats appeared to be in good agreement with the results obtained from the large production heats, each being influenced by the deoxidation practice in a similar manner.

An investigation of the grain-growth characteristics, temper brittleness, and nitrogen content failed to reveal any correlation between these factors and the extent of underbead cracking.

INTRODUCTION

This investigation is a continuation of the O.S.R.D. Project NRC-87, entitled "Metallurgical Quality of Steels Used for Hull Construction".* The research program under the O.S.R.D. sponsorship was terminated August 31, 1945, and since then, the work has been continued under Navy Contract NObs 31219.

This report is a summary of the first three progress reports covering work carried out under the new contract. In presenting this report, it is assumed that the reader is familiar with the information given in the four progress reports issued under the O.S.R.D. sponsorship

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* See progress reports issued on N.D.R.C. Research Project NRC-87 entitled "Investigation of Metallurgical Quality of Steels Used for Hull Construction" (NS-255) by H. M. Banta, Fred Dunkerley, and C. E. Sims, dated May 14, August 24, and October 14, 1945, also final report dated October 14, 1945. OSRD #5062, M-497; OSRD #5492, M-569; OSRD #6073, M-587 and OSRD #6075, M-610, respectively.

The investigation is being carried out along the original lines established during the first year's work, that is, an investigation of the metallurgical quality of HTS hull steel with an emphasis upon those factors which might influence the welding characteristics and the performance of the welded structure. The ultimate objective is to obtain information that will lead to development of an improved high-tensile steel for welded hull construction, either by altering the composition or by controlling the steelmaking and processing practices to give a steel of the desired characteristics. As in the previous work, underbead weld cracking referred to as crack sensitivity is considered one of the more important criteria for evaluating hull steel. Consideration is also given to the mechanical properties that are essential to satisfactory fabrication and service in welded ship construction.

EXPERIMENTAL WORK

The Effect of Homogenizing Treatments Upon Weld Crack Sensitivity and Alloy Segregation

Homogenization Studies on Steel No. 31

Exploratory work previously reported showed that the weld crack-sensitive Steel No. 31 could be made quite insensitive by homogenizing at 2350°F. for four hours followed by normalizing at 1650°F. for one hour, the latter treatment being added to refine the grain structure and improve the physical properties.

In order to obtain more data concerning the temperature and time required for homogenizing and its effect upon the weld crack sensitivity and physical properties, specimens from Steel No. 31 (see Table 4) were treated at 2250°F. and 2350°F. for time intervals ranging from a few minutes to six hours. The homogenizing was carried out in an atmosphere controlled furnace to minimize decarburization and scaling. Following the high-temperature treatment, the specimens were normalized at 1650°F.

Crack-Sensitivity Tests. The crack-sensitivity tests were made using the single-bead weld test, five duplicate weld specimens being made for each heat treatment. (See Appendix for description of weld test.)

The results of the weld tests are summarized in Table 1. These data show that the time required to heat to 2350°F., approximately 3-1/2 hours, was sufficient to reduce the weld cracking to a negligible value. To obtain similar results when homogenizing at the lower temperature, 2250°F., one to two hours at temperature was required.

The results from this work on homogenization are especially significant because they reveal the importance of alloy segregation with respect to underbead cracking. The segregating alloy in this grade of steel is principally manganese, an element which is known to diffuse rather slowly. This subject will be discussed more fully later in this report.

Microstructure. The influence of the homogenizing treatments upon the degree of alloy segregation was determined by microscopic examination of the specimens following an annealing treatment which consisted of holding at 1500°F. for one hour followed by furnace cooling. During the slow cooling, the carbon, which diffuses very readily, segregates in the high alloy areas because these regions remain austenitic for the longest period. Therefore, the distribution of the

TABLE 1. SUMMARY OF CRACK-SENSITIVITY DATA ON STEEL 31 AFTER VARIOUS HOMOGENIZING TREATMENTS

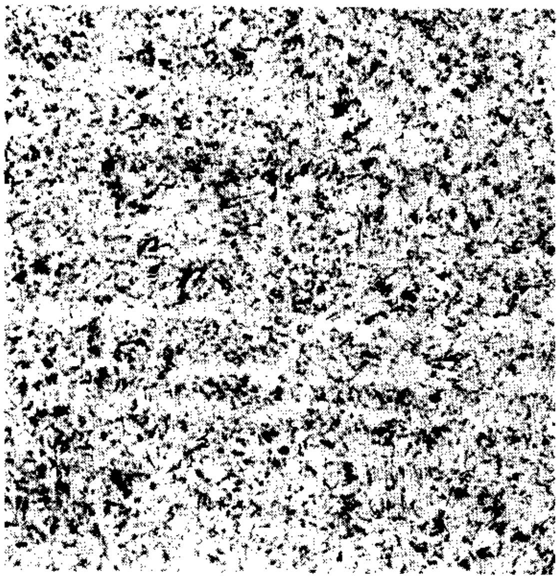
Heat Treatment	Crack-Sensitivity Index
1 minute at 2350°F.	8
10 " " "	7
20 " " "	3
30 " " "	11
1 hour at 2350°F.	8
1.5 " " "	6
2.0 " " "	1
3 " " "	<1
4 " " "	<1
1 minute at 2250°F.	60
15 " " "	43
30 " " "	19
1 hour at 2250°F.	14
2 " " "	5
3 " " "	9
4 " " "	5
6 " " "	5
Hot rolled, as received	65

carbon in the annealed samples can be used as a rough index of alloy segregation or banding.

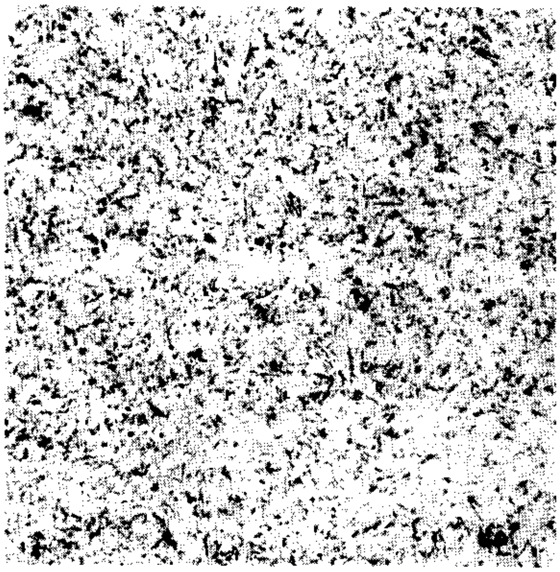
Figures 1 and 2 show how the degree of banding is reduced as the temperature and time of the homogenizing treatment is increased. From Figure 2 it will be noted that the banding is still quite prominent after heating to 2250°F. but decreases rather rapidly upon holding at this temperature. While evidence of banding still exists after 30 minutes at 2250°F., it is significant to note that complete homogeneity is not necessary to reduce the underbead cracking to an appreciable extent. Presumably, it is only necessary to reduce the exceedingly high peaks of alloy segregation to produce a marked decrease in the underbead cracking.

From Figure 1 it will be noted that the high-temperature treatment, 2350°F., was much more effective than 2250°F. for reducing the banding.

Tensile Properties. A summary is shown in Table 2 of the tensile properties of Steel 31 after being homogenized at the various times and temperatures followed by normalizing. These data indicate that the tensile strength of the homogenized and normalized steels is about equal to that of the hot rolled. The yield strength, however, in the case of this heat is slightly higher than that of the hot-rolled steel but is also somewhat less than that of the hot-rolled normalized steel. The ductility appeared to be improved by the homogenizing, but this is not always the case as will be shown later. These results are significant because they reveal that the underbead cracking can be reduced without adversely affecting the tensile properties.

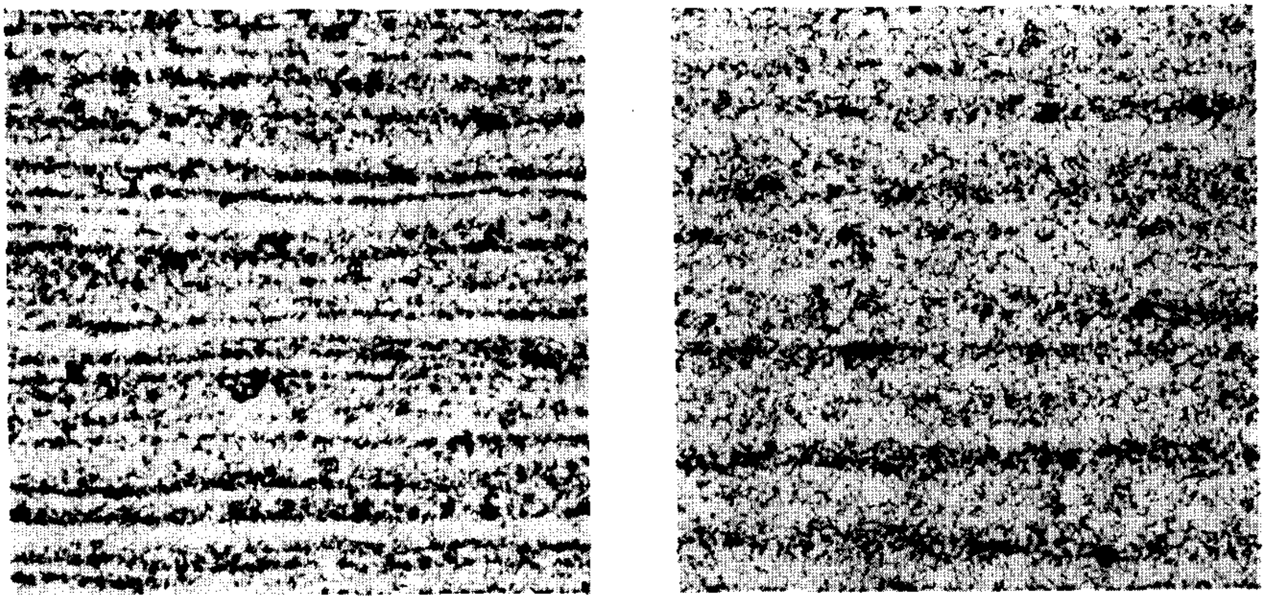


42200
Homogenized 1 minute at 2350°F.



42201
Homogenized 10 minutes at 2350°F.

Figure 1. Microstructure of Steel 31 after homogenizing at 2350°F. for one and for 10 minutes, followed by annealing to bring out any banding. 100X

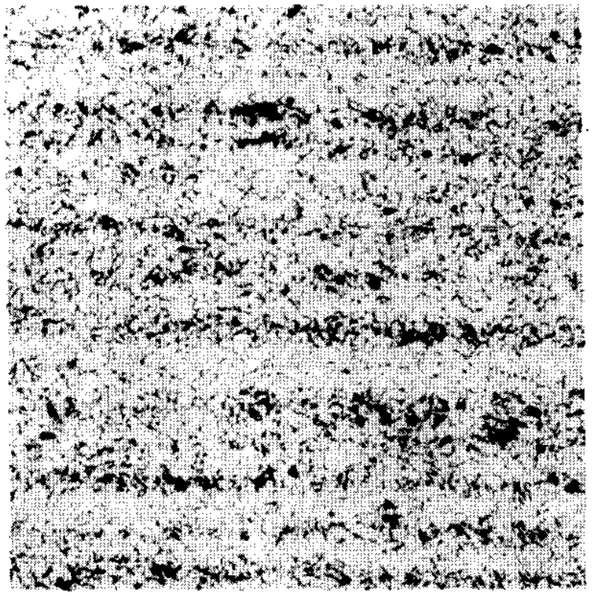


42202

Homogenized 1 minute at. 2250°F

42203

Homogenized 15 minutes at 2250°F.



