SSC-25-

FINAL PROGRESS REPORT

ON

METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

BY

C. E. SIMS, H. M. BANTA and A. L. WATERS

Battelle Memorial Institute
Under Bureau of Ships Contract NObs-31219

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

NATIONAL RESEARCH COUNCIL

ADVISORY TO

SHIP STRUCTURE COMMITTEE

UNDER

Bureau of Ships, Navy Department
Contract NObs-34231

SERIAL NO. SSC-25

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DATE: MAY 10, 1949

NATIONAL RESEARCH COUNCIL
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May 10, 1949

Chief, Bureau of Ships
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Dear Sir:

Attached is Report Serial No. SSC-25 entitled "Metallurgical Quality of Steels Used for Hull Construction." This report has been submitted by the contractor as a Final Progress Report of the work done on Research Project SR-87 under Contract NObs-31219 between the Bureau of Ships, Navy Department and the 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,

C. Richard Soderberg

C. Richard Soderberg, Chairman
Division of Engineering and
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CRS:es
Enclosure

PREFACE

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals who were actively associated with the research work. 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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NAVY RESEARCH PROJECT NObs 31219

METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

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FINAL PROGRESS REPORT

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NAVY RESEARCH PROJECT NObs 31219

METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

From:
Battelle Memorial Institute

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

C. E. Sims, Supervisor

SUMMARY

Using laboratory heats, it was demonstrated that 1-inch hot-rolled plate with a yield strength of approximately 85,000 psi. and low crack sensitivity could be obtained from a 0.20 per cent carbon steel with 1.30 per cent manganese, 0.60 per cent molybdenum, and 0.18 per cent vanadium, when deoxidized with 4 pounds of aluminum per ton. The notched-bar impact strength of this steel, however, was quite low.

A study of the influence of aluminum content, 1 to 4 pounds per ton, upon the notched-bar impact properties of high yield strength, hot-rolled steels of the above chemical analysis, indicated that an addition of one pound per ton gave the best results, but the notched-bar behavior

of this was still quite poor, being about 5 to 10 foot-pounds Charpy at 0°F. The crack sensitivity of this steel, however, was quite high. These results again demonstrated that the crack sensitivity was reduced by the addition of 4 pounds of aluminum per ton.

A study of 2.5 and 3.5 per cent nickel steels proved to be inconclusive because very recent work on another project has shown that it is necessary to modify the crack-sensitivity testing procedure in order to determine the cracking characteristics of steels containing 2 to 5 per cent nickel. These steels show little or no tendency to crack when the crack-sensitivity specimens are welded at 0°F. but may crack extensively when welded at higher initial temperatures. This phase of the subject obviously requires additional investigation.

An investigation of the influence of chromium in the range of 0.25 to 1.0 per cent showed that this alloy had little, if any, influence on the crack sensitivity of hot-rolled 0.20 per cent carbon steel with 1.30 per cent manganese. Since, however, the addition of chromium did not materially increase the yield strength of the hot-rolled steel, the use of this alloy did not appear promising.

While the crack sensitivity can be reduced appreciably by homogenizing the hot-rolled plate, such a treatment would not be commercially feasible because of excessive scaling and warping of the plate. Such a treatment would be practical, however, if it could be carried out in a reasonable length of time on the slabs prior to rolling to plate. The results from slab homogenizing trials made in the mill indicated that the homogenizing time required to benefit the steel would be entirely too long for practical purposes.

A comparison of the maximum hardness of the heat-affected zone under the weldbead in hot-rolled steels, with the same steels after homogenizing, showed no difference, even though the crack sensitivity was reduced to a marked extent.

A study of fully quenched tensile and notched-bar impact specimens which were not tempered showed that the martensite developed in the HTS type of steel was not brittle but had both good ductility and impact strength, although the tensile strength was in the neighborhood of 200,000 psi. The object in view was to demonstrate that the hard martensite under the weld was not necessarily brittle and that weld cracks do not occur for this reason.

Butt-welded joints made on 1-inch quenched and tempered plate, using high-strength lime-coated electrodes, were found to be practically 100 per cent efficient. This indicates that the improved properties obtained from quenched and tempered plate may be utilized for welded structures without loss of strength at the joints.

A comparison of E 6010, E 6015, and E 6020 showed that a hot-rolled steel, which was quite crack sensitive, when welded with a high-hydrogen cellulosic-coated E 6010, could be welded without cracking when using the lime-coated E 6015 electrode, while the mineral-coated E 6020 reduced the cracking to a marked extent.

The results of crack-sensitivity tests on a sensitive quenched and tempered steel showed that this steel did not crack when welded with the lime-coated electrodes. In making these tests, 3/16-inch electrodes were used, as it was found that the 3/16-inch E 6010 electrode caused more cracking than the 1/8-inch E 6010 electrode which is normally used for this test. While these results were opposite from what might normally have been expected, they appear to be in agreement with those obtained with nickel-alloy steel and indicate the need for a study of the effect of electrode size.

The results of crack-sensitivity tests made on a group of commercial quenched and tempered steels indicated the necessity of limiting the carbon and manganese contents in order to minimize the underbead cracking.

INTRODUCTION

This is the final progress report on this project and is a continuation of the phase of the investigation discussed in the previous progress report, that is, a study of the influence of chemical composition with the object being to develop a hot-rolled steel with high yield strength and a low level of crack sensitivity that is satisfactory for welded construction.

In addition to chemical composition, the results of commercial homogenizing tests are discussed as well as the influence of electrode coatings upon underbead cracking.

In order to summarize the work of this project, a final summary report (SSC-26) covering both the results of this investigation and the preceding project on this subject which was conducted for the OSRD as Project NRC-87, will be published.

EXPERIMENTAL WORK

High Yield Strength Laboratory Heats

Preparation of Manganese-Molybdenum-Vanadium Laboratory Heats

Previous work on hot-rolled laboratory heats showed that 75,000 psi. minimum yield strength could be developed from steels with 0.13/0.15 per cent carbon, 1.25/1.30 per cent manganese, approximately 0.70 molybdenum, and 0.10 per cent vanadium which showed little or no tendencies towards underbead cracking, provided they were deoxidized with a large excess of aluminum. The notched-bar impact properties of these steels, however, were relatively low.

In order to determine if still higher yield strengths, 80,000 psi. to 85,000 psi., could be obtained together with low underbead cracking, two split heats were made in which the carbon was raised to 0.18 to 0.20 per cent, the vanadium to 0.15 to 0.18 per cent, and the molybdenum decreased from 0.70 to 0.60 in the case of one heat and to 0.37 in the second heat. In order to further investigate the influence of large additions of aluminum, these heats were split, the aluminum being omitted from the steel used for pouring the first ingot, while four pounds per ton was added prior to pouring the second ingot. Since the carbon is frequently lower in the second ingot because of oxidation in the furnace, approximately four points of carbon was added prior to pouring the second ingot in order to make up for this probable loss.

Each of these two heats were cast into two 6-5/8-inch-square hot-topped ingots and forged to 2 by 5-inch slabs. The chemical analyses of these two split heats, Heats X-51 and X-53, are shown in Table 1. It will be noted that in each case the second ingot is higher in carbon than the first ingot, because of lower loss than expected; otherwise the analyses are identical with the exception of the aluminum content. Half of the 2 by 5-inch slab from each ingot was then homogenized at 2350° for four hours. Following reheating, the slabs were hot rolled into plates slightly greater than one inch in thickness. These plates were then brought to 1900°F. and rolled to a thickness of one inch in one pass which insured a uniform finishing temperature. Following this final pass, the plates were stood on edge and allowed to cool as in normalizing.

TABLE 1. CHEMICAL ANALYSES OF HEATS X-51 AND X-52

Heat No.	Ingot No.	Chemical Composition, Per Cent							
		C	Mn	P	S	Si	Mo	V	Al*
X-51	1	0.17	1.28	.018	.026	0.31	0.37	0.15	Nil
X-51A	2	0.19	1.28	.020	.026	0.32	0.37	0.18	0.185
X-53	1	0.16	1.30	.020	.026	0.33	0.60	0.18	Nil
X-53A	2	0.20	1.33	.018	.026	0.31	0.60	0.18	0.185

* Acid-soluble aluminum contents

Tensile Properties

The tensile properties were determined from standard 0.505-inch-diameter specimens machined from the center of the test plate, duplicate specimens being prepared longitudinal with respect to the direction of rolling. Yield strengths were calculated from the stress-strain curves using the load at 0.2 per cent offset. A summary of the tensile data is given in Table 2, and the complete data will be found in Table 1 of the Appendix.

TABLE 2. LONGITUDINAL TENSILE PROPERTIES OF HOT-ROLLED AND HOMOGENIZED ONE-INCH PLATES FROM HEATS X-51 AND X-53

Heat No.	Ingot No.	Processing Method	Elong. in 2 Inches, %	Red. of Area, %	Yield * Strength, psi.	Tensile Strength, psi.
X-51		Hot rolled	23.0	61.0	68,800	99,300
X-51A	2	" "	21.5	58.0	76,500	107,800
X-53	1	Hot rolled	22.0	59.5	71,000	103,900
X-53A	2	" "	19.0	53.5	84,300	114,700
X-51	1	Homogenized+	23.0	64.0	71,300	100,500
X-51A	2	"	21.0	60.0	78,000	109,300
X-53	1	Homogenized+	20.0	55.0	77,000	107,800
X-53A	2	"	19.0	51.5	86,400	117,000

* Yield strength at 0.2 per cent offset.

\+ Homogenized steels were heated at 2350°F. for four hours in the form of 2 by 5-inch slabs, reheated, and rolled into one-inch plates.

Tensile Properties

Table 2 shows that the yield strength of the regular hot-rolled steels falls between 68,800 and 84,300 psi. and the tensile strength between 99,300 and 114,700 psi. Both the yield and tensile strength of the homogenized steel were slightly higher, the yield strength varying from 71,300 to 86,400 psi. and the tensile 100,500 to 117,000 psi. The ductility of both groups was essentially the same.

Weld Crack Sensitivity

The underbead cracking tendencies were determined from the single-bead test as described in previous reports pertaining to this project. Because of the possible effect which slight surface decarburization may have on the underbead cracking test, a groove 1/2 inch wide by 1/16 inch deep was cut in the surface of the specimen and the bead deposited in it. Other than this, there has been no change from the practice formerly used. When making the test, ten specimens from each heat were welded. Average cracking values are listed in Table 3, and the results from individual specimens appear in Table 2 of the Appendix.

As shown in Table 3, the regular hot-rolled steels with 0.17 and 0.16 per cent carbon made without aluminum, Heats X-51 and X-53, cracked 24 and 18 per cent, respectively. The aluminum-treated steel from the same heats, X-51A and X-53A, which were higher in carbon, cracked 12 and 18 per cent. Since the higher carbon would increase the cracking, these results indicate that the aluminum was effective in reducing the crack sensitivity.

TABLE 3. RESULTS OF UNDERBEAD CRACKING TESTS ON HEATS X-51 AND X-53

Heat No.	Ingot No.	Processing Method	Carbon Content, %	Aluminum Content, %	Underbead Cracking, %
X-51	1	Hot rolled	0.17	Nil	24
X-51A	2	" "	0.19	0.185	12
X-53	1	Hot rolled	0.16	Nil	18
X-53A	2	" "	0.20	0.185	18
X-51	1	Homogenized+	0.17	Nil	6
X-51A	2	"	0.19	0.185	2
X-53	1	Homogenized+	0.16	Nil	12
X-53A	2	"	0.20	0.185	5

+ Homogenized by heating the 2 by 5-inch slabs to 2350°F. for 4 hours, reheated and rolled to 1-inch plate.

It will be noted that the homogenizing treatment reduced the crack sensitivity as compared with the regular hot-rolled steel. A similar effect of aluminum was also noted in the homogenized steels as was found in the hot-rolled steels, the large addition of aluminum reducing the crack sensitivity.

Notched-Bar Impact Properties

The impact strengths were determined from standard Charpy bars with V-type notches cut perpendicular to the plate surface. All specimens were prepared from the center of one-inch-thick plates, the length being in the direction of rolling. Tests were run at each of six temperatures in the range of -75°F. to +210°F., four specimens from each heat being broken at each temperature. The data from these tests are shown graphically in Figures 1 to 4, inclusive. The notched-bar impact strength of all four of these steels was found to be relatively low at room temperatures and below. It will be noted that the addition of aluminum did increase the impact strength. (See Table 3 of Appendix for complete data.)