42204

Homogenized 30 minutes at 2250°F.

Figure 2. Microstructure of Steel 31 homogenized at 2250°F. for 1, 15, and 30 minutes, respectively, followed by annealing to bring out any banding. 100X

TABLE 2. SUMMARY OF THE TENSILE PROPERTIES OF STEEL 31 HOMOGENIZED FOR VARIOUS TIMES AT 2350°F. AND 2250°F. THEN NORMALIZED AT 1650°F.

Heat Treatment	Elong. in 2", %	Red. in Area, %	Yield Strength, p.s.i.	Tensile Strength, p.s.i.	Yield to Tensile Ratio
1 minute at 2350°F.	35.7	69.1	54,175	80,250	67.5
30 " " "	37.0	72.1	52,185	78,125	66.7
1.0 hour " "	36.4	71.8	51,875	78,300	66.2
1.5 " " "	36.0	71.7	52,800	78,650	67.2
2 " " "	36.2	71.9	53,425	78,750	67.8
3 " " "	35.6	71.7	53,750	79,125	67.8
4 " " "	34.9	71.4	50,000	77,875	64.4
1 " " 2250°F.	35.7	71.3	51,875	77,750	66.7
2 " " "	35.7	71.6	52,500	77,825	67.5
3 " " "	36.2	71.6	52,175	78,125	66.8
4 " " "	36.0	72.0	51,550	77,500	66.6
6 " " "	36.0	72.9	52,500	77,875	67.6
Hot rolled "As received"	30.6	61.2	47,875	79,350	61.0
Normalized	32.5	62.8	55,000	80,000	68.8

Homogenization Studies on Steel No. 34 (High Composition Heat)

In order to determine if steels that are abnormally high in chemical composition for commercial HTS hull steels would respond to homogenizing treatments, steel from Heat 34 containing 0.23 per cent carbon and 1.50 per cent manganese was investigated. (See Table 4 for complete chemical analysis.)

Specimens from Heat 34 were homogenized at two temperatures, 2250°F. and 2350°F., for time intervals ranging from a few minutes to four hours.

Crack-Sensitivity Tests. A summary of the results of the underbead weld-cracking tests is shown in Table 5. These data indicate that the weld crack sensitivity of this high-composition steel can be reduced to an appreciable extent by homogenizing. It will be noted, however, that a longer homogenizing time is required as compared with steels of normal chemical analysis such as those listed in Table 3.

Tensile Properties. The tensile strength of the steel from Heat 34 after being homogenized at 2350°F. for various periods of time is shown in Table 6. As previously indicated, the homogenizing followed by normalizing does not influence the tensile strength but the yield strength is raised, the normalizing probably accounting for the later improvement. It will be noted that in this case the ductility was the same as in the hot-rolled steel. It is significant to note that a steel with a yield strength of approximately 57,000 p.s.i. can be treated so that it will not be unduly weld crack sensitive.

TABLE 3. CHECK ANALYSES OF ALL THE HEATS OBTAINED FROM FIVE STEEL PRODUCERS

Heat No.	C	Mn	P	S	Si	Ti	Cu	Ni	Mo	Cr	V	Al*
1	0.16	1.26	.024	.022	0.26	.014	0.10	0.05	.012	0.04	.002	.016
2-a	0.16	1.23	.023	.020	0.21	.011	0.08	0.05	.010	0.06	.003	--
2-b	0.15	1.29	.023	.020	0.29	.014	0.10	0.06	.014	0.05	.002	.015
2-c	0.16	1.29	.021	.020	0.29	.013	0.10	0.08	.013	0.06	.002	.014
3	0.16	1.23	.030	.032	0.21	.016	.007	0.02	.006	0.03	.003	.012
4	0.15	1.16	.032	.040	0.20	.010	0.23	0.11	.014	0.03	.003	.007
5	0.15	1.28	.024	.021	0.28	.009	0.24	0.15	.040	0.05	.003	.006
6-t	0.15	1.16	.021	.025	0.28	.015	0.03	0.14	.019	0.04	.031	.003
6-m	0.14	1.16	.021	.024	0.27	.015	0.03	0.14	.019	0.04	.031	.005
6-b	0.14	1.15	.022	.021	0.28	.015	0.03	0.14	.019	0.04	.031	.007
7	0.15	1.17	.035	.028	0.28	.005	0.13	0.13	.026	0.14	.032	nil
9	0.17	1.27	.020	.026	0.34	.011	0.06	0.18	.033	0.03	.023	.012
10	0.17	0.81	.013	.023	0.21	nil	0.05	0.03	.004	0.03	.068	.002
11	0.17	1.17	.017	.017	0.29	.011	0.35	0.16	.018	0.05	.045	.020
12	0.17	1.11	.021	.025	0.26	.009	0.12	0.16	.022	0.04	.030	.004
13	0.19	0.98	.011	.027	0.22	.015	0.03	0.03	.005	0.07	.050	.012
17	0.15	0.98	.014	.019	0.21	.015	0.14	0.09	.014	0.07	.027	.010

* Acid-soluble aluminum content

TABLE 4. CHECK ANALYSES OF STEELS OBTAINED FROM SHIPYARDS

Steel No.	C	Mn	P	S	Si	Ti	Cu	Ni	Mo	Cr	V	Al*
30	0.18	1.25	.023	.026	0.28	.007	0.19	0.14	.020	.05	.004	.016
31	0.19	1.38	.023	.026	0.30	.010	0.19	0.14	.031	.05	.004	.010
32	0.17	1.44	.025	.020	0.28	.009	0.36	0.22	.034	.07	.007	.015
33	0.16	1.27	.020	.023	0.30	.005	0.22	0.12	.018	.07	.003	.004
34	0.23	1.53	.016	.022	0.24	.008	0.15	0.21	.023	0.15	.003	.013
35	0.17	1.19	.023	.026	0.25	nil	0.26	0.23	.018	0.10	.080	.006
36	0.19	1.39	.023	.022	0.31	.012	0.16	0.10	.040	.07	.003	.009
37+	0.16	1.21	.017	.033	0.28	nil	0.07	0.01	.030	.03	0.120	.020
38	0.17	1.50	.029	.018	0.32	.013	0.14	0.09	.011	.02	nil	.017

* Acid-soluble aluminum content.

\+ Heat 37 used for control steel in making weld crack-sensitivity tests.

TABLE 5. UNDERBEAD CRACKING DATA FOR HEAT 34 AFTER VARIOUS HOMOGENIZING CYCLES AT 2250°F. AND 2350°F. FOLLOWED BY NORMALIZING

Homogenization Treatment	Number of Specimens Tested	Underbead Cracking Index
1 minute at 2250°F.	5	84
15 " " "	5	66
30 " " "	5	61
1 hour " "	5	40
2 " " "	5	27
3 " " "	5	9
4 " " "	5	11
10 minutes at 2350°F.	5	65
40 " " "	5	56
1 hour " "	5	28
2 " " "	5	21
3 " " "	5	16
4 " " "	5	2
Hot rolled, as received	20	71

TABLE 6. SUMMARY OF TENSILE PROPERTIES FOR HEAT 34 AFTER VARIOUS HOMOGENIZING CYCLES AT 2350°F. FOLLOWED BY NORMALIZING AT 1600°F.

Heat Treatment	Elong. in 2", %	Red. in Area, %	Yield Strength, p.s.i.	Tensile Strength, p.s.i.
Homogenized 10 min. at 2350°F.	33	71	58,750	86,975
" 40 " " "	33	71.2	57,750	86,250
" 1 hour " "	33.1	71.1	57,180	85,625
" 2 " " "	33	71.8	58,750	87,180
" 3 " " "	33.7	72.4	57,185	85,000
" 4 " " "	33.2	72.2	57,250	84,935
Hot rolled, as received	32.2	71.2	50,625	85,275

Effect of Hot Work on the Rate of Homogenization

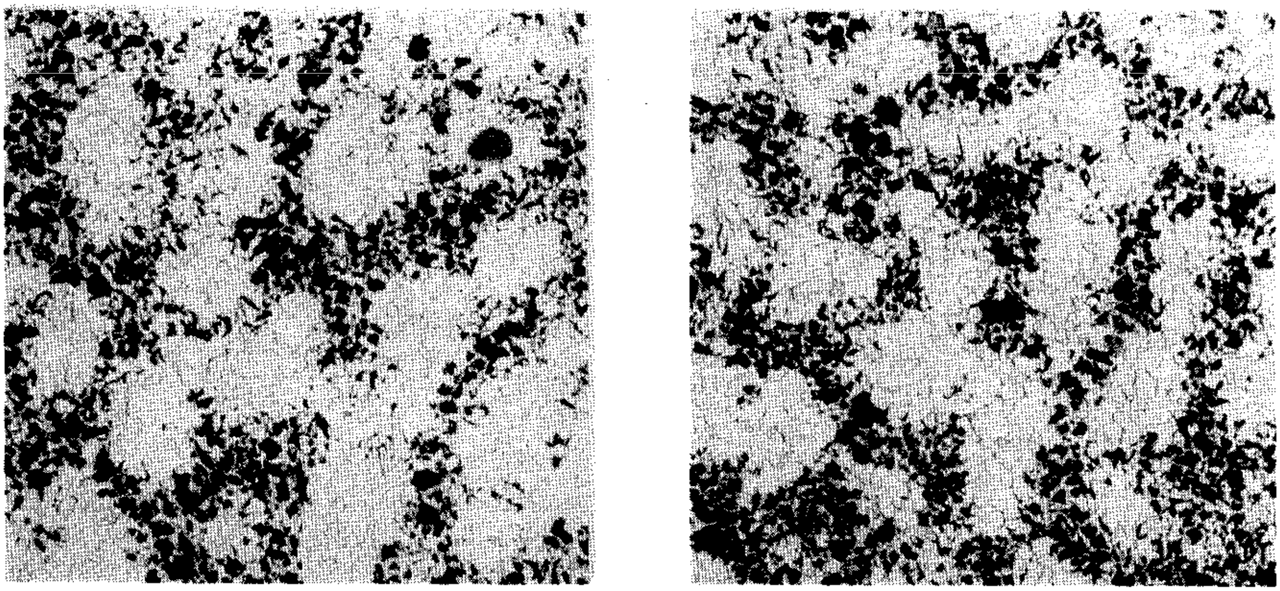
In order to determine the effect of hot work upon the subsequent rate of homogenization, sections were rolled to various gages from a laboratory ingot representing reductions in thickness of 12.5 to 81.3 per cent. These sections were then homogenized at 2350°F. for time intervals ranging from a few minutes to 10 hours. After annealing to bring out the segregation, the specimens from each treatment were examined metallographically. From this examination, the data in Table 7 were compiled showing how the homogenization time decreases with increased reduction.

TABLE 7. TIME REQUIRED TO HOMOGENIZE THE SECTIONS FROM INGOT 1719 AFTER VARYING AMOUNTS OF HOT REDUCTION

Per Cent Reduction	Time at 2350°F. to Homogenize
0 (cast structure)	11 hours
12.5	7 "
21.5	3 "
37.5	1 "
50	less than 1 "
62.5	less than 1 "
81.3	less than 1 "

Micrographs showing the effect of various degrees of hot reduction upon the rate of homogenization are given in Figure 3.

In summarizing, it may be said that hot reduction increases the rate of response to the homogenizing treatment by a very marked extent.