Study of the Effect of Aluminum Content Upon the Impact Properties of High Yield Strength Steels

In an attempt to improve the impact properties of the hot-rolled high yield strength steels, 80,000 to 85,000 psi., which were alloyed with a combination of manganese, molybdenum, and vanadium, three split heats were made and deoxidized with one, two, and three pounds of aluminum per ton prior to pouring the ingots. A fourth split heat was made with the aluminum being omitted from the steel poured into the first

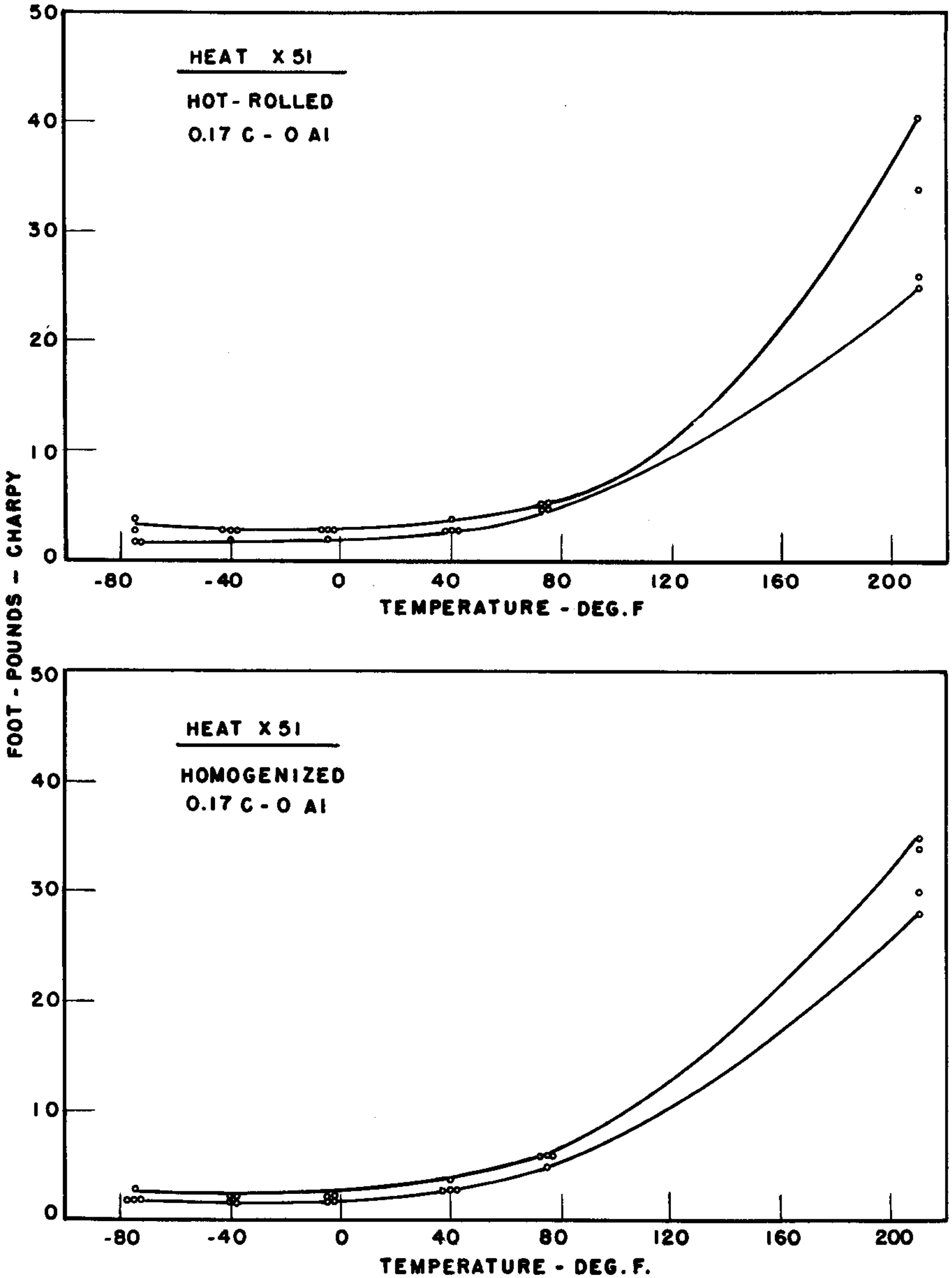

FIGURE 1. NOTCHED-BAR IMPACT PROPERTIES OF STEELS MADE WITHOUT ALUMINUM.

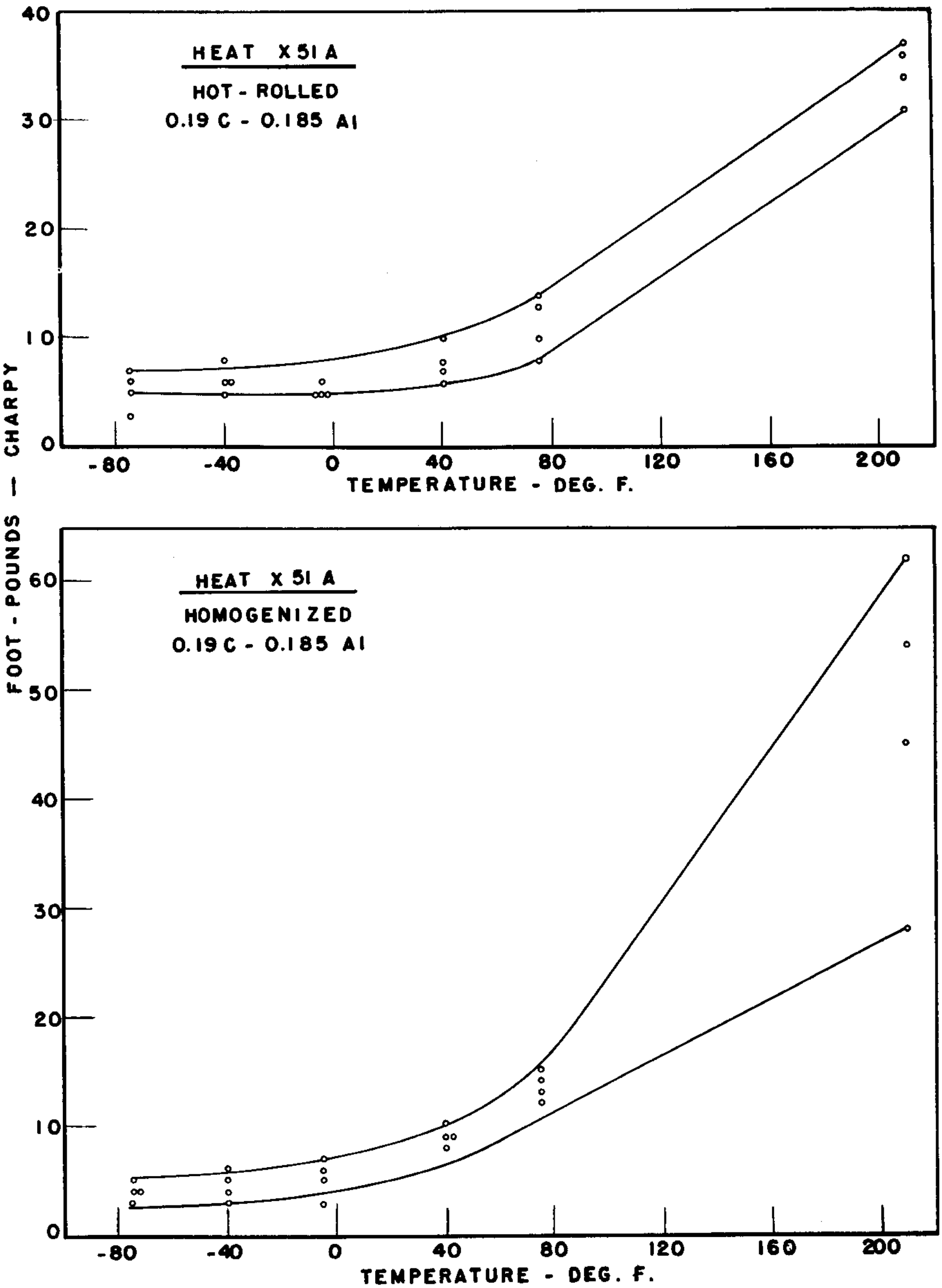

FIGURE 2. NOTCHED-BAR IMPACT PROPERTIES OF HIGH-ALUMINUM STEELS.

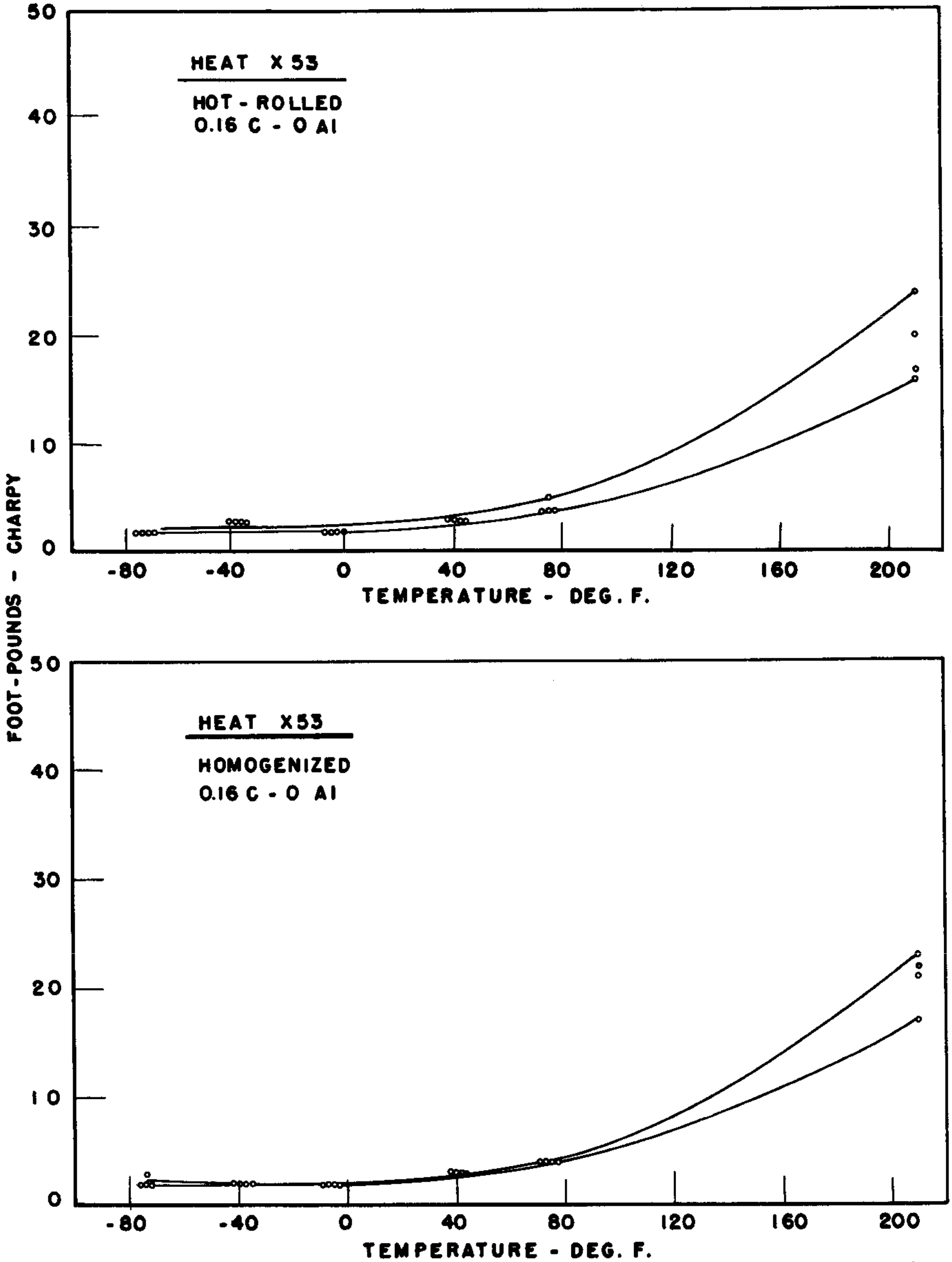

FIGURE 3. NOTCHED-BAR IMPACT PROPERTIES OF STEELS MADE WITHOUT ALUMINUM.

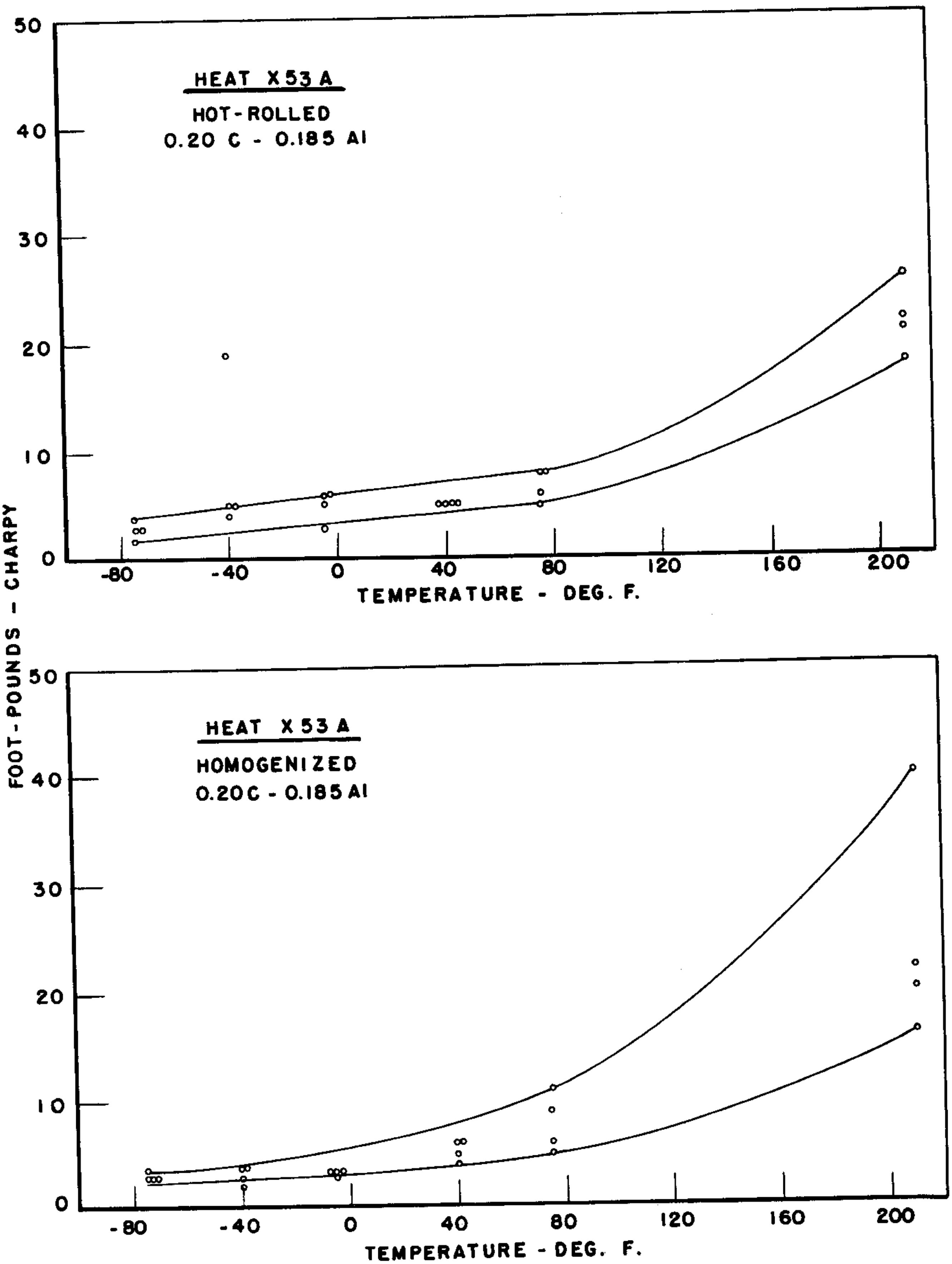

FIGURE 4. NOTCHED-BAR IMPACT PROPERTIES OF HIGH-ALUMINUM STEELS.

ingot, while the steel used for the second ingot was deoxidized with four pounds of aluminum per ton in order to further investigate the effect of aluminum upon underbead cracking. Aside from these differences in aluminum, each heat was made to contain approximately 0.21 per cent carbon, 1.35 per cent manganese, 0.50 per cent molybdenum, and 0.22 per cent vanadium.

The heats were cast and processed in the manner previously described.

The chemical analyses of these heats, X-55 to X-58, inclusive, are listed in Table 4. It will be noted that the chemical analyses of these heats are quite similar with the exception of the aluminum content which was purposely varied.

TABLE 4. CHEMICAL ANALYSES OF HEATS X-55 TO X-58, INCLUSIVE

Heat No.	Ingot No.	Chemical Composition, Per Cent								Lb. Al/ton
		C	Mn	P	S	Si	Mo	V	Al*	
X-55	1	0.21	1.35	.015	.024	0.32	0.50	0.21	Nil	0
X-55A	2	0.20	1.35	.015	.025	0.33	0.52	0.21	0.130	4
X-56	1	0.21	1.35	.019	.027	0.27	0.51	0.22	0.020	1
X-56A	2	0.22	1.35	.021	.028	0.28	0.51	0.23	0.070	2
X-57	1	0.21	1.35	.018	.031	0.28	0.52	0.23	0.015	1
X-57A	2	0.22	1.33	.020	.033	0.28	0.51	0.23	0.105	3
X-58	1	0.20	1.34	.019	.028	0.27	0.52	0.23	0.070	2
X-58A	2	0.21	1.35	.022	.030	0.30	0.51	0.23	0.105	3

* Acid-soluble aluminum content

Tensile Properties

The tensile properties were determined from standard 0.505-inch-diameter specimens machined from the center of the test plate, duplicate specimens being prepared longitudinal to the direction of rolling. The yield strengths were determined from the stress-strain curve using the load at 0.2 per cent offset.

The results of the tensile tests from Heats X-55 to X-58, inclusive, in the hot-rolled condition, and for Heats X-56 to X-58, inclusive, after tempering at 1000°F. for one hour and cooling in air, are listed in Table 5. The complete data are listed in Table 1 of the Appendix.

From Table 5, it will be seen that the yield strengths of the hot-rolled plates were 84,000 to 88,400 psi. and the tensile strengths 111,500 to 120,300 psi. The elongation varied from 16 to 20 per cent in two inches and reduction in area from 40.5 to 59 per cent. There appeared to be little, if any, relationship between aluminum content and tensile properties.

Tempering these steels at 1000°F. raised the yield strength to 90,800 to 93,300 psi. but had practically no effect upon the tensile strengths. The per cent elongation was 19 to 20 per cent and the reduction of area 52.5 to 58 per cent.

Underbead Crack Sensitivity

The underbead cracking characteristics for Heats X-55 to X-58, inclusive, in the hot-rolled condition, were determined from the single-

TABLE 5. LONGITUDINAL TENSILE PROPERTIES OF HOT-ROLLED AND TEMPERED ONE-INCH PLATES FROM HEATS X-55 TO X-58, INCLUSIVE

Heat No.	Ingot No.	Processing Method	Elong. in 2 Inches, %	Red. of Area, %	Yield Strength, * psi.	Tensile Strength, psi.
X-55	1	Hot rolled	18.0	54.0	86,500	118,900
X-55A	2	" "	19.0	51.5	88,400	120,300
X-56	1	Hot rolled	19.5	59.0	84,000	112,300
X-56A	2	" "	20.0	58.0	86,500	116,300
X-57	1	Hot rolled	19.0	57.0	84,100	114,400
X-57A	2	" "	16.0	40.5	87,300	115,800
X-58	1	Hot rolled	17.0	43.5	84,300	111,500
X-58A	2	" "	19.0	56.0	87,800	117,400
X-56	1	Tempered 1 hr.	20.0	58.0	93,300	113,700
X-56A	2	at 1000°F., air cooled	19.0	54.5	91,300	116,600
X-57	1	Ditto	20.0	56.0	90,800	115,200
X-57A	2	"	19.0	52.5	91,300	116,800
X-58	1	"	19.0	55.5	92,500	116,100
X-58A	2	"	19.0	54.0	92,300	116,700

* Yield strengths were calculated from the stress-strain curve using the load at 0.2 per cent offset.

bead test, ten specimens from each steel being welded using the standard procedure. A summary of the cracking data will be found in Table 6, and the complete data are listed in Table 2 of the Appendix.

As observed from Table 6, the extent of underbead cracking for the steels treated with 0 to 3 pounds of aluminum per ton, 0 to 0.105 per cent acid-soluble aluminum contents, was 52 to 75 per cent as compared to 29 per cent when four pounds of aluminum per ton were added.

TABLE 6. RESULTS OF UNDERBEAD WELD-CRACKING TESTS FROM HEATS X-55 TO X-58, INCLUSIVE, IN THE HOT-ROLLED CONDITION

Heat No.	Ingot No.	Carbon Content, %	Aluminum* Content, %	Aluminum Added in lbs./Ton	Underbead Cracking, %
X-55	1	0.21	Nil	0	66
X-56	1	0.21	.020	1	56
X-57	1	0.21	.015	1	73
X-56A	2	0.22	.070	2	55
X-58	1	0.20	.070	2	52
X-57A	2	0.22	.105	3	75
X-58A	2	0.21	.105	3	61
X-55A	2	0.20	.185	4	29

* Acid-soluble aluminum content

This, and data shown previously, indicates that the cracking drops sharply when the acid-soluble aluminum content is increased to somewhere above 0.105 per cent.

Notched-Bar Impact Properties

The impact properties of Heats X-56 to X-58, inclusive, were determined from standard Charpy bars with V-type notches cut perpendicular to the surface of the plate. All specimens were prepared from the center of one-inch hot-rolled plates, the length of the specimens being in the direction of rolling. These steels were tested at six temperatures in the range -75°F. to +210°F., four specimens from each heat being broken at each temperature.

The notched-bar properties are shown graphically in Figures 5 to 7, inclusive, and the data from which the curves were drawn are listed in Table 3 of the Appendix.

The impact strength of these steels, as shown by Figures 5, 6, and 7, were low when tested at room temperature and below. The steels deoxidized with one pound of aluminum per ton were, however, somewhat superior in this respect to those treated with two and three pounds of aluminum per ton.

Study of Laboratory Heats Containing Manganese, Molybdenum, Vanadium, Nickel, and Copper

In order to determine the advantages that might be obtained by the use of 2.5 or 3.5 per cent nickel in addition to molybdenum and vanadium, three laboratory heats were made of the analysis shown in Table 7. In addition to the above alloys, 0.65 per cent copper was added to the fourth heat in order to further increase the yield strength, by precipitation hardening.

Since carbon and manganese are especially detrimental with respect to underbead cracking, the carbon and manganese in these heats were limited to 0.18 and 1.00 per cent, respectively.

Each heat was deoxidized with two pounds of aluminum per ton, this addition being considered the most desirable from the standpoint of impact properties. All heats were 225-pound induction-furnace melts and were cast into 6-5/8-inch-square ingots.