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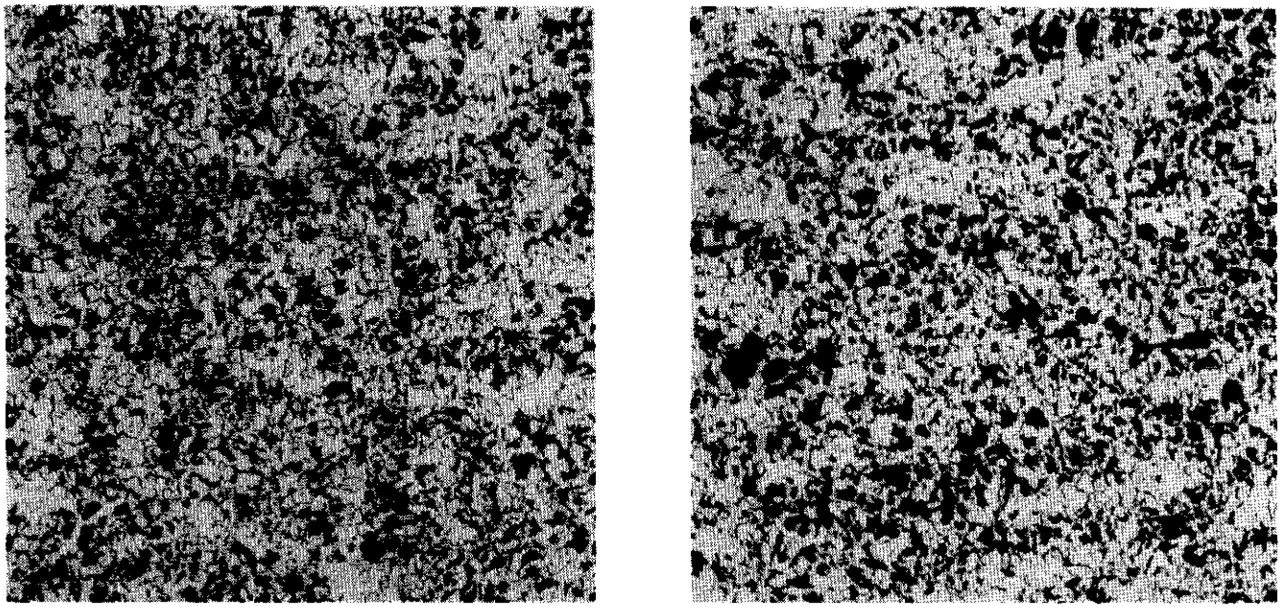
Hot reduced 12.5 per cent

Hot reduced 21.5 per cent



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Hot reduced 37.5 per cent

Hot reduced 50 per cent.

Figure 3. Microstructures of longitudinal sections from laboratory Heat 1719, hot-reduced 12.5, 21.5, 37.5, and 50 per cent, then homogenized at 2350°F. for one hour, followed by annealing to bring out any banding. 100X

This can be accounted for by the decrease in the distance that the alloys must diffuse in the reduced sections and the breaking up of the structure which increases the surface area from which diffusion can occur.

For commercial application, these results indicate that a homogenizing treatment would be much more effective after the ingot has been reduced to a slab than if carried out in the ingot soaking pit.

The Mechanism of Banding

In this investigation, it has been shown that annealing will bring out banding in steels that may appear quite homogeneous in the hot-rolled or normalized states.(1) The explanation has been advanced that dendritic segregation of manganese persisted and was present as bands in the hot-rolled plate. Slow cooling reveals these high-manganese bands, because there is time for the carbon to diffuse during the transformation of the austenite and segregate in the high-manganese areas which are the last to transform. This explanation is based on the general theory of alloy segregation which occurs during the freezing of metals, but no direct evidence has been presented showing that manganese segregation will cause pearlite banding. Experimental evidence will be shown to illustrate how banding is produced.

Preparation of Manganese Banded Steel. A composite steel was made by hot rolling a stack of 1/8-inch sheets of alternately high- and low-manganese steels containing 2.80 per cent and 0.30 per cent manganese, respectively, and both containing 0.14 per cent carbon. The final composite produced was a one-inch plate having the average

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[1] See Reference

chemical analysis of medium-manganese hull steel, but made up of macroscopic bands of high and low manganese contents.

Microstructures After Fast and Slow Cooling. Typical microstructures are shown in Figure 4 of the composite steel after hot rolling and following furnace cooling from 1600°F. For comparison purposes, the structures of hot-rolled and annealed specimens from the commercial Heat 35 are included.

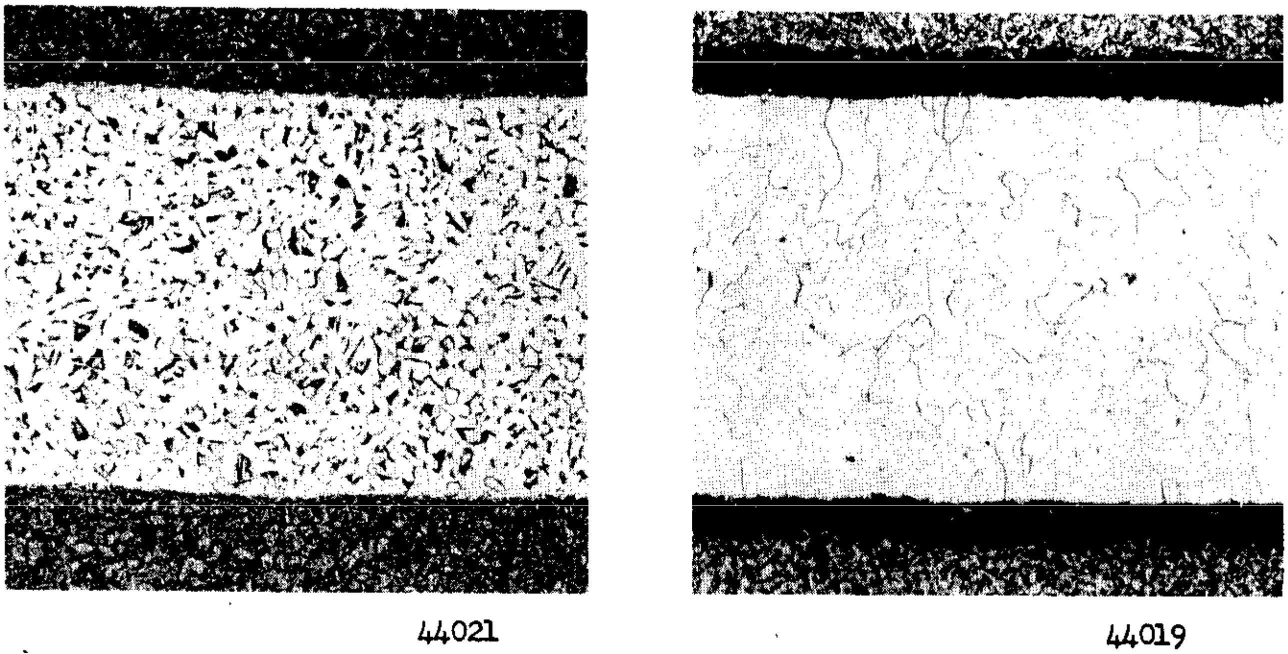
From Figure 4(a) it can be seen that the carbon is uniformly distributed between the low- and high-manganese areas, a condition which resulted from the rapid air cooling following hot rolling. In the slow-cooled specimen, Figure 4(b), however, the carbon has diffused completely out of the low-manganese layer and segregated in the edge of the high-manganese layers. The mobility of carbon was further demonstrated by reheating the annealed sample to 1600°F. and air cooling, the microstructure reverting to that of the original hot-rolled steel.

As can be seen from Figure 4 (c and d), a similar treatment produced an analogous microstructure in the commercial steel, except that the bands are much closer together.

Effect of High Strength Obtained by Quenching and Drawing Upon Underbead Weld Cracking and Physical Properties

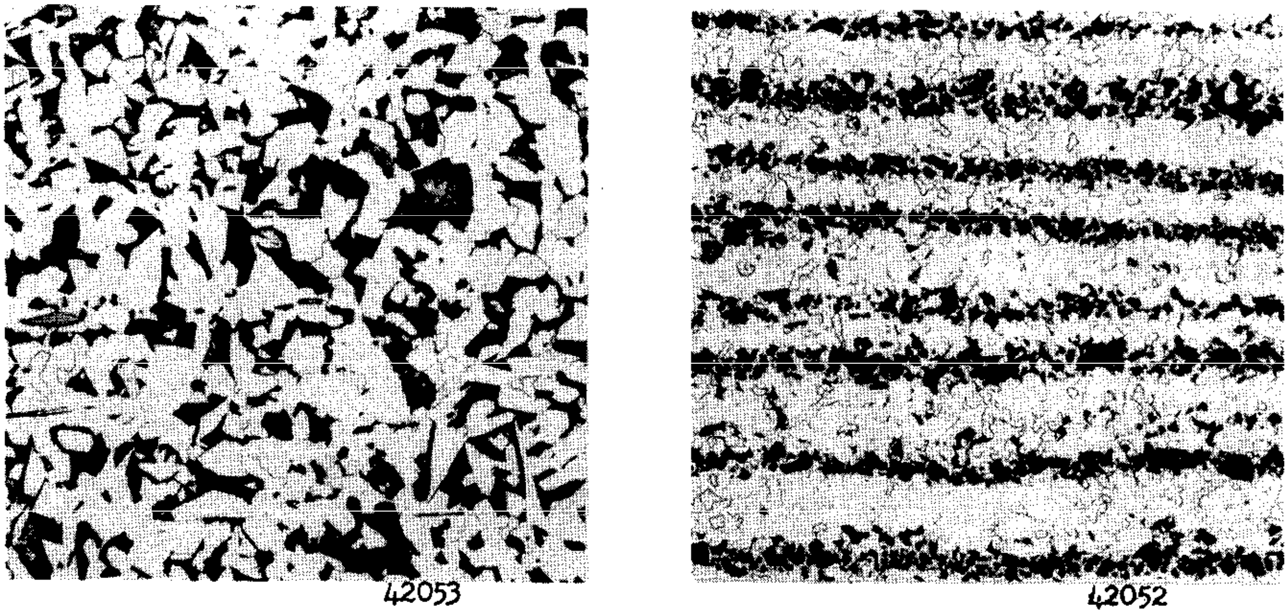
Quenched and Drawn HTS Hull Plate Steel

Steels with high yield strengths, 80,000 to 100,000 p.s.i., are normally expected to be weld crack sensitive, especially if the high strength is obtained by high chemical composition.



(a) Air cooled from hot-rolling temperature

(b) Furnace cooled from 1600°F.



(c) Air cooled from hot-rolling temperature

(d) Furnace cooled from 1600°F.

Figure 4. Microstructures of composite steel and commercial hull steel Heat 35 in the hot-rolled and full-annealed states. 100X, Nital Etch.

In order to avoid the high chemistry and yet obtain a high yield strength, it was decided to investigate the welding characteristics of quenched and drawn HTS plate steel. Since segregation has been found to be an important factor in establishing the weld crack sensitivity of hot-rolled plate, it was also decided to include homogenization in the evaluation of quenched and drawn steels.

Selection of Steels. For this phase of the investigation, Heats 30 and 34 were selected, Heat 30 being a typical commercial vanity HTS steel and Heat 34 representing a steel quite high in chemical composition for the commercial HTS hull plate grade. The chemical analyses of these two steels are listed in Table 4.

Heat Treatment. Three lots of steel from Heat 30 were treated as follows:

Lot 1. Specimens were heated to 2350°F. with the furnace and upon reaching 2350°F. were air cooled. The specimens were then heated to 1600°F. for one hour followed by water quenching and drawing at 1000°F. for one hour and water quenched from the draw.

Lot 2. Same as Lot 1, except that the steel was homogenized at 2350°F. for one hour.

Lot 3. Same as Lot 1, except that the steel was homogenized at 2350°F. for three hours.