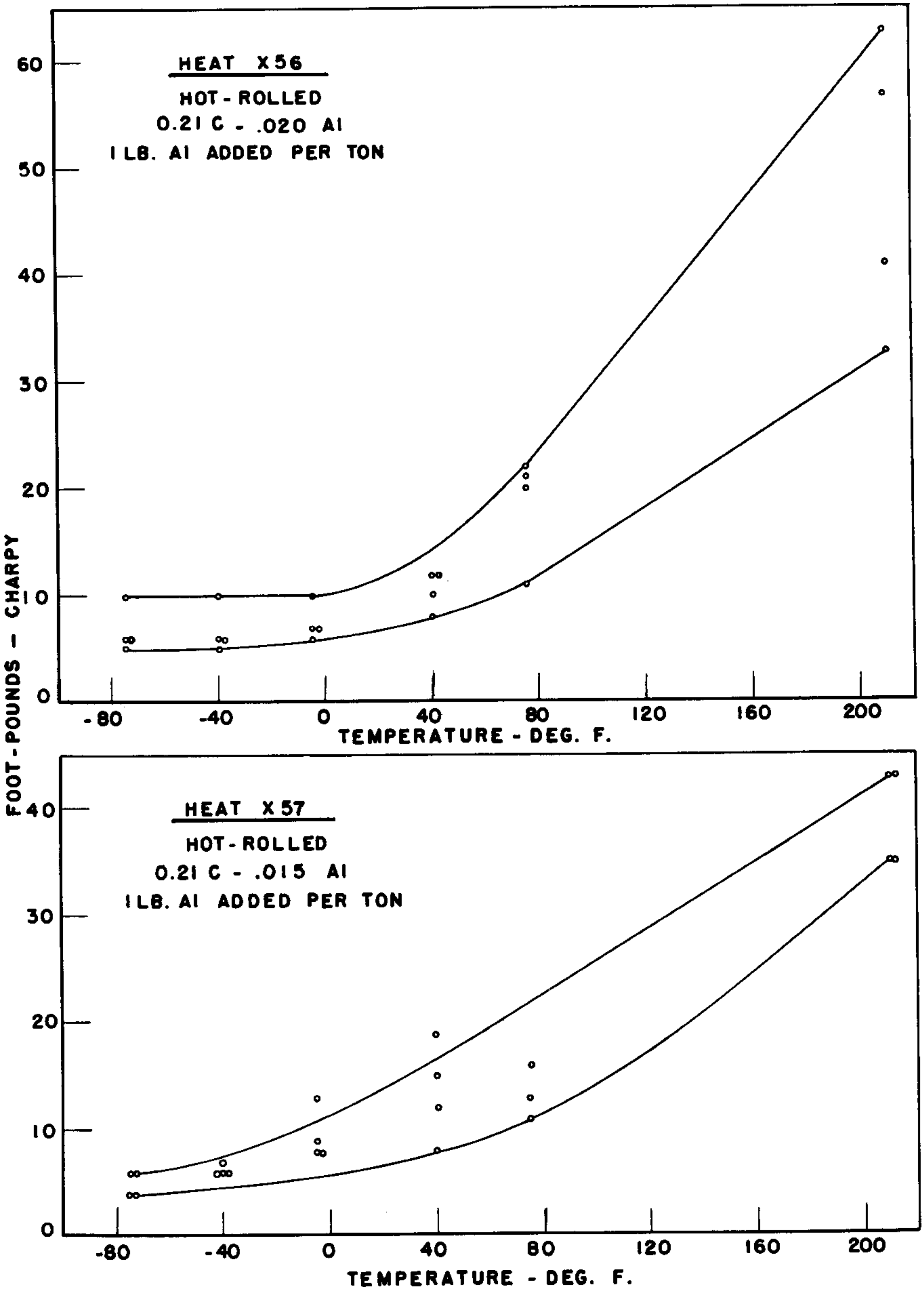

FIGURE 5 . NOTCHED-BAR IMPACT PROPERTIES
OF STEELS MADE WITH 1 LB. ALUMINUM PER TON.

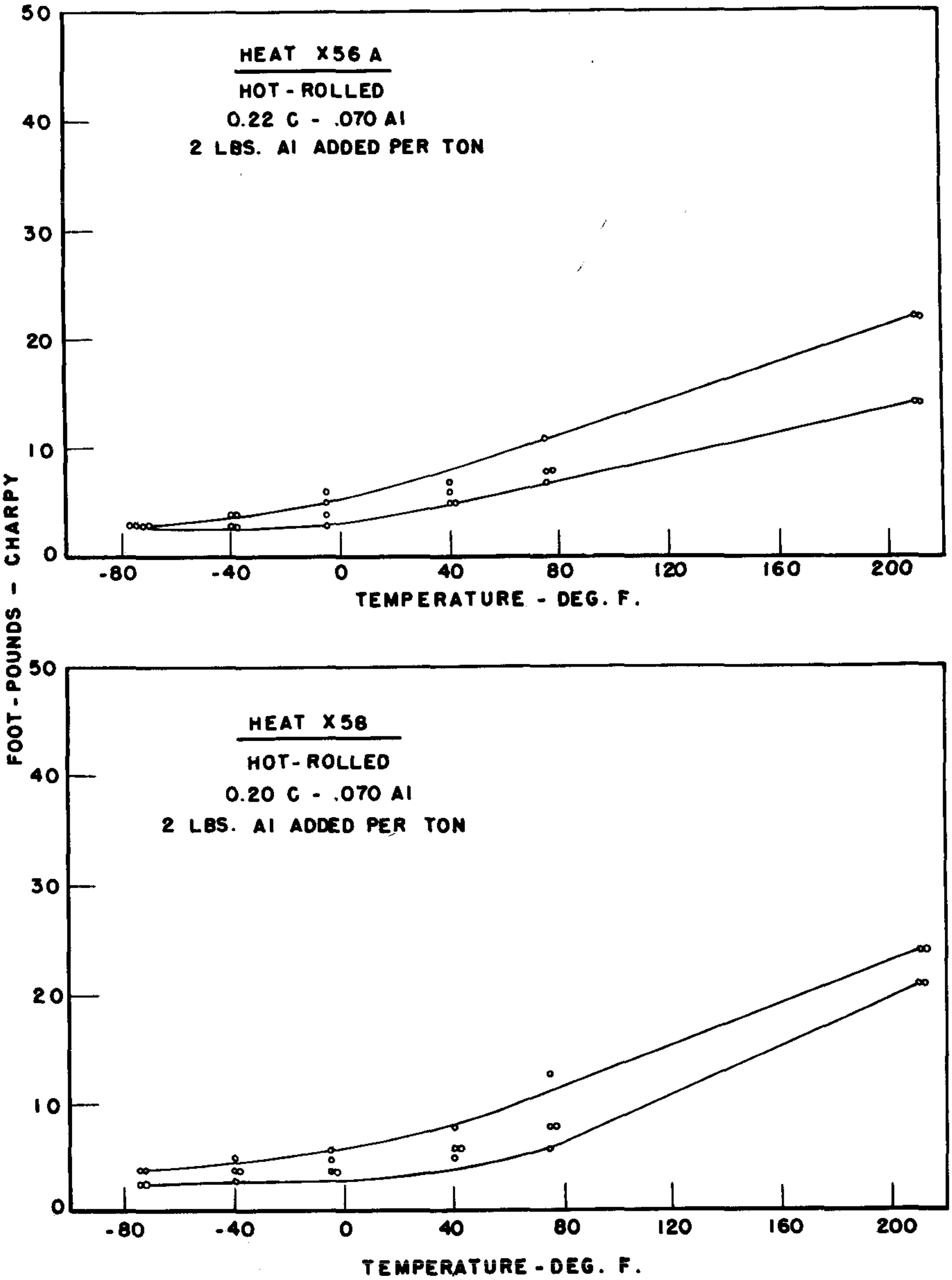

FIGURE 6. NOTCHED-BAR IMPACT PROPERTIES OF STEELS MADE WITH 2 LBS. ALUMINUM PER TON.

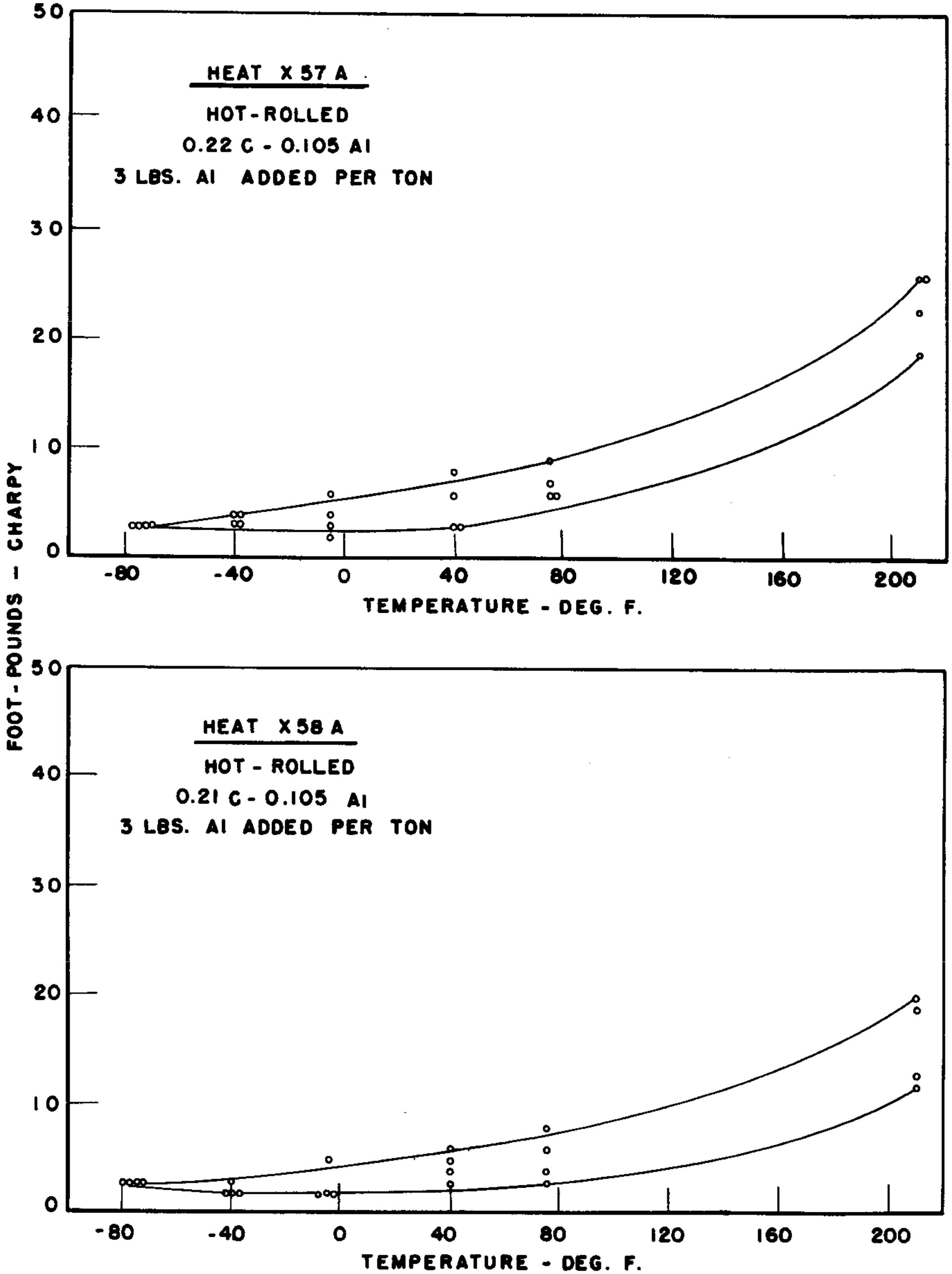

FIGURE 7. NOTCHED-BAR IMPACT PROPERTIES OF STEELS MADE WITH 3 LBS. ALUMINUM PER TON.

TABLE 7. CHEMICAL ANALYSES OF LABORATORY HEATS CONTAINING NICKEL

Heat No.	Chemical Composition, Per Cent									
	C	Mn	P	S	Si	Mo	V	Ni	Cu	Al*
X-63	0.18	1.03	.027	.026	0.26	0.37	-	3.34	-	.075
X-64	0.18	1.03	.021	.031	0.24	-	0.22	3.46	-	.065
X-65	0.17	1.02	.021	.027	0.23	0.31	0.15	2.56	-	.075
X-66	0.17	1.02	.025	.027	0.25	0.34	0.16	2.59	0.65	.075

* Acid-soluble aluminum content

In processing these steels, the same procedure as described earlier was followed, that is, the ingots were forged from 2300°F. into 2 by 5-inch slabs, reheated and rolled into plates slightly over one inch in thickness. The final operation then consisted of adjusting the plates to 1900°F., rolling to one inch in one pass and standing the plates on edge to cool. The finishing temperature was approximately 1850°F. in all cases.

Tensile Properties

The tensile properties of these heats in the hot-rolled, normalized, and normalized and tempered conditions were determined from threaded-end standard 0.505-inch-diameter test bars, duplicate specimens being machined from the center of the plate and longitudinal to the direction of rolling. Yield strengths were taken from the stress-strain curve using the load at 0.2 per cent offset. A summary of the tensile results is given in Table 8, and the data for the individual specimens are listed in Table 4 of the Appendix.