Five lots of steel from Heat 34 were treated as follows:

Lot 4. The specimens were homogenized by heating to 2350°F. and upon reaching temperature were immediately air cooled, reheated to 1600°F. for one hour, water quenched, drawn at 1000°F. for one hour, and water quenched.

Lot 5. Same as Lot 4, except the steel was held at 2350°F. for one hour.

Lot 6. Same as Lot 4, except the time at 2350°F. was 2 hours.

Lot 7. Same as Lot 4, except the time at 2350°F. was 3 hours.

Lot 8. Same as Lot 4, except the time at 2350°F. was 4 hours.

All of the above treatments were carried out in an atmosphere-controlled furnace to keep decarburization to a minimum.

Tensile Properties. The tensile properties of Heat 30 and Heat 34, after being treated as outlined above, are listed in Table 8. These data are the average values of two duplicate tests obtained from standard 0.505-inch-diameter test bars taken in the direction of rolling. For comparison purposes, the tensile properties of the two steels in the hot-rolled condition are included.

From Table 8, it will be seen that the yield strength of the quenched and drawn specimens from Heat 30 vary from 65,000 to 82,000 p.s.i., whereas, the tensile strengths lie in the range of 90,000 to 101,000 p.s.i. These values are considerably above those of the hot-rolled plate.

The yield and tensile strengths of the steels from Heat 34 are even higher than for Heat 30 as a result of the higher carbon and manganese contents.

Weld Crack Sensitivity. After having been heat treated as described above, weld crack-sensitivity tests were made using the single-bead deposit test. A summary of the results of these tests is listed in Table 9. These data also include the underbead cracking data for

TABLE 8. SUMMARY OF TENSILE PROPERTIES OF HEATS 30 AND 34 HOMOGENIZED AS INDICATED, THEN QUENCHED AND DRAWN

Heat No.	Homogenization Treatment	Elong. in 2", %	Red. in Area, %	Yield Strength, p.s.i.	Tensile Strength, p.s.i.
30	1 minute at 2350°F.	23.4	57.6	65,250	90,375
30	1 hour at 2350°F.	22.1	60.1	79,500	98,750
30	3 " " "	23	61.7	82,625	101,750
30	Hot rolled only	34.6	64.9	50,350	76,150
30	Hot rolled, quenched and drawn	23.4	62.8	90,880	108,200
34	1 minute at 2350°F.	24.1	62.4	90,375	103,250
34	1 hour at 2350°F.	21.8	64.8	101,625	115,890
34	2 " " "	22	64.8	103,125	116,060
34	3 " " "	23	63.2	101,750	115,750
34	4 " " "	21.8	63.8	103,750	117,250
34	Hot rolled only	32.2	71.2	50,630	85,280

TABLE 9. UNDERBEAD CRACKING INDEXES FOR HEATS 30 AND 34 AFTER VARIOUSLY HOMOGENIZING, THEN QUENCHING AND DRAWING

Heat No.	Heat Treatment	Number of Specimens Tested	Underbead Cracking Index
30	Homogenized 1 minute at 2350°F., then quenched and drawn*	5	33
30	Homogenized 1 hour at 2350°F., then quenched and drawn*	5	0
30	Homogenized 3 hours at 2350°F., then quenched and drawn*	5	1
30	Hot rolled, then quenched and drawn*	20	38
30	Hot rolled only	20	28
34	Homogenized 1 minute at 2350°F., then quenched and drawn*	10	64
34	Homogenized 1 hour at 2350°F., then quenched and drawn*	10	63
34	Homogenized 2 hours at 2350°F., then quenched and drawn*	10	21
34	Homogenized 3 hours at 2350°F., then quenched and drawn*	10	9
34	Homogenized 4 hours at 2350°F., then quenched and drawn*	10	16
34	Hot rolled only	20	71
34	Homogenized 10 minutes at 2350°F., then normalized	5	65
34	Homogenized 40 minutes at 2350°F., then normalized	5	56

TABLE 9. (Continued)

Heat No.	Heat Treatment	Number of Specimens Tested	Underbead Cracking Index
34	Homogenized 1 hour at 2350°F., then normalized	5	28
34	Homogenized 2 hours at 2350°F., then normalized	5	21
34	Homogenized 3 hours at 2350°F., then normalized	5	16
34	Homogenized 4 hours at 2350°F., then normalized	5	2
Control average of previous tests	Hot rolled, as received	-	10

* Quenched from 1600°F., drawn at 1000°F. for one hour

Heats 30 and 34 in the hot-rolled condition and for Heat 30 in the quenched and drawn state without a prior homogenizing treatment.

The underbead cracking tests from Heat 30 reveal that homogenizing for one hour at 2350°F., prior to quenching and drawing, eliminated the cracking although the yield strength of the steel was 79,500 p.s.i. It is significant to note that the steel from Heat 30 which was quenched and drawn, omitting the homogenizing treatment, had an underbead cracking index of 33.

The cracking results from Heat 34 show the need of a more drastic homogenizing treatment for this high composition steel, three hours at 2350°F., reducing the cracking to an index of about ten. It is of interest to note that the yield strength of this steel is 101,750 p.s.i.

It can be concluded from this study of homogenized and quenched and drawn steels that heat-treated steels of the medium-manganese HTS type, having yield strengths in the range of 80,000 to 100,000 p.s.i. can be welded without serious underbead cracking, provided the steels are properly homogenized.

Comparison of Laboratory Heats With Commercial HTS Hull Steels

Since laboratory heats are more convenient and less costly to make than commercial heats for investigating the effect of various steelmaking practices, different chemical analysis, and processing procedures, upon the properties of the finished steel, it was decided to make a study of laboratory heats to see if they behaved in a manner similar to the large commercial heats. In starting this work, it was realized that the dendritic segregation in the ingot which leads to the microsegregation and banding in the finished product would be on a smaller scale in the laboratory ingots. Therefore, it would probably require some experience to produce a hull steel of equivalent weld crack sensitivity in the laboratory.

Laboratory Heats of HTS Hull Steel

For this first study, four 250-pound induction furnace heats were made and cast into 6 x 6-inch cross-section ingots. The aluminum added for deoxidation was varied from 0 in the first ingot to 0.38, 0.75, and 2 pounds per ton of steel, respectively, in the following three heats. The chemical analyses of these four heats and a commercial steel, Heat No. 30, included for comparison, are listed in Table 10. Note the similarity in analysis, the carbon contents of all falling in the two point range of 0.17 to 0.18 per cent and the manganese contents between 1.19 and 1.25 per cent, with the exception of one heat, Heat 1517, which is somewhat lower.

The 6 x 6-inch ingots were processed by heating to 2300°F. and holding at this temperature for three hours prior to forging to slabs 4 x 2 inches in cross section. These slabs were reheated to 2150°F. and hot rolled to one-inch plate.

Tensile Properties. The tensile data were obtained from standard 0.505-inch specimens prepared in duplicate from the center of the 1-inch hot-rolled plates cut in the direction of rolling. A summary of the tensile data is given in Table 11.

These data show that both the tensile and yield strengths are from 5000 to 8000 p.s.i. lower than commercial hot-rolled plate of

TABLE 10. CHEMICAL ANALYSES OF EXPERIMENTAL STEELS 972, 1517, 997, 998, AND COMMERCIAL STEEL 30

Heat No.	C	Mn	P	S	Si	Ti	Al*
972	0.17	1.22	.008	.018	0.29	.005	Nil
1517	0.17	1.08	.012	.019	0.28	.003	.006
998	0.18	1.19	.007	.013	0.28	.004	.016
997	0.17	1.21	.009	.021	0.29	.005	.073
30	0.18	1.25	.023	.026	0.28	.007	.016

* Acid-soluble aluminum content.

TABLE 11. SUMMARY OF TENSILE PROPERTIES AND UNDERBEAD CRACKING OF EXPERIMENTAL STEELS 972, 1517, 997, 998, AND COMMERCIAL STEEL 30 IN HOT-ROLLED STATE

Heat No.	Elong., %	Red. of Area in Inches	Yield Strength, p.s.i.	Tensile Strength, p.s.i.	Underbead Cracking, %
972	38.3	72.9	41,500	70,750	2
1517	34.5	69.4	46,125	67,875	0
998	36.3	74.6	41,500	71,000	2
997	38.5	74.3	41,125	68,875	0
30	34.6	64.9	50,350	76,150	28

similar chemical composition. The ductility, however, as measured by the reduction in area was considerably better than that of the commercial steel. A possible explanation is that the commercial steel is higher in residual alloys, which collectively contribute to the higher strength.

Weld Crack Sensitivity. The results of the weld crack-sensitivity tests made on 1-inch hot-rolled plate from the laboratory heats are given in Table 11. For comparison purposes, the crack sensitivity of the commercial Heat 30 is also listed.

From the data in Table 11, it is obvious that none of the laboratory heats are crack sensitive, the extent of cracking being extremely low considering the chemical composition of the steels. This phenomenon may be explained on the basis of the greater homogeneity which naturally accompanies the small laboratory ingot.

The Effect of the Residual Aluminum Content

It was previously shown in this project that aluminum contents in commercial HTS hull plate heats improved the notched-bar impact properties but was detrimental to the tensile properties in the direction normal to the plate surface.[2]

Tensile Properties of Laboratory Heats Normal to the Plate Surface. Welded tensile specimens as illustrated in Figure 5 were used to determine the tensile properties of the laboratory heats normal to the plate surface. The data from these tests are shown in Table 12. It is obvious from these data that the residual aluminum content did not influence the tensile properties as expected.

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[2] See reference

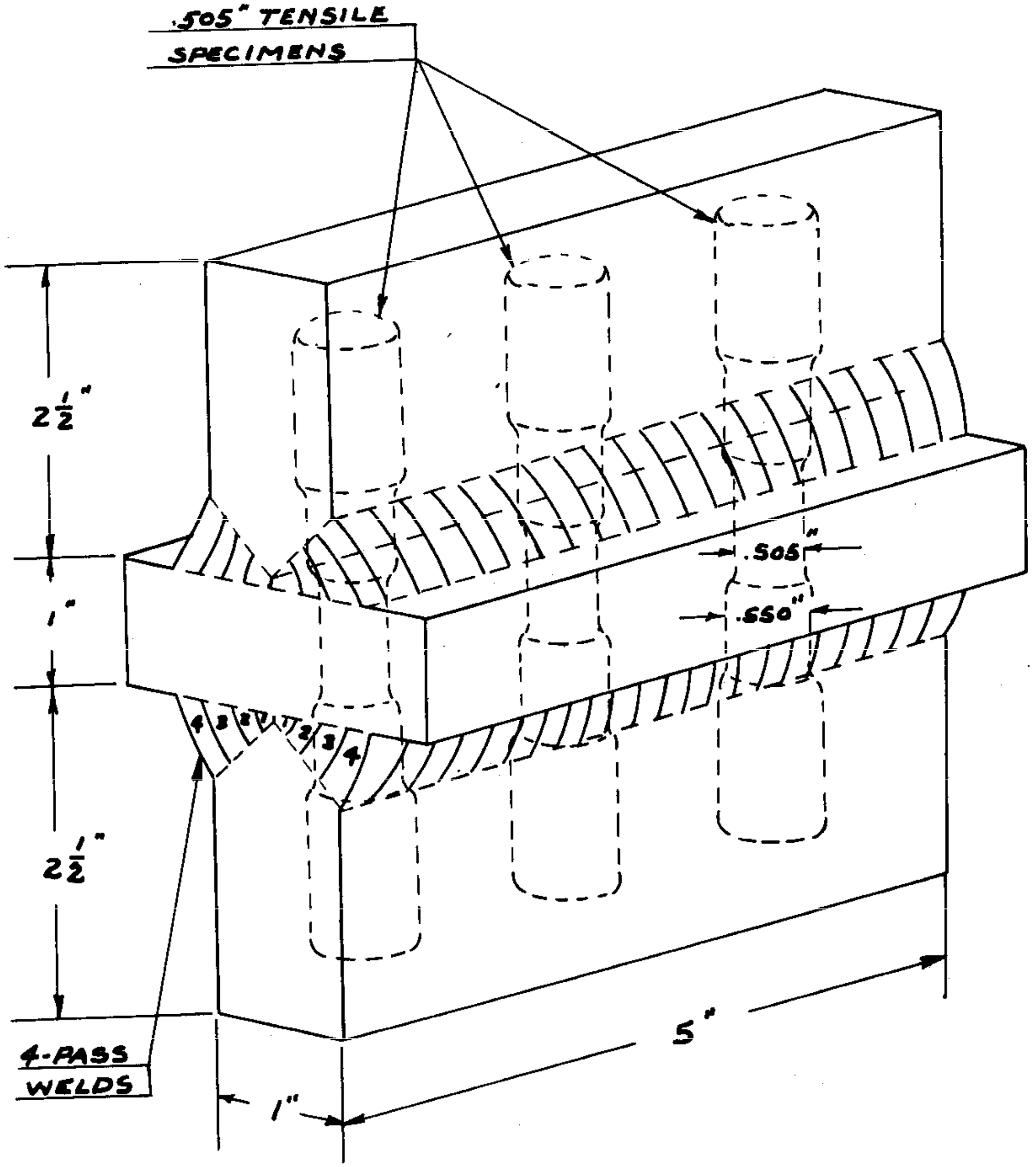


FIGURE 5 - An illustration of the procedure used for making the specimens to determine the tensile properties normal to the plate surface.

TABLE 12. TENSILE PROPERTIES OF LABORATORY HEATS 972, 1517, AND 997 NORMAL TO PLATE SURFACE AND IN LONGITUDINAL DIRECTION

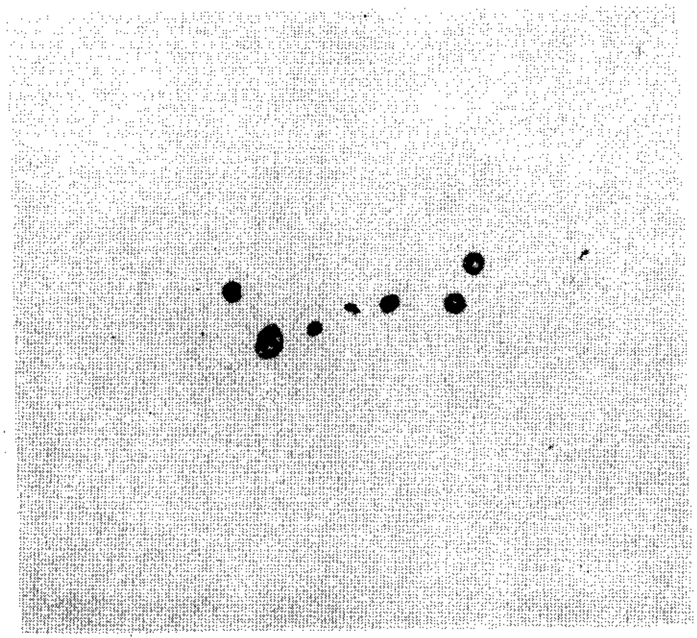
Heat No.	Direction Taken	Residual Aluminum Content	Elong. in 3/4", %	Red. of Area, %	Yield Strength, p.s.i.	Tensile Strength, p.s.i.
			Normal to Plate Surface			
972	Normal to plate surface	nil	10.5	16.5	50,750	70,600
1517	Ditto	.006	14.0	28.2	53,250	70,875
997	"	.073	12.0	24.8	49,000	71,750
			Longitudinal Direction			
			Elong. in 2", %			
972	Longitudinal to direction of rolling	nil	38.4	72.9	43,050	70,750
1517	Ditto	.006	34.2	65.4	46,175	67,350
997	"	.073	38.5	74.3	46,125	68,825

Microscopic examination of these steels in the cast state showed the types of inclusions normally associated with the different degrees of deoxidation, or residual aluminum content. These are shown in Figure 6. Obviously, these three types of inclusions exert different degrees of influence upon the properties of the cast steel. It appears that these different types of inclusions aid in establishing the directional properties developed in hot-rolled steels, the directional difference becoming more pronounced as the per cent of hot reduction is increased. It is believed, therefore, that because of the small amount of hot reduction, the laboratory steels did not develop the directional properties found in commercial hot-rolled steels. It now appears that the influence of aluminum content upon the directional properties of hull steel cannot be accurately appraised from laboratory heats.

Notched-Bar Impact Strength. Longitudinal notched-bar specimens, Charpy specimens with the Izod-V notch cut parallel to the plate surface, were machined from the center of the one-inch plate. The data from these tests are presented graphically in Figure 7. From this figure it will be seen that the transition temperature decreases as the aluminum content (acid soluble) is increased, and that the impact strength of these steels fall within about the same range as commercial steels of similar composition.(2)

Discussion of Results Obtained From Laboratory Heats

The results obtained from the laboratory heats indicated that, in order to obtain tensile properties and weld crack sensitivity similar to that of commercial HTS hull steel, it will be necessary to use slightly higher carbon and manganese contents. The reason for the



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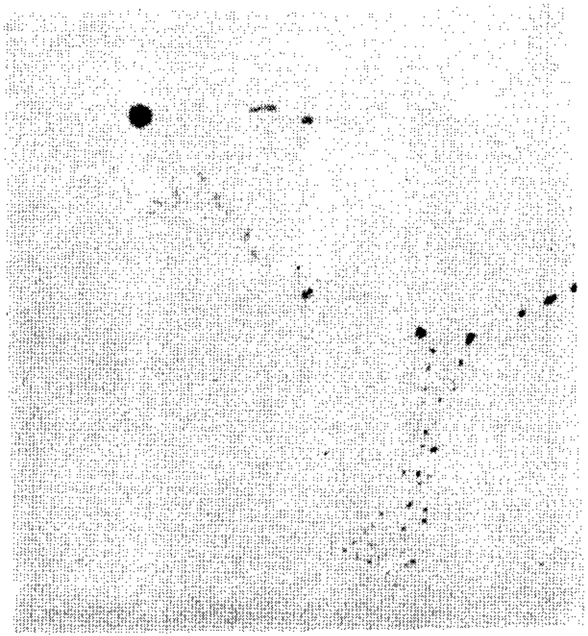
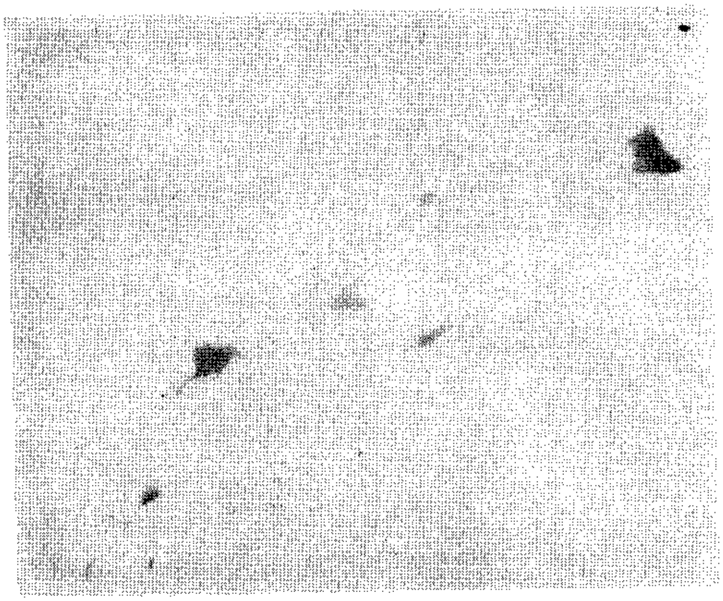
Type I sulfides found in Heat 972, no aluminum used for deoxidation.



42272

Type II sulfides found in Heat 1517, 0.38 pound of aluminum per ton used for deoxidation.



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Type III sulfides found in Heat 997, 2 pounds of aluminum per ton used for deoxidation.

Figure 6. Micrographs of Types I, II, and III sulfides present in hull steels made with 0, 0.38, and 2 pounds of aluminum per ton. 500X

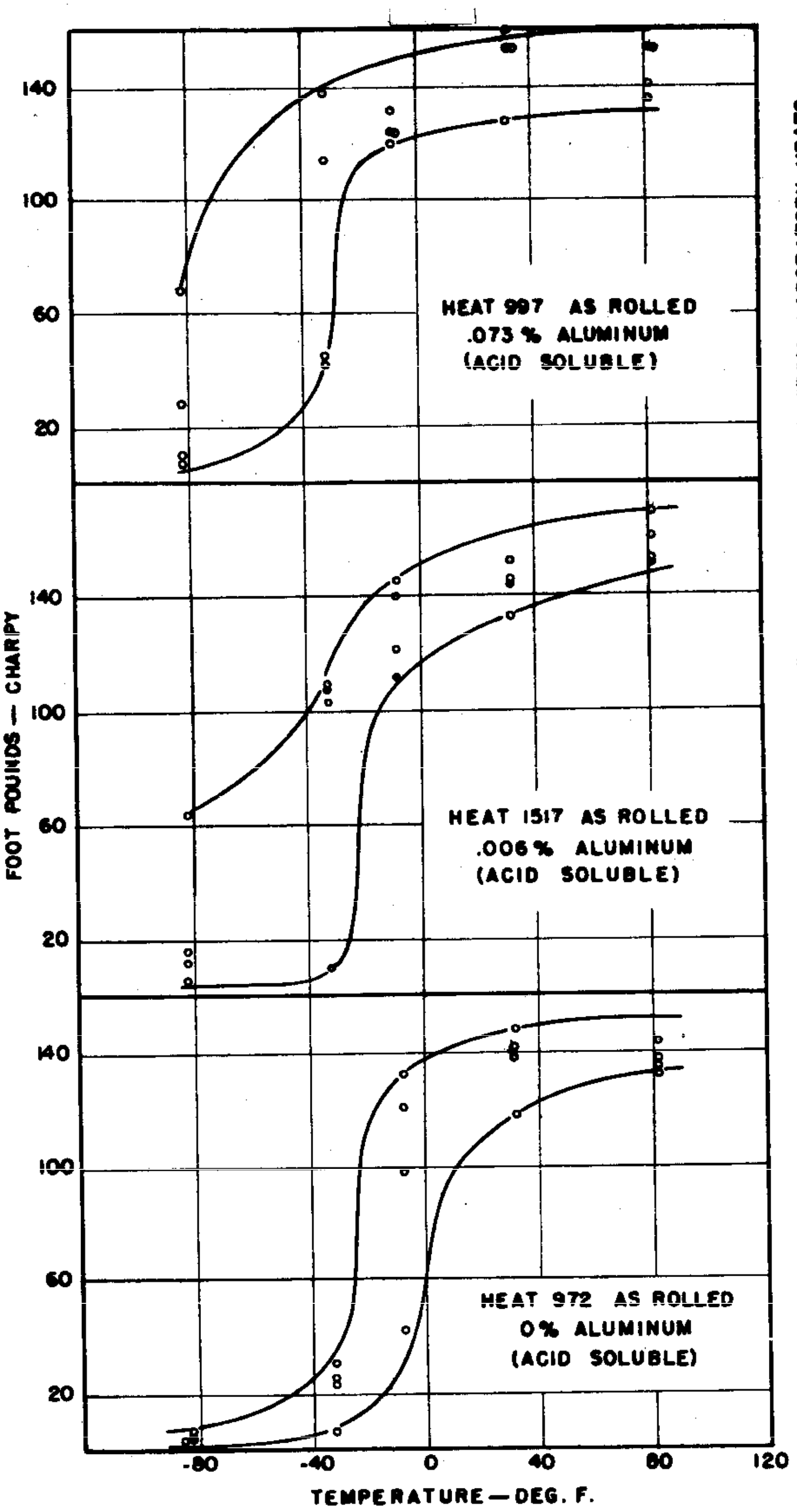


FIGURE 7. NOTCHED-BAR IMPACT PROPERTIES OF 1" HOT-ROLLED PLATES FROM LABORATORY HEATS 997, 1517, AND 972, TAKEN LONGITUDINAL TO THE DIRECTION OF ROLLING AND NOTCHED PARALLEL TO THE PLATE SURFACE

O-2778

lower tensile strength is not too obvious. The absence, however, of the residual alloys normally present in the commercial steels may account for the difference. This lack of residual alloys together with the greater homogeneity resulting from the small ingots may account for the low weld crack sensitivity of the laboratory heats.