TABLE 8. TENSILE PROPERTIES OF LABORATORY HEATS X-63 TO X-66 IN VARIOUS HEAT-TREATED CONDITIONS

Heat No.	Condition**	Elong. in 2 Inches, %	Red. of Area, %	Yield* Strength, psi.	Tensile Strength, psi.
X-63	A	20.0	42.0	74,000	115,100
"	B	20.0	55.5	84,000	126,100
"	C	24.0	61.0	79,800	107,500
X-64	A	20.5	45.0	78,900	116,200
"	B	21.5	52.0	82,000	128,500
"	C	21.0	59.0	109,800	130,800
X-65	A	21.5	54.5	79,300	108,400
"	B	21.5	59.0	78,000	119,800
"	C	21.5	60.5	103,300	125,300
X-66	A	17.0	33.5	83,600	119,300
"	B	20.0	49.5	92,500	136,300
"	C	20.0	55.5	115,300	136,300
"	D	20.0	54.0	111,400	136.900
"	E	19.0	50.5	96,000	132,700

* Yield strength at 0.2 per cent offset.

** Condition:

A. Hot rolled
B. Normalized 1650°F.
C. Normalized 1650°F., tempered one hour 1200°F., air cooled.
D. Same as "C", except tempered at 1100°F.
E. Same as "C", except tempered at 1000°F.

Hot-Rolled Properties

Table 8 shows that the yield strengths of the hot-rolled plate from Heats X-63, X-64, and X-65 ranged from approximately 74,000 to 79,000 psi. with the copper-bearing Heat X-66 being slightly higher, 83,600 psi. The tensile strength of all four steels were well over 100,000 psi., ranging from about 108,000 to 119,000 psi. The ductilities of the first three heats were quite similar as indicated by the elongation in 2 inches, while that of the copper-bearing steel, Heat X-66, was slightly lower.

Effect of Normalizing at 1650°F.

Normalizing increased the yield strength of both the 3.5 per cent nickel steels, the increase in the molybdenum-bearing steel, Heat X-63, being 10,000 psi. as compared to about 3000 psi. for the vanadium-bearing steel, Heat X-64.

The yield strength for the 2.5 per cent nickel steel, Heat X-65, containing molybdenum, vanadium, and no copper, was practically unaffected by normalizing, while the companion steel with 0.65 per cent copper showed an increase in yield strength of 9000 psi.

The tensile strengths of the three hot-rolled steels without copper were increased approximately 10,000 psi. as the result of normalizing, whereas, the strength of the copper-bearing heat was increased 17,000 psi.

Normalizing had practically no influence upon the ductility, as shown by per cent elongation, of the three heats without copper, but increased the reduction of area appreciably. Both elongation and reduction in area of the copper-bearing heat were improved by this treatment.

Effect of Tempering

The tensile properties of each of the four nickel-bearing steels were determined after normalizing at 1650°F., and tempering for one hour at 1200°F. and air cooling. As observed from Table 8, this treatment decreased the yield strength of the 3.5 per cent nickel steel containing molybdenum and no vanadium, Heat X-63, by about 4000 psi. as compared to the strength after normalizing, while the yield strength of the companion heat, Heat X-64, which contained vanadium, was increased approximately 28,000 psi. as a result of the tempering treatment.

Yield strength of Heats X-65 and X-66 was increased approximately 23,000 psi. by the tempering treatment. Tempering steel from Heat X-66 at temperatures of 1000°F. and 1100°F. for 1 hour resulted in less gain in yield strength than was obtained from the 1200°F. tempering treatment.

The tensile strength of the 3.5 per cent nickel heat with molybdenum and no vanadium, Heat X-63, was decreased from 126,100 to 107,500 psi. by the tempering treatment, while the strength of the remaining three heats was either unaffected or increased slightly.

The ductility, as indicated by the reduction in area, was increased slightly in most cases by the tempering treatment. The complete tensile data for these steels will be found in Table 4 of the Appendix.

Weld Crack Sensitivity

The underbead cracking tendencies were determined from the single-bead tests as described previously. Ten grooved specimens were welded from each steel in the various heat-treated conditions with the exception of the tests on the normalized, and normalized and tempered steel from Heat X-66, and the tests welded at 75°F. and 120°F. which were made with five specimens because of insufficient steel.

Table 9 shows low underbead cracking tendencies for each of the steels in the hot-rolled condition when welded at 0°F., the highest

TABLE 9. RESULTS OF UNDERBEAD CRACKING TESTS FROM HEATS X-63 TO X-66 FOLLOWING VARIOUS HEAT TREATMENTS

Heat No.	Chemical Analyses, Per Cent						Condi-tion*	Per Cent Cracking** When Welded at		
	C	Mn	Ni	Mo	V	Cu		0°F.	+75°F.	+120°F.
X-63	0.18	1.03	3.45	0.37	-	-	A	5	7	9
"	"	"	"	"	-	-	B	0	-	-
X-64	0.18	1.03	3.46	-	0.22	-	A	24	-	-
"	"	"	"	-	"	-	C	1	-	-
X-65	0.17	1.02	2.56	0.31	0.15	-	A	14	19	17
"	"	"	"	"	"	-	C	0	-	-
X-66	0.17	1.02	2.59	0.34	0.16	0.65	A	9	-	-
"	"	"	"	"	"	"	B	8	-	-
"	"	"	"	"	"	"	C	13	-	-

* Condition: A. Hot rolled
B. Normalized 1650°F.
C. Normalized 1650°F. then tempered for one hour at 1200°F.; air cooled from tempering temperature.

** Specimens welded in carbon tetrachloride bath at 0°F. A water bath was used to maintain specimen temperatures of +75° and +120°F. at start of welding.

cracking being 24 per cent for Heat X-64. Normalizing or normalizing and tempering reduced the cracking in the specimens from Heats X-63, X-64, and X-65 to almost zero, but had practically no effect on the steel containing copper, Heat X-66. (See Table 5 of Appendix.)

Since this work was started, however, it was found, as the result of work on another project, that the higher alloy steels behave in a much different manner than the HTS steel, or similar steels containing small alloy addition, when subjected to the crack-sensitivity test. The effect of initial specimen temperature was found to be quite pronounced and different from that generally expected. Early in this project, it was shown that increasing the initial preheat temperature from 0°F. to 120°F. resulted in a slight increase in the extent of cracking in HTS steels. This trend was found to be much more pronounced in the higher alloy steels that have been investigated than in the HTS steels. For example, a steel which showed no evidence of cracking when welded at 0°F. cracked in excess of 30 per cent when welded at 180°F., while cracking was practically eliminated by further increasing the initial specimen temperature to 200°F. Therefore, after completing the tests at 0°F., a limited number of weld tests were made using initial temperatures of 75°F. and 120°F., the specimens being held in a water bath maintained at the above temperatures. Because of the lack of additional steel, this work was limited and only five specimens were welded from Heats X-63 and X-65 at these temperatures. The average of these tests is shown in Table 9.

The results of these few tests indicate that the cracking in the hot-rolled steel from Heats X-63 and X-65 is not materially changed by increasing the initial temperature. Because of the small number of tests and the limited temperature range covered, no definite conclusions can be made concerning the crack sensitivity of these steels. Before the crack sensitivity of alloy steels can be accurately determined, it appears that considerable research must be conducted.

Notched-Bar Impact Properties

The impact properties of this series of heats were determined from standard-size Charpy bars cut from the center of one-inch-thick plates and notched perpendicular to the plate surface, the length of the specimens being in the direction of rolling.

In order to be consistent with the practice followed in the past, V-type notches were used, although, at the testing temperature of -40°F., both keyhole and V-type notch specimens were used.

The noncopper-bearing hot-rolled steels from Heats X-63, X-64, and X-65 were tested at six temperatures within the range of -75°F. to +210°F., whereas, copper-bearing Heat X-66 was tested at -40°F., -5°F., and +75°F., only. Four specimens from each steel were broken at each temperature.

Specimens were also prepared from normalized and normalized and tempered plates and the impact strengths at -40°F. compared with those of the same steels in the hot-rolled condition. The particular heat treatment selected was one of the two just mentioned which developed the higher yield strength in the steel.

The impact properties are shown in Figures 8, 9, and 10, and the results from individual specimens are listed in Table 6 of the Appendix.

Hot-Rolled Notched-Bar Properties

Figures 8 and 9 show relatively low impact strength at +40°F. and below for Heats X-63, X-64, and X-65 in the hot-rolled condition, the values at -40°F. being comparable for either type of notch used. At temperatures above +40°F., the impact values rose sharply, the increase being most pronounced in the molybdenum-bearing Heats X-63 and X-65. The highest strength at +210°F. was attained by Heat X-65, which contains 2.5 per cent nickel.

The impact characteristics of Heat X-66, which contained 0.65 per cent copper, compared favorably with those of the other three heats

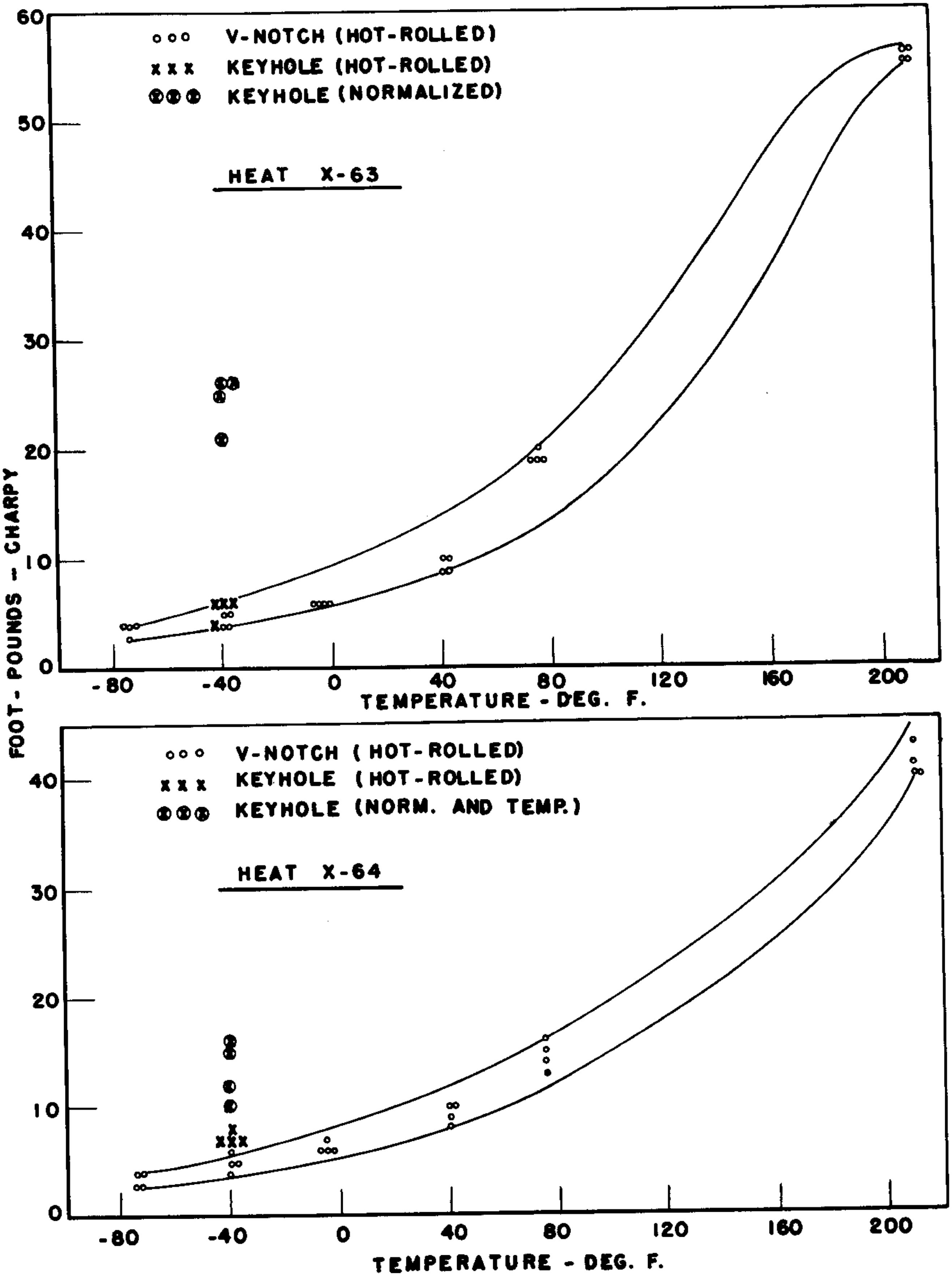

FIGURE 8. NOTCHED-BAR IMPACT PROPERTIES OF 3 ½ % NICKEL STEELS.

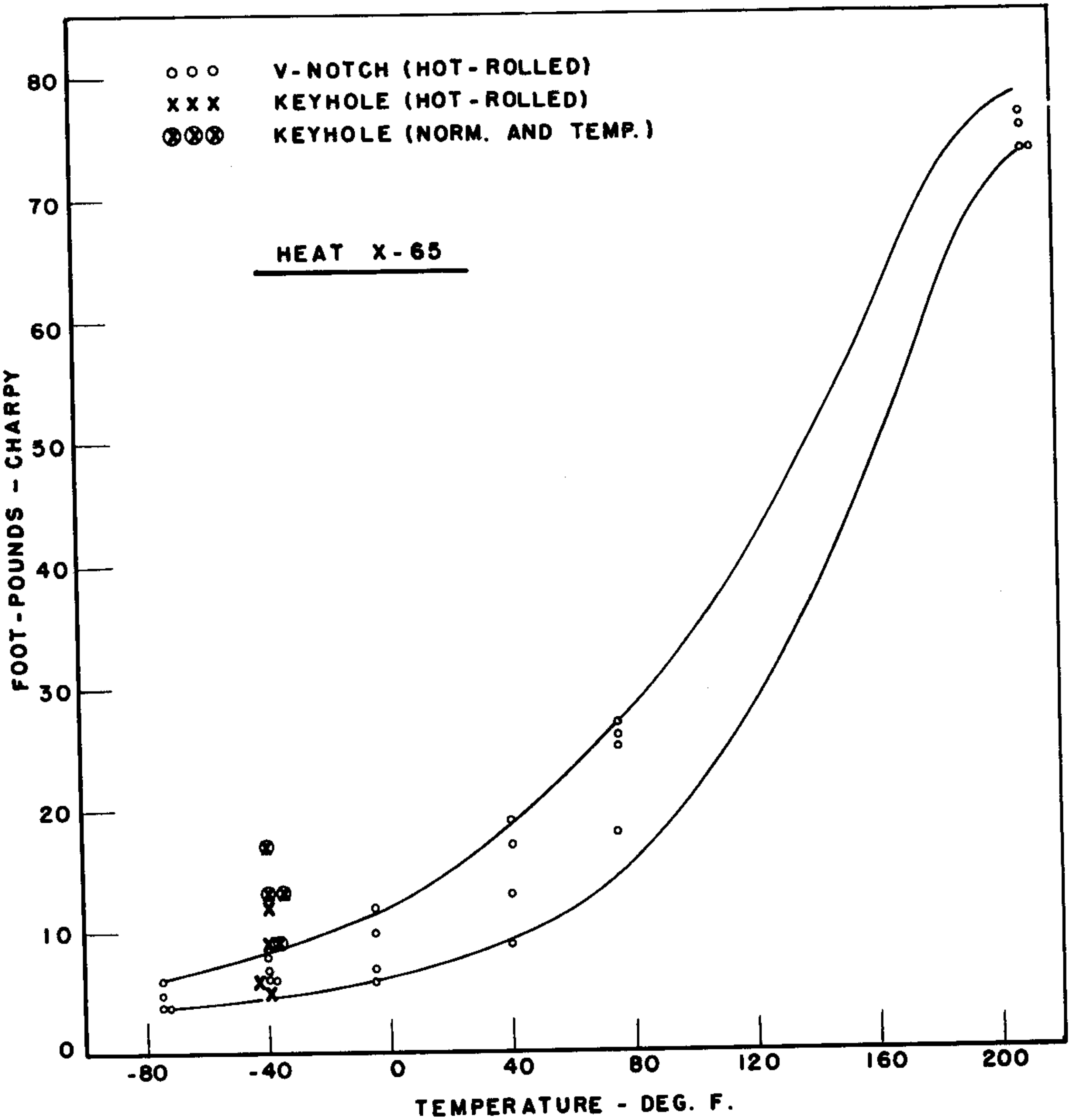

FIGURE 9 . NOTCHED-BAR IMPACT PROPERTIES OF A 2 ½ % NICKEL STEEL.

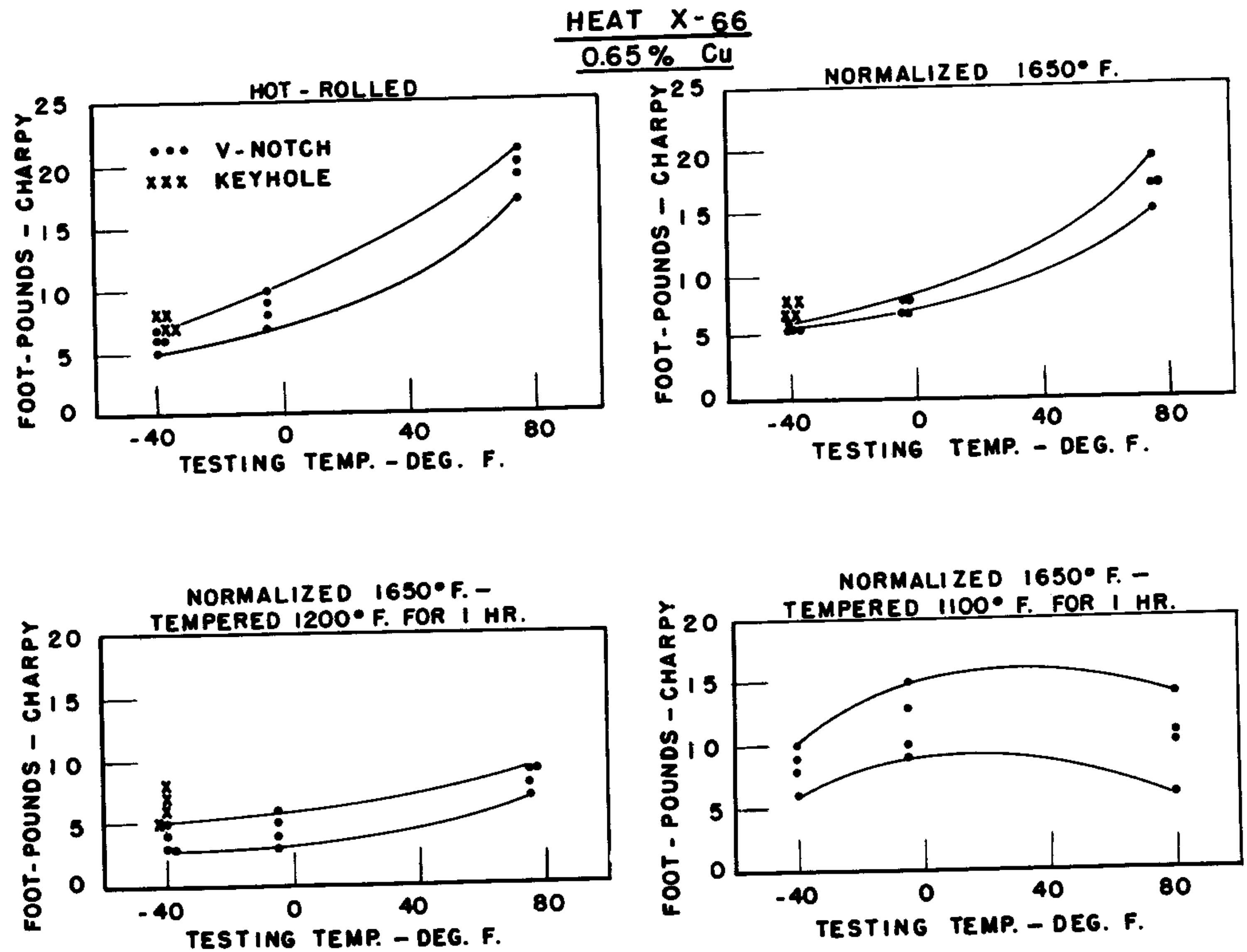

FIGURE 10. NOTCHED-BAR IMPACT PROPERTIES OF A 2 ½ % NICKEL STEEL FOLLOWING VARIOUS HEAT TREATMENTS.

when tested at temperatures -40°F., -5°F., and +75°F.

Effect of Normalizing

Normalizing improved the notched-bar properties of Heat X-63 to a marked extent when tested at -40°, the values from keyhole type specimens being 21 to 26 and 4 to 6 foot-pounds for the normalized and hot-rolled steels, respectively. The only other steel of the series tested after normalizing was Heat X-66, the impact strengths at -5°F. and -40°F. being quite low in both the hot-rolled and normalized conditions. Also, practically no difference was observed in the values obtained from either of the two types of specimens.

Effect of Normalizing and Tempering

Figures 8 and 9 show a slight improvement in a keyhole Charpy strength of Heats X-64, X-65, after normalizing followed by tempering. A comparison of V-notch properties of Heat X-66 shows that the best low-temperature notch resistance is developed by tempering at 1100°F.

Significance of Precipitation Hardening

A comparison of data for Heats X-65 and X-66, both being similar in composition, except the latter contains 0.65 per cent copper, shows an increase in yield strength of 4000 psi. for the hot-rolled condition as a result of the copper addition. This difference became more pronounced upon heat treating, the yield strengths after normalizing being 78,000 psi. and 92,500 psi., respectively. This represents a slight decrease in strength for the heat without copper and an increase of almost 9000 psi. for the copper-bearing heat. Both heats increased in yield strength after being tempered at 1200°F. for one hour, the yield strength of the noncopper-bearing heat reaching 103,800 psi. compared to 115,300 psi. for the copper steel. The increase resulting from the tempering treatment was about 25,000 psi. in either case. The final difference in yield strength was about 11,000 psi. in favor of the copper-bearing steel.

The notched-bar impact strength of the copper steel after normalizing and tempering was slightly lower than that of the copper-free material, but this difference would be expected in view of the higher yield strength of the copper steel.

The cracking characteristics of the copper steel in the hot-rolled and normalized-tempered conditions were essentially the same, these steels cracking 9 and 13 per cent, respectively, when tested at 0°F. The copper-free heat, however, cracked 14 per cent in the hot-rolled state and showed no evidence of cracking after being normalized and tempered.

Study of Chromium-Manganese Steels

Preparation of Laboratory Heats Containing Manganese and Chromium

The effect of the elements carbon, manganese, silicon, molybdenum, and vanadium, when added singularly in various amounts to a standard analysis, was determined and the data were included in the November 17, 1947, Progress Report. In order to investigate the influence of chromium, a series of four 225-pound induction-furnace heats was made to which approximately 0.25, 0.50, and 0.75 and 1.00 per cent chromium, respectively, was added to the standard analysis. As before, each heat was deoxidized with 0.4 pound of aluminum per ton and cast into a 6-5/8-inch-square ingot. The chemical analyses of these heats appear in Table 10, together with the standard composition Heats X-45 and X-46.

The procedure followed in processing these steels was the same as given earlier in this report for the manganese-molybdenum-vanadium heats.

TABLE 10. CHEMICAL ANALYSES OF LABORATORY HEATS MADE TO STUDY THE EFFECT OF CHROMIUM, HEATS X-59 TO X-62, INCLUSIVE

Heat No.	Analyses, Per Cent							
	C	Mn	P	S	Si	Ti	Cr	Al*
X-59	0.20	1.37	.025	.026	0.32	.014	0.28	.003
X-60	0.20	1.33	.024	.030	0.33	.012	0.52	.003
X-67	0.21	1.36	.024	.026	0.34	.012	0.78	.003
X-62	0.22	1.30	.024	.025	0.31	.015	1.0[illegible]	.003
				(Standard Composition Heats)				
X-45	0.21	1.35	.021	.030	0.27	.015		.003
X-46	0.22	1.35	.023	.032	0.28	.015		.003

* Acid-soluble aluminum content

Tensile Properties

A summary of tensile properties for the chromium series and standard composition heats is listed in Table 11. The complete data are listed in Table 7 of the Appendix. These properties were determined from standard 0.505-inch-diameter tensile bars, duplicate specimens longitudinal to the direction of rolling being prepared from the center of one-inch plates. As before, yield strengths were calculated from the stress-strain curve using the load at 0.2 per cent offset.