It was established that small ingots, 6 x 6 inches, forged and hot rolled to one-inch plate do not have the directional properties found in commercial plate. This lack of marked directional properties, especially in the direction normal to the plate surface, probably results from the small degree of reduction by hot rolling. If any factor is to be studied, therefore, which includes directional properties, it appears that it will be necessary to use larger ingots and carry out the entire reduction by hot rolling.

The results obtained from the laboratory heats do indicate that such steels are satisfactory for studying the influence of deoxidation practice, such as residual aluminum content, upon the notched-bar impact properties.

Laboratory Heats With High Chemical Composition

The first group of laboratory heats showed that the conventional commercial hull steel composition was too low to produce underbead cracking in steel processed from small ingots. In order to produce a crack-sensitive steel, it was decided to increase the carbon content to 0.21 per cent and the manganese to 1.32 per cent. In addition to the composition, it was also decided to investigate the effect of ingot heating practice.

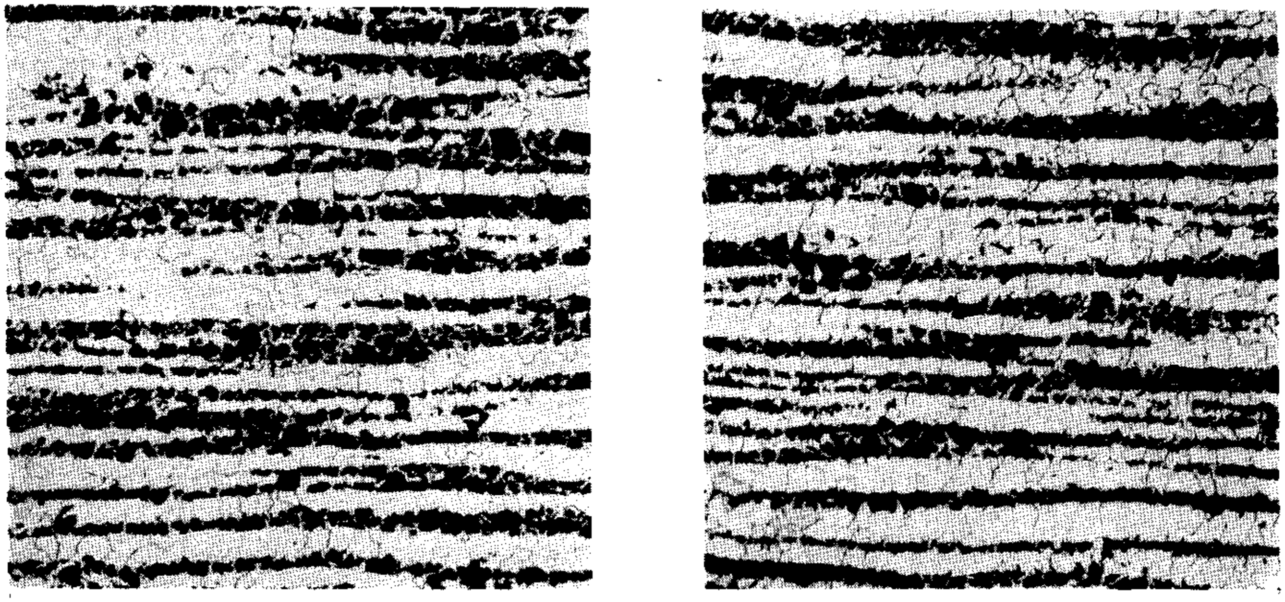
Steel Processing Practice. The three 225-pound ingots for this study were cast in 6 x 6-inch molds from induction furnace heats. After reheating to 2300°F., the ingots were held at this temperature for 1/4, 1, and 3 hours, respectively, after which they were forged to 2 x 2-inch slabs. These slabs were then reheated to 2100°F. and rolled to one-inch plate. The analyses of the three heats are shown in Table 13.

Microstructure. The structures of the three heats after being annealed are shown in Figure 8. From this figure, it is obvious that the difference in the ingot heating practice had no perceptible effect upon the extent of banding.

TABLE 13. CHEMICAL ANALYSES AND UNDERBEAD CRACKING DATA FOR LABORATORY HEATS 1764, 1765, AND 1767

Heat No.	Composition, Per Cent					Underbead Cracking Index
	C	Mn	P	S	Si	
1764	0.21	1.32	.026	.025	0.31	38
1765	0.22	1.34	.019	.028	0.28	41
1767	0.22	1.33	.025	.025	0.30	47

Underbead Weld Cracking. From the underbead cracking data, which are also listed in Table 13, it will be noted that the three steels are quite similar, all cracking between the limits of 38 and 47, an ideal range of crack sensitivity for experimental work since it falls in about the middle of the test range. These results also indicate that the differences in ingot heating procedure had no appreciable effect upon underbead cracking.

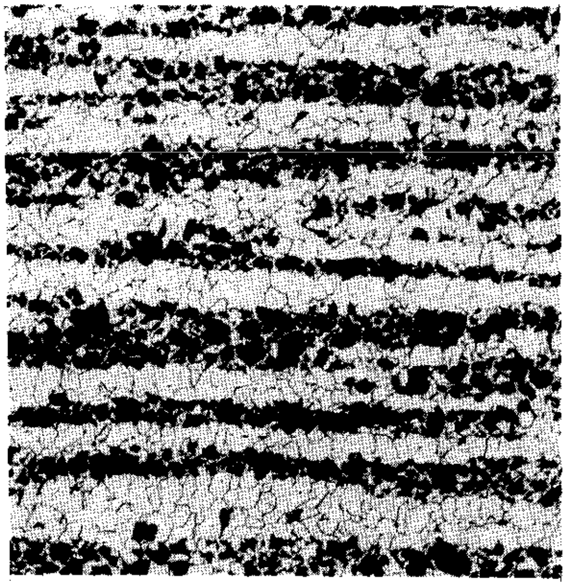


44016

(a) Annealed structure of Heat 1764, soaked at 2300°F. 1/4 hour before forging and rolling.

44017

(b) Annealed structure of Heat 1765, soaked at 2300°F. 1 hour before forging and rolling.



44018

(c) Annealed structure of Heat 1767, soaked 3 hours at 2300°F. before forging and rolling.

Figure 8. Microstructure of Laboratory Heats 1764, 1765, and 1767 after full annealing at 1600°F. These heats were held in the soaking furnace at 2300°F. for 1/4, 1, and 3 hours, respectively, prior to forging and rolling.

Miscellaneous Factors Investigated

Grain Growth

Since grain growth may occur for a depth of several grains in the heat-affected zone, it appeared desirable to determine if there was any obvious relationship between the temperature at which grain-growth starts and underbead cracking.

An examination of twenty-one commercial steels showed no correlation between weld cracking and grain growth. There was, however, a relationship between the residual aluminum content and the temperature at which grain growth started, high aluminum content raising the temperature.

Nitrogen Content

The nitrogen contents of the 23 commercial heats being studied in this project were determined and are listed in Table 14. These results are typical for basic open hearth steel ranging from .003 per cent to .006 per cent. There is no reason to suspect that nitrogen in this range and grade of steel should have any appreciable effect upon the properties or behavior.

Temper Brittleness

While there is no reason to suspect any relationship between temper brittleness and the performance of welded steel, it can be an important factor with respect to notch sensitivity. For this reason, a study was made of the susceptibility of commercial hull steels to temper

TABLE 14. NITROGEN CONTENTS OF HULL STEELS

Heat No.	N_2 Content
1	.003
2b	.003
3	.003
4	.004
5	.005
6m	.004
7	.005
9	.005
10	.004
11	.003
12	.006
13	.004
16	.004
17	.004
30	.005
31	.003
32	.003
33	.005
34	.006
35	.003
36	.005
37	.004
38	.003

brittleness. While this type of brittleness is not uncommon in medium-manganese steels, only two heats out of the eight examined showed any tendency towards temper brittleness, and in these two cases, the extent of the brittleness could be considered negligible.

CONCLUSIONS

The following conclusions should be regarded as tentative since some modifications may be required as additional data are obtained.

(1) Homogenizing at 2350°F. for 1/2 hour or at 2250°F. for 1 hour will reduce underbead cracking in 1-inch HTS hull plate to an appreciable extent. In the case of abnormally high chemical composition, a longer homogenizing time is required.

(2) To completely eliminate banding, a relatively long homogenizing cycle is required, approximately 2 hours at 2350°F. or 4 hours at 2250°F.

(3) The homogenizing treatment is not detrimental to the tensile properties of the HTS steel.

(4) Banding is caused by alloy segregation which is principally manganese in the HTS hull steels.

(5) The time required for homogenizing decreases rapidly with increased reduction of the steel by hot rolling.

(6) Relatively high tensile properties may be obtained from quenched and drawn HTS hull steel accompanied with a low degree of underbead cracking provided the steel was homogenized.

(7) It is necessary to increase the carbon and manganese contents of laboratory heats slightly above that of commercial hull steel in order to obtain the same degree of underbead cracking.

(8) Steel plate rolled from laboratory heats lacked the directional characteristics found in commercial steel.

(9) The notched-bar impact properties of laboratory heats appeared to reflect the influence of deoxidation practice in a manner similar to that observed in commercial steels.

(10) No correlation was found between underbead cracking and grain-growth characteristics, temper brittleness or nitrogen content.

FUTURE WORK

In order to obtain information that will lead to the development of a steel analysis that will give the highest mechanical properties together with a permissible level of underbead cracking, a study is being made of the influence of the various individual alloying elements upon the welding characteristics and mechanical properties.

A series of thirty-five laboratory heats has been made in which the following alloys were varied through the range that appeared to be the most promising; carbon, manganese, silicon, vanadium, molybdenum, and aluminum. The purpose in studying the first four elements; namely, carbon, manganese, silicon, and vanadium, is to obtain information that will indicate the best possible combination of these elements for mechanical properties and welding characteristics. The use of molybdenum is being investigated, because this element raises the critical temperature and, therefore, may be an aid to overcoming the detrimental effect of the segregating alloys that lower the critical temperature and promote banding. Aluminum content is being studied because of its influence on notched-bar impact properties, especially at low temperature.

Commercial slabs of hull steel have been obtained in order to determine the feasibility of homogenizing commercial hull steel by holding the slabs in the slab-heating furnace prior to rolling into plate. After the time-temperature cycle required to homogenize slabs has been established, it is proposed that actual mill tests should be made.