TABLE 11. TENSILE PROPERTIES OF CHROMIUM-BEARING AND STANDARD-COMPOSITION LABORATORY HEATS

Heat No.	Condition	Elong. in 2 Inches, %	Red. of Area, %	Yield* Strength, psi.	Tensile Strength, psi.
		(Manganese-Chromium Heats)			
X-59	Hot rolled	33.5	69.5	48,400	80,000
X-60	" "	31.5	70.0	49,800	81,900
X-61	" "	28.0	65.0	51,600	88,400
X-62	" "	27.0	66.0	54,500	91,900
X-63	Homog. & Norm.**	24.5	61.5	61,200	101,300
		(Standard-Composition Heats)			
X-45	Hot rolled	33.8	67.2	52,100	79,100
X-46	" "	35.0	70.1	50,750	80,300

* Yield strength at 0.2 per cent offset.

** One-inch-thick plates were homogenized for 4 hours at 2350°F. and then normalized at 1650°F.

All specimens from one-inch plate.

An examination of Table 11 shows little difference in hot-rolled yield strength of the highest chromium, Heat X-62, and the standard-composition heats without chromium. The yield strength of the lower chromium steels was similar, or slightly lower, than that of standard-composition heats, indicating that chromium additions of 0.5 per cent have little effect upon the hot-rolled yield strength. The tensile strength, however, was increased by 8000 to 10,000 psi. by the addition of 0.78 to 1.00 per cent chromium.

The ductility, as indicated by the per cent elongation, was decreased with increasing chromium content, while the reduction of area was practically unchanged.

Homogenizing one-inch-thick plate from the 1.00 per cent chromium heat for four hours at 2350°F. followed by normalizing, increased the yield strength from 54,500 to 62,200 psi. and the tensile strength from 91,900 to 101,300 psi. The ductility was decreased slightly by this treatment.

Underbead Weld-Crack Sensitivity

The underbead cracking tendencies were determined by the single-bead test, ten grooved specimens being welded from each heat. In the case of the homogenized steel from Heat X-62, five specimens were welded.

Average cracking values are listed in Table 12, and the data for the individual tests will be found in Table 8 of the Appendix.

Table 12 indicates that the addition of 0.25 or 0.50 per cent chromium to the steel is not detrimental, but may actually decrease the crack sensitivity, since the cracking in these two steels was less than one-half of that for the standard-composition heats, 28 and 20 per cent compared to 57 and 60 per cent. The carbon content for the two lower chromium heats was about one point lower than for the standard heats, but it is improbable that this could account for the wide difference in cracking.

TABLE 12. RESULTS OF CRACK-SENSITIVITY TESTS ON CHROMIUM-BEARING LABORATORY STEELS

Heat No.	Composition, Per Cent C	Mn	Cr	Al*	Condition	Average Cracking, %
			(Manganese-Chromium Heats)			
X-59	0.20	1.37	0.28	.003	Hot rolled	28
X-60	0.20	1.33	0.52	.003	" "	20
X-61	0.21	1.36	0.78	.003	" "	65
X-62	0.22	1.30	1.00	.003	" "	54
X-62	0.22	1.30	1.00	.003	Homog. & Norm.+	5
X-61	0.21	1.36	0.78	.003	" " "	14
			(Standard-Composition Heats)			
X-45	0.21	1.35	-	.003	Hot rolled	57
X-46	0.22	1.35	-	.003	" "	60

* Acid-soluble aluminum content.

\+ Plate homogenized 4 hours at 2350°F., then normalized 1650°F.

The 0.78 and 1.00 per cent chromium heats cracked about the same amount as the standard heats in the hot-rolled condition, but the cracking in each case was greatly reduced by homogenizing.

Notched-Bar Impact Properties

The impact strengths of these steels were determined from standard V-notch Charpy bars, four duplicate specimens being broken at each of six temperatures in the range of -75°F. to +210°F. All specimens were taken from the center of the plate and machined longitudinal to the direction of rolling. Two sets of specimens were made from each steel, one notched perpendicular to the plate surface, and the second set parallel to the surface.

The impact properties for the chromium-bearing and standard composition heats are shown graphically in Figures 11 to 15, inclusive. The data from which these curves were drawn are listed in Table 9 of the Appendix. Specimens from the standard-composition heats were notched parallel to the plate surface only, and the data are shown in Figure 11.

Figures 12 to 15, inclusive, show low impact strengths at -40°F. and below, and relatively little scatter among individual values throughout the entire temperature range when notching was perpendicular to the plate surface. More scatter was noted in the tests notched parallel to the plate surface. As the chromium content was increased, a corresponding decrease in impact strength occurred.

In the case of the 1.0 per cent chromium steel, Figure 15 shows that homogenizing followed by normalizing produced a wide scatter of the values in what appeared to be the transition zone.

Effect of Homogenizing Steel in the Form of Slabs Prior to Rolling to Plates

Numerous data are available to show the beneficial influence of high-temperature homogenizing, especially with respect to its effect upon underbead weld crack sensitivity and notch-bar impact properties of finished plates of various compositions. Since, however, it would not be commercially feasible to treat the finished plates in this manner, because of the excessive furnace size and capacity required, necessity of normalizing following this treatment, poor surface of the plate as the result of scaling, warping, etc., it would be necessary to carry out the

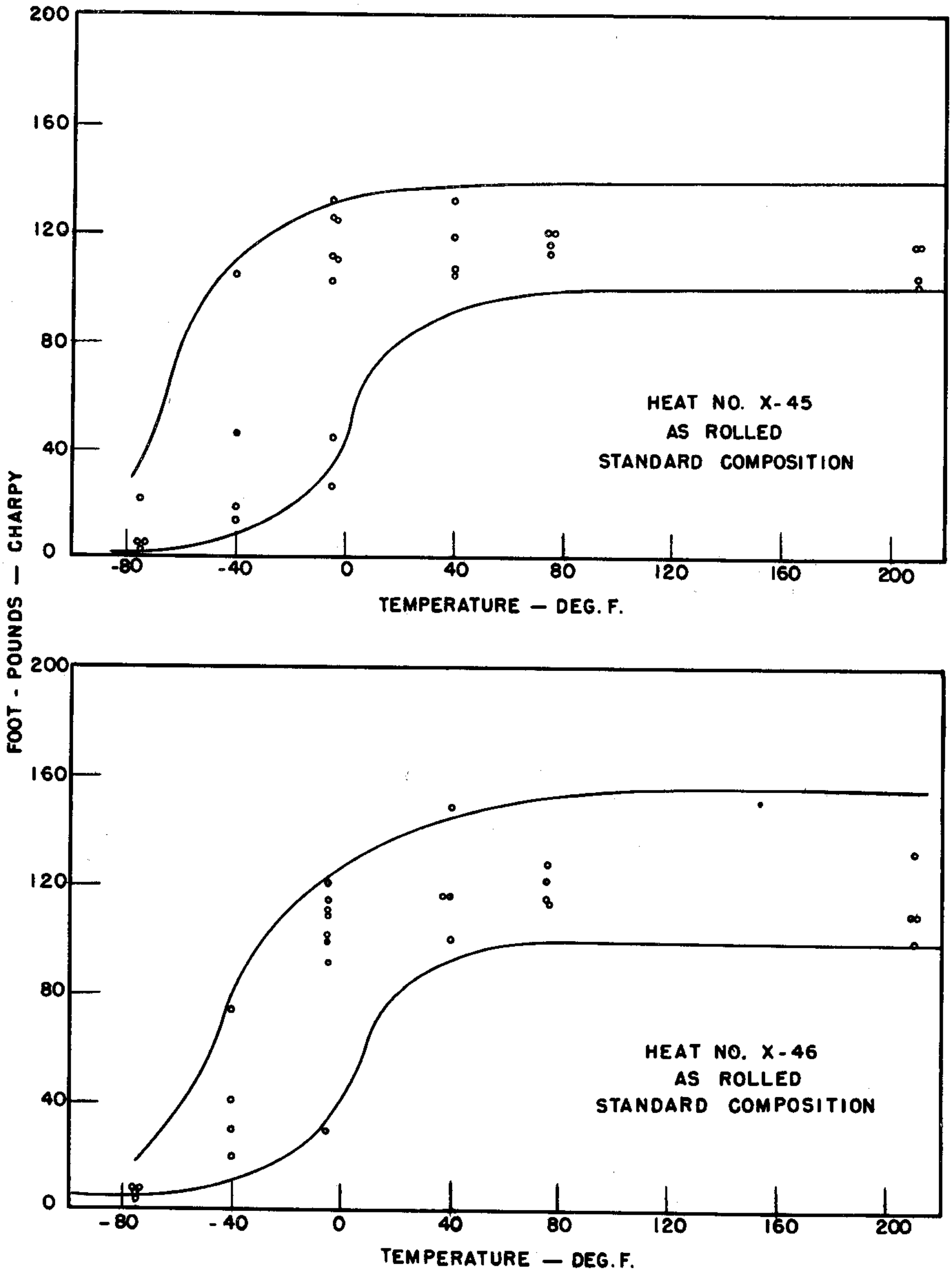

FIGURE 11. NOTCH-BAR IMPACT PROPERTIES OF STANDARD COMPOSITION HEATS. 0-5437

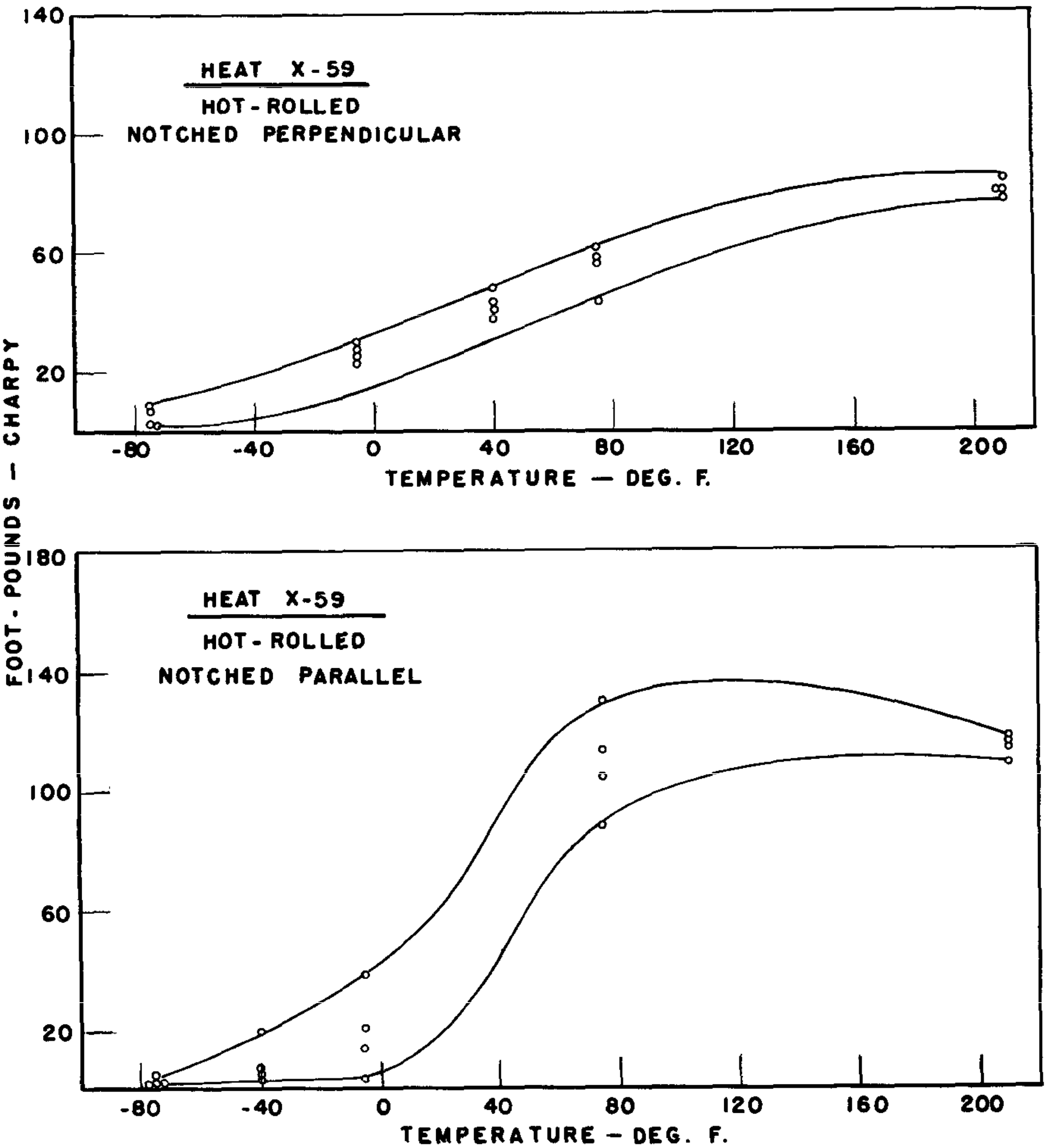

FIGURE 12. NOTCHED-BAR IMPACT PROPERTIES OF A 0.28% CHROMIUM STEEL.