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APPENDIX

Underbead Crack-Sensitivity Test
for High-Tensile Hull Steel

by

C. B. Voldrich

UNDERBEAD CRACK-SENSITIVITY TEST FOR HIGH-TENSILE HULL STEEL

Introduction

The underbead cracking test was made by depositing a weld bead on a block of the test steel and measuring the length of cracks that develop in the heat-affected metal. A cooling rate or series of cooling rates is used, by the selection of electrode diameter, welding current, welding speed and preheat, which will produce cracking in the less sensitive steels of a class. While the laboratory welding conditions may be more drastic than those that obtain in the average ship weld, they are still within the range of production welding conditions.

An important requirement of this type of test is to obtain an index of crack sensitivity which can be used quantitatively, rather than as a crack-or-no-crack indication. This is accomplished by using the average cracking value for a reasonably large number of identical specimens. It has been found that, while individual specimens of a set may vary in cracking as much as 20 or 30 per cent, the average cracking values for several sets of specimens of a given steel will fall within a much narrower range if the number of specimens in a set is adequate.

Test Method

Control Steels

At the beginning of this investigation, because of the large number of test steels and weld specimens involved, it was necessary to divide the steels into groups of three to five, and to continue the welding of individual specimens over a period of several days. To check the possible variations from day to day in welding conditions and incidence of underbead cracking, two commercial heats were designated as "control" steels, which were tested on every day that a group of the other steels was tested. One of the control steels had a relatively low crack sensitivity, while the second steel was highly crack sensitive. This provided the desirable range in crack sensitivity for the controls.

During the past two years, a great many tests have been made, and no significant variations in the cracking index, for a given steel and constant welding conditions, have been observed. The more recent practice has been to make the tests without the daily use of controls, but to make an occasional group of tests on one of the control steels.

Preparation of Steels for Welding

The steels used in these tests were rolled plates of structural high-tensile steels received from various mills and shipyards and steels made at Battelle.

Electrodes

The electrodes used in the tests described above were 1/8-inch G. E. W22, AWS Class E6010. The electrode cartons were opened and stored in a cabinet maintained at 60 to 80°F. and 25 to 35 per cent relative humidity for several weeks prior to the weld tests.

Welding Method

A typical group of test specimens consisted of five to twenty 2- by 3-inch steel blocks from each steel. Using an automatic stick-feed welding head, a 300-ampere direct-current motor-generator set, and the 1/8-inch cellulose-type electrodes described above, a 1-1/4-inch weld bead was deposited on each block. A new electrode was used for each bead.

The welding current was about 100 amperes at about 25 arc volts (electrode positive), with a welding speed of 10.0 inches per minute (9.0 seconds arc time).

Each block was precooled in a carbon tetrachloride-dry ice bath to 0°F., and then clamped in a welding jig in a similar bath at 0°F. The level of the liquid was held at about 1/4 inch from the top surface of the block.*

After the completion of the weld bead, the block was held in the cold bath for 1/2 minute (the crater of the bead was cold to the touch after about 20 seconds), and then placed into a circulating-air cabinet at 60°F. for 22 to 26 hours.

The welding setup is shown in Figure A1, and a typical current record in Figure A2.

Measurement of Underbead Cracking

After the 24-hour storage at 60°F., the welded blocks were stress-relieved one hour at 1150°F. and sectioned longitudinally as shown in Figure A3. The sections were polished through No. 600 emery paper, and

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* It has been found that the test can also be conducted with the blocks at room temperature, with no significant change in the amount of cracking. (See Ref. 3 on page 55.)

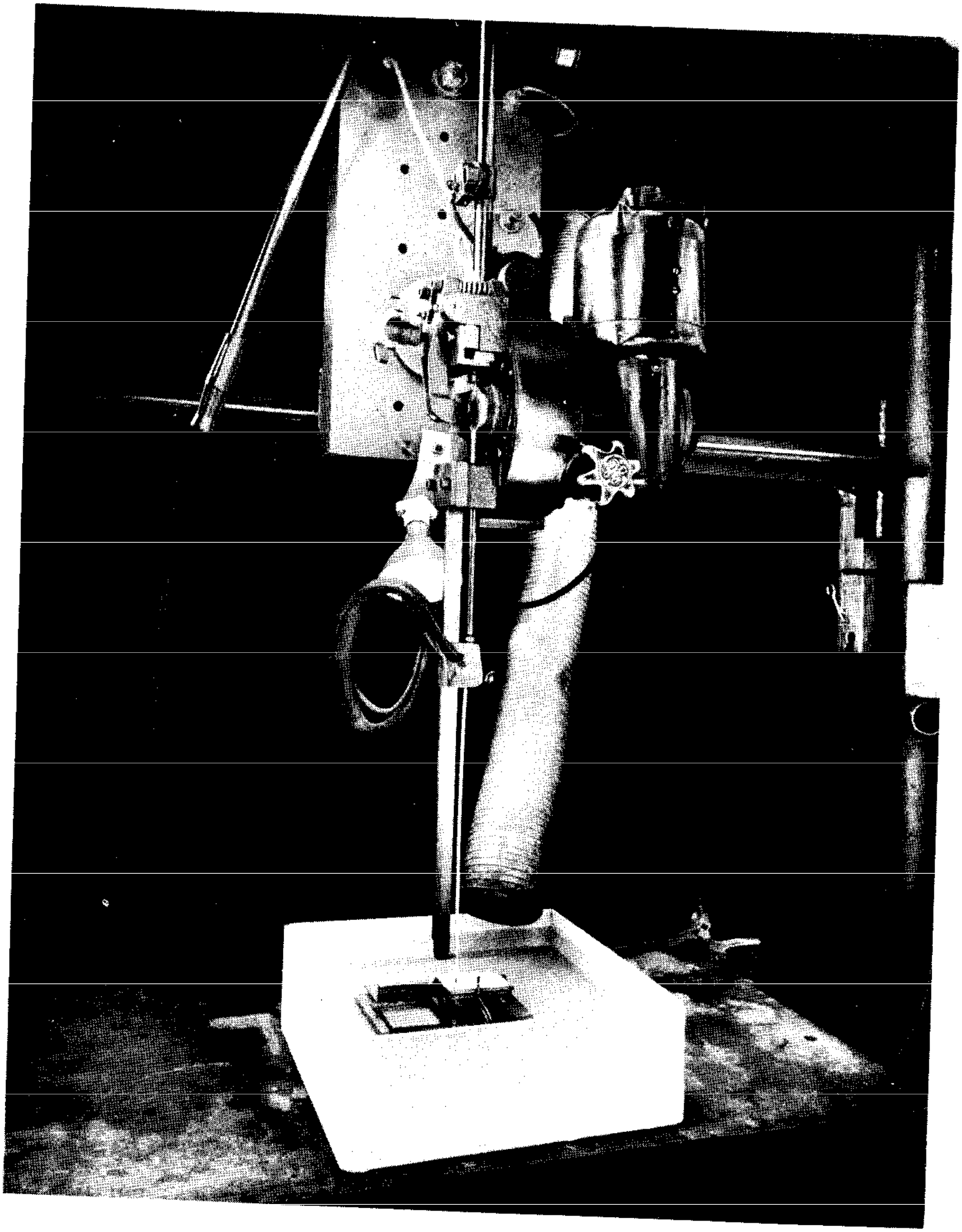

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Figure A1. Automatic Welding Bead, Jig, and Cooling Bath Used for Underbead Cracking Test.

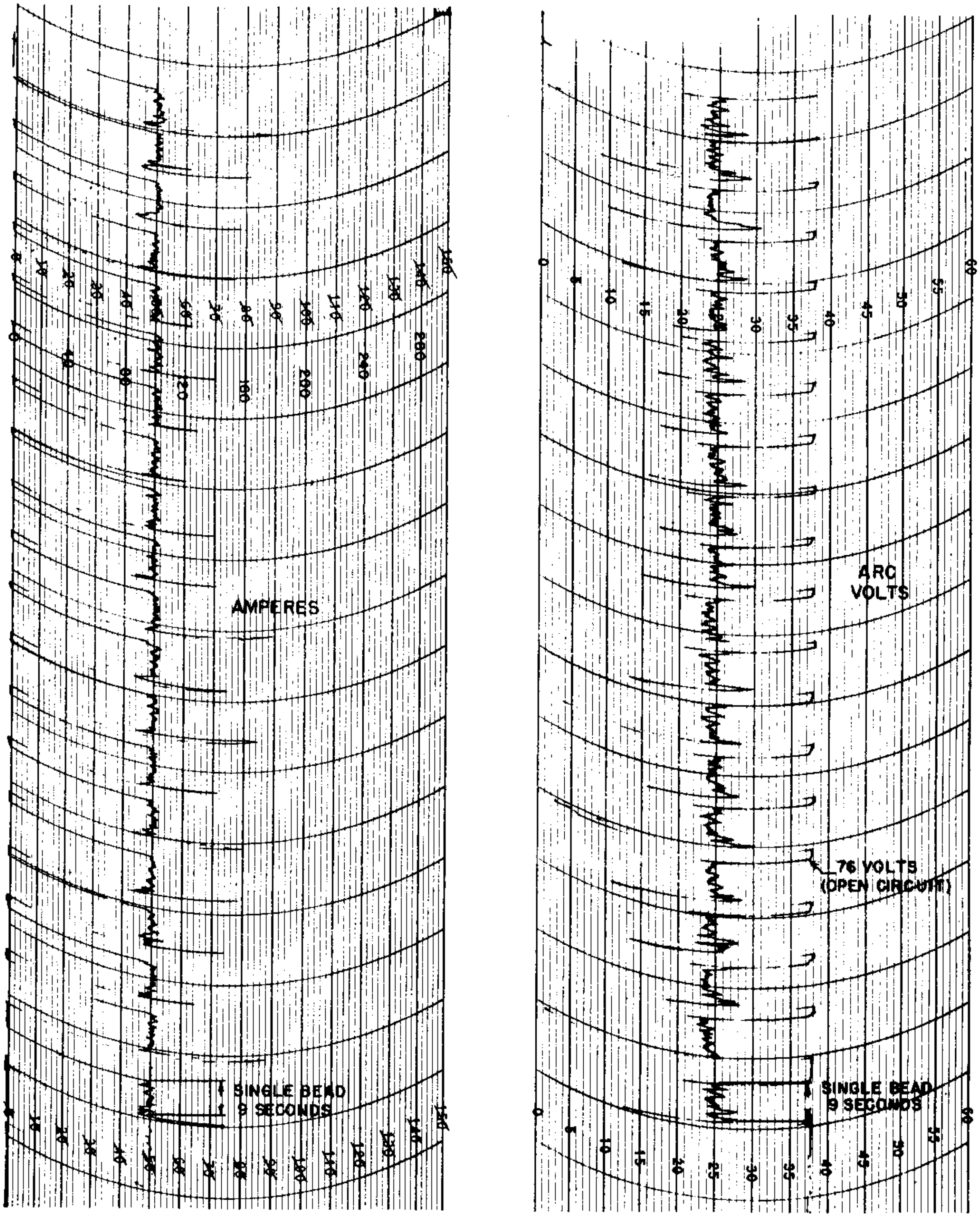

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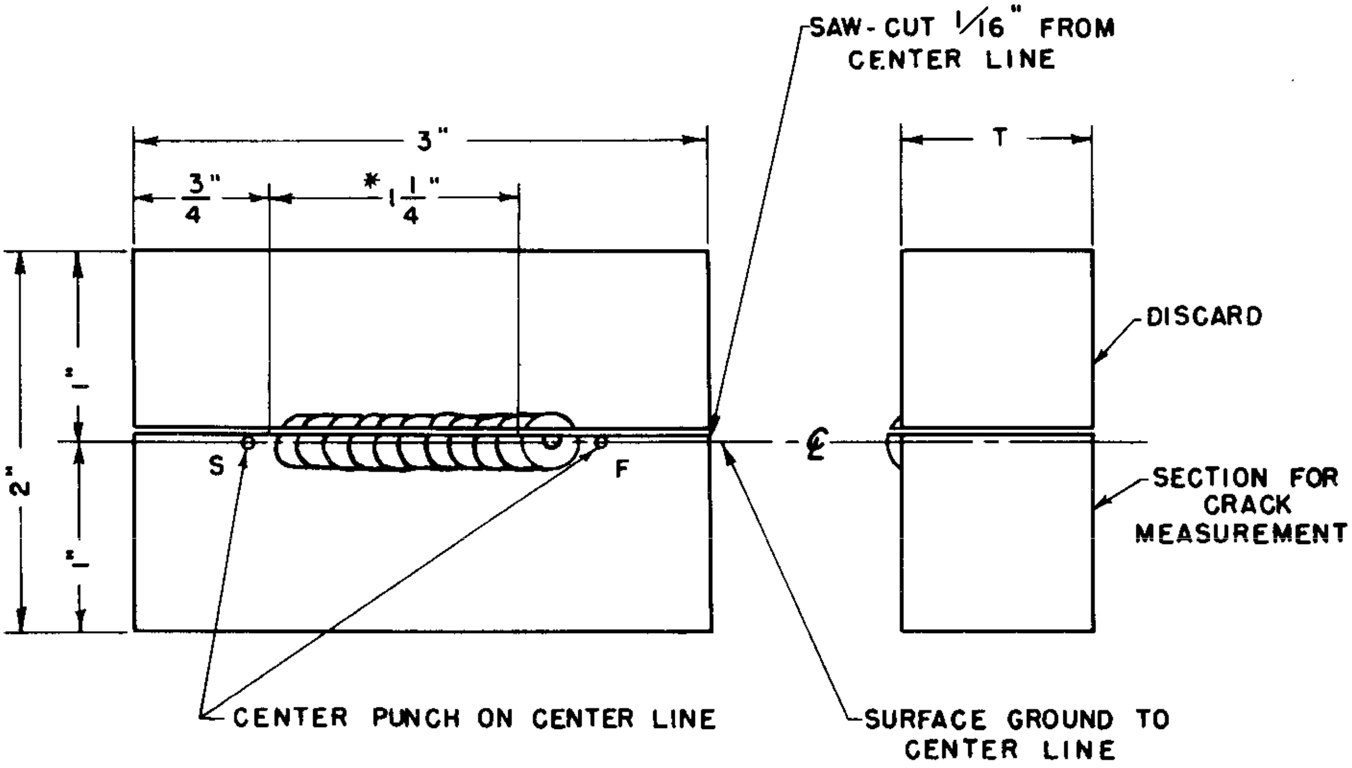
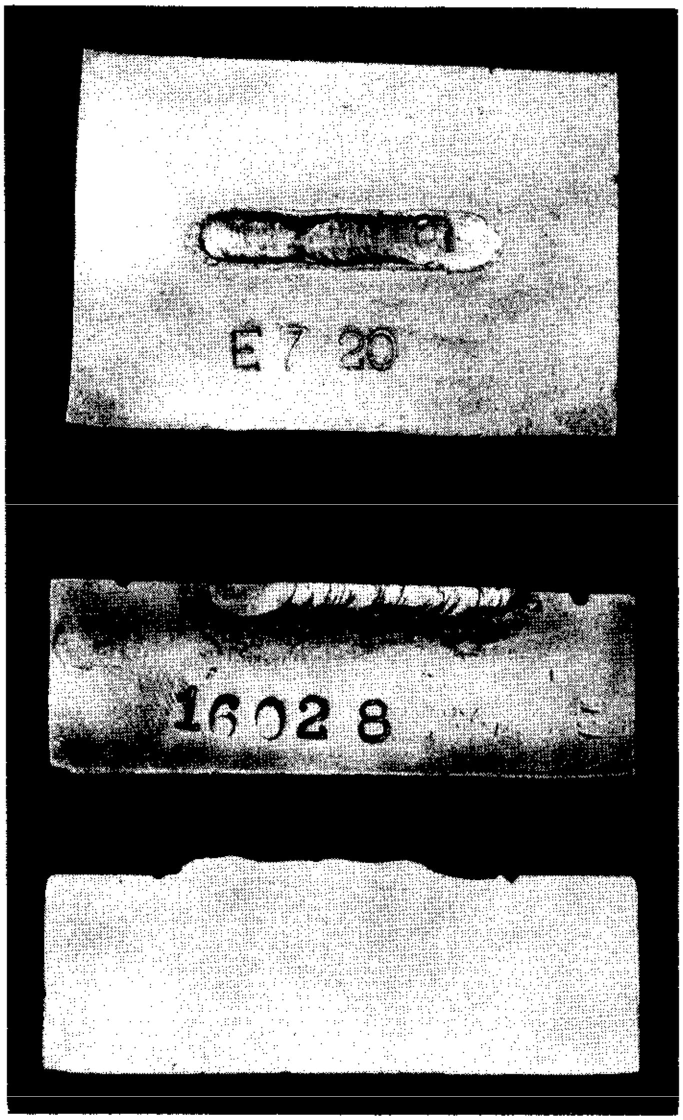
Figure A2. Typical Welding Current and Voltage Record for a Series of Crack-Sensitivity Specimens.



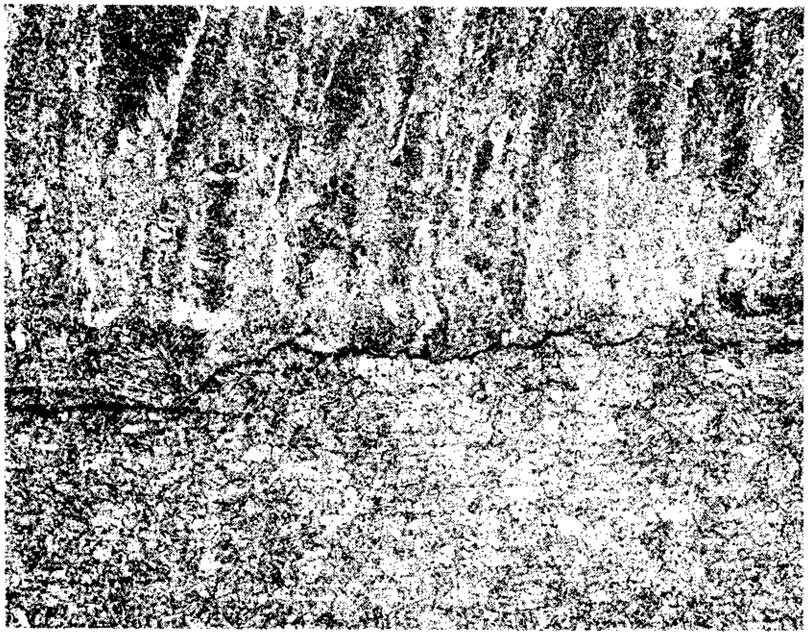
* 9.0 SEC. ARC TIME, AT 10 IN. MIN.
1/8" GE-W22 ELECTRODE, POSITIVE POLARITY,
AT 100 AMPS AND 25 ARC-VOLTS

FIGURE A3. SINGLE-BEAD WELD SPECIMEN, SHOWING LOCATION OF SECTION FOR MEASUREMENT OF UNDERBEAD CRACKING

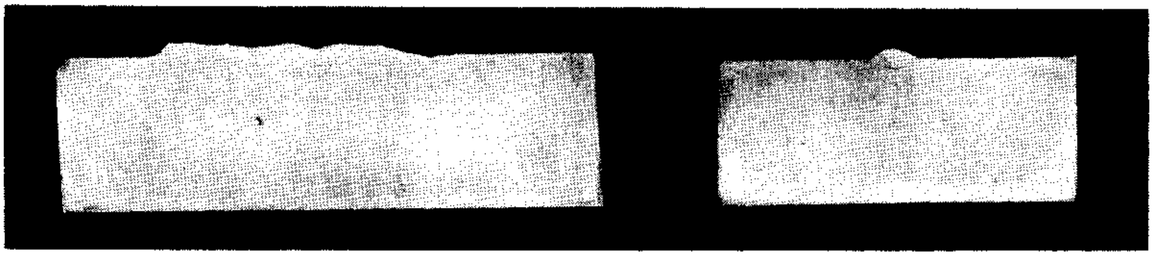


Full Size 36306

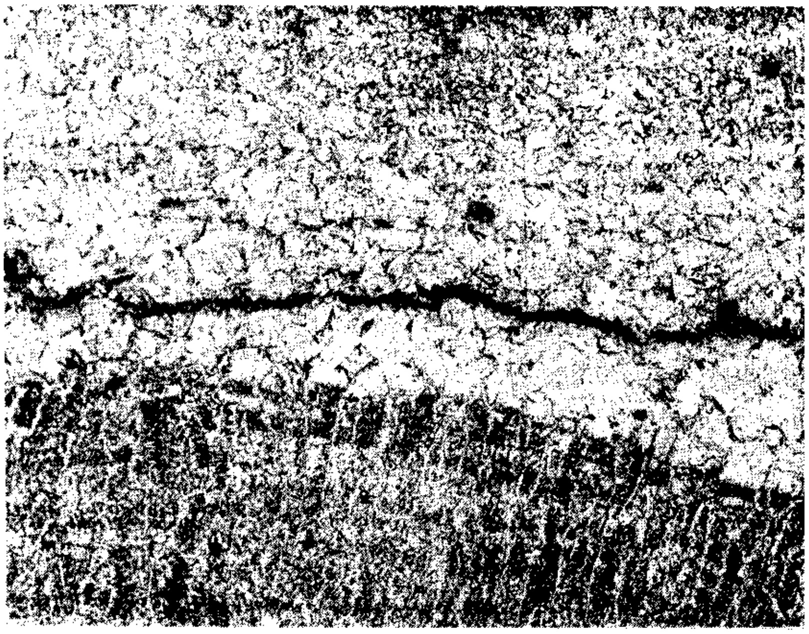
Figure A4. Single-bead weld specimen, showing typical magnaflux indications of underbead cracks on longitudinal section along center line of weld bead.



100X Longitudinal Section 36727



1X 36705



100X Transverse Section 36728

Figure A5. Typical underbead weld cracks.

magnafluxed (direct-current wet method) to bring out underbead cracks. A typical welded block and magnafluxed section are shown in Figure A4, and a photomicrograph of a typical crack is shown in Figure A5.

The magnaflux indications were transferred to record cards with adhesive transparent tape, and the length of cracks under each bead was measured, to the nearest hundredth of an inch, from the record cards.

The length of intermittent cracks was added, but when adjacent cracks overlapped, the length of overlap was counted only once.

For each set of twenty specimens, the individual per cent crack lengths were averaged to give the cracking index for the steel.

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(1) NDRC Final Report on "Investigation of Metallurgical Quality of Steels Used for Hull Construction" (NS-255), Final Report on Research Project NRC-87, October 14, 1945, OSRD No. 6075, Serial No. M-610, pages 278 to 281, inclusive.

(2) NDRC Progress Report on "Investigation of Metallurgical Quality of Steels Used for Hull Construction" (NS-255), August 24, 1945, OSRD No. 5492, Serial No. M-569, Figures 23 to 45, pages 98 to 103, inclusive.

(3) NDRC Progress Report on "Investigation of Metallurgical Quality of Steels Used for Hull Construction" (NS-255), October 14, 1945, OSRD No. 6073, Serial No. M-587, Appendix F, pages 238 to 255, inclusive.

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