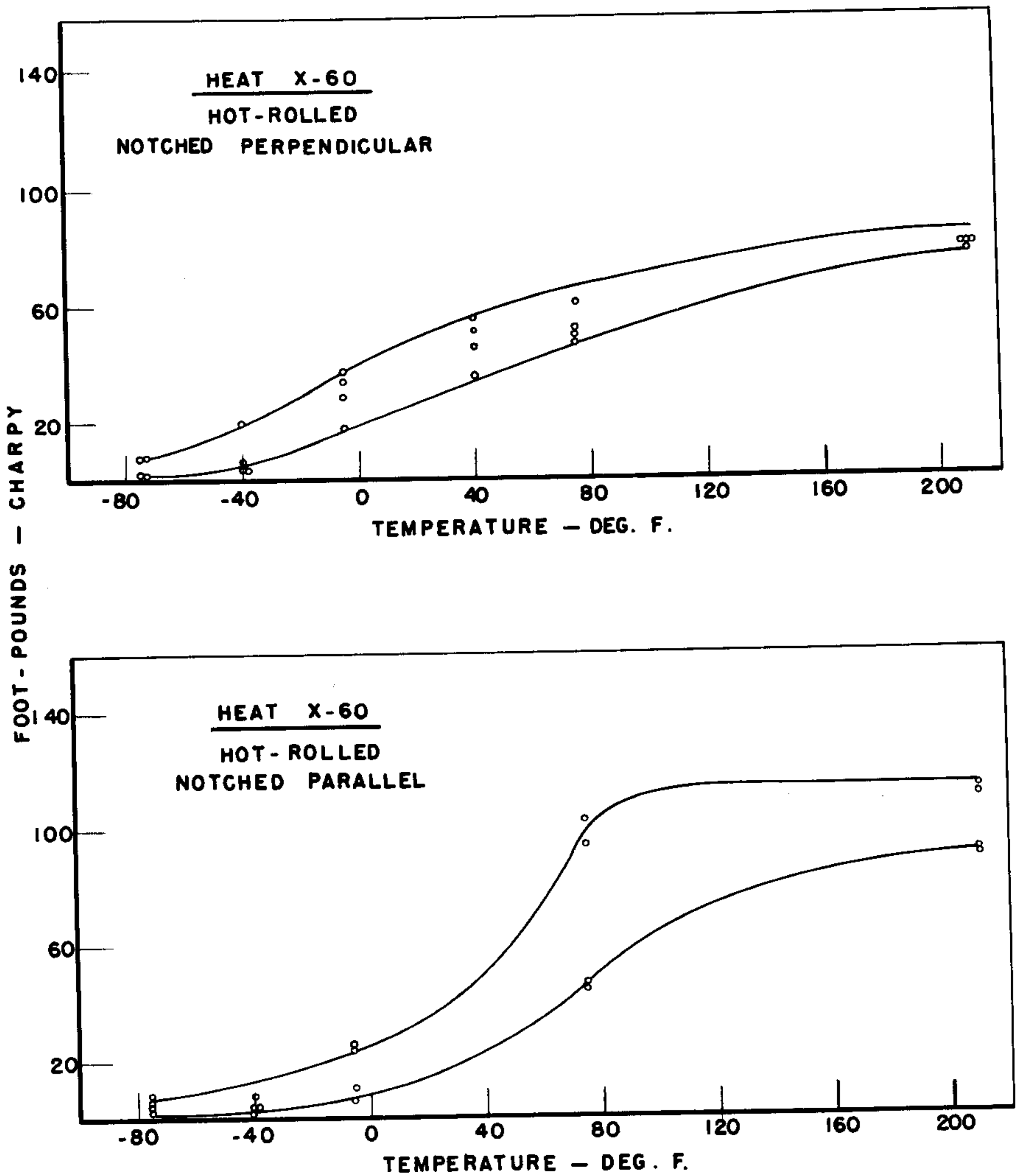

FIGURE 13. NOTCHED-BAR IMPACT PROPERTIES OF A 0.52 % CHROMIUM STEEL.

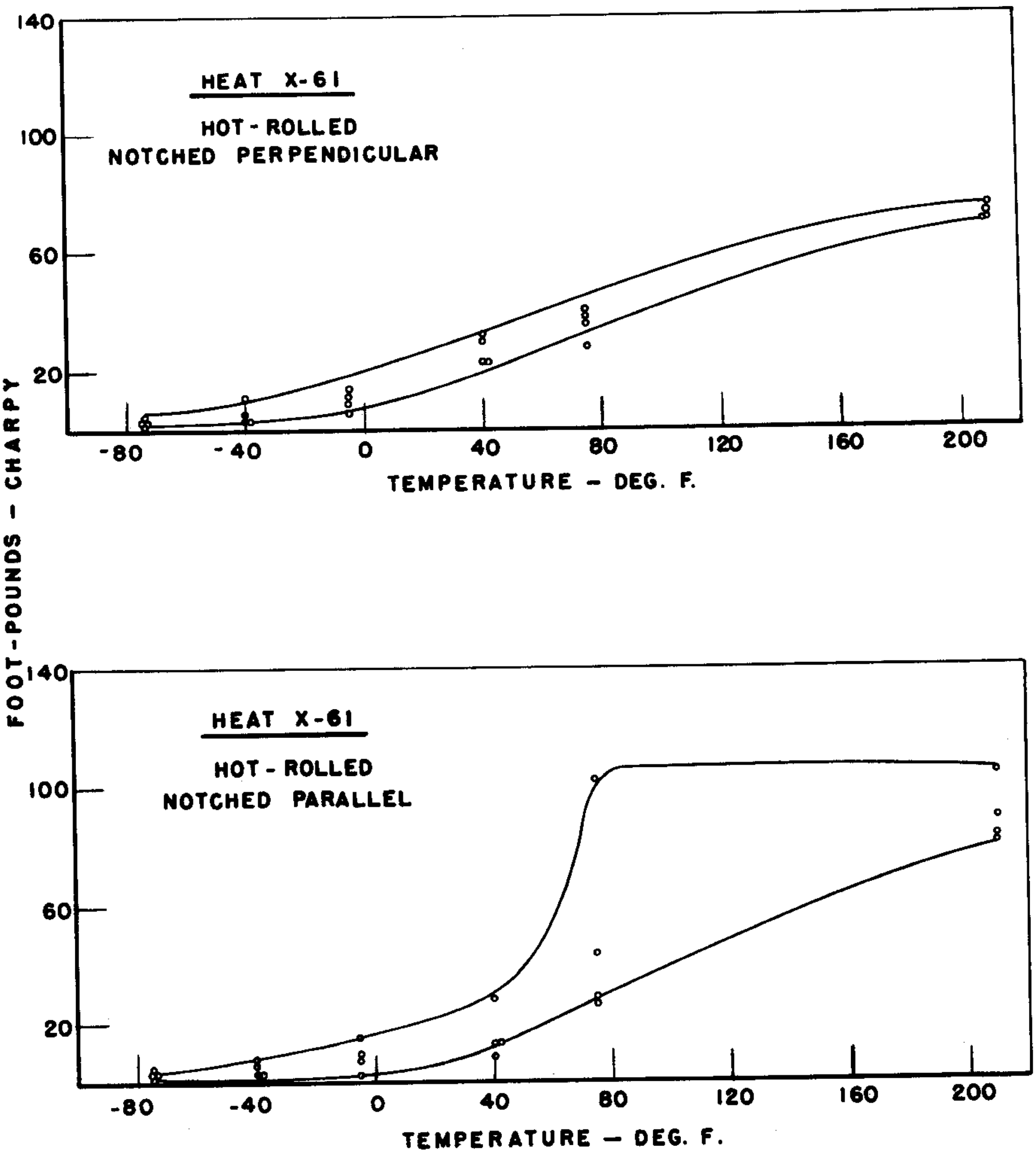

FIGURE 14. NOTCHED-BAR IMPACT PROPERTIES OF A 0.78 % CHROMIUM STEEL.

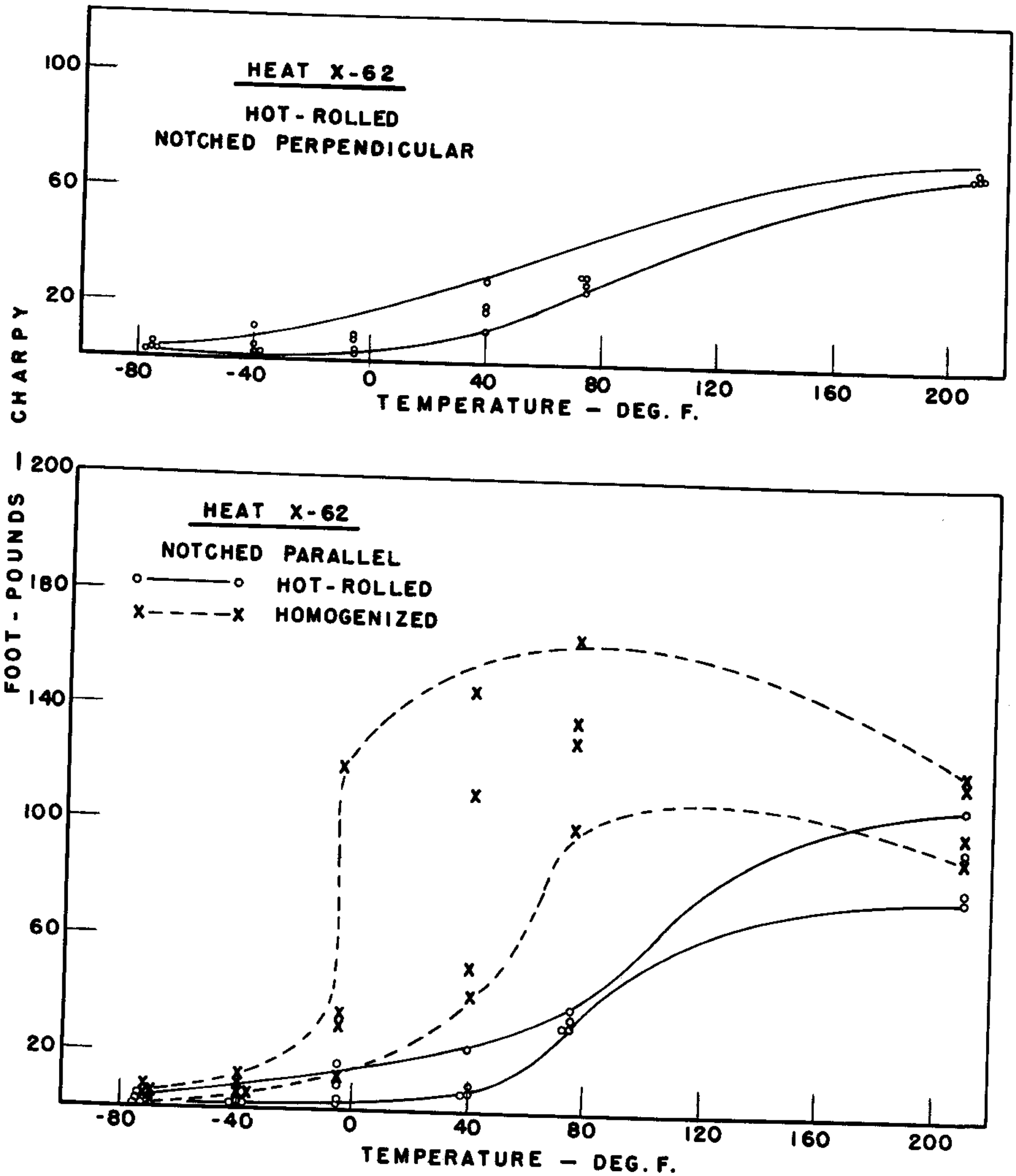

FIGURE 15. NOTCHED-BAR IMPACT PROPERTIES OF A 1.0 % CHROMIUM STEEL.

homogenizing treatment in either the ingot or slab. Homogenizing the steel in the form of ingots would require excessive time, because eleven hours at 2350°F. were required to completely homogenize a small laboratory ingot, and, on this basis, a large commercial ingot would require an exceedingly long time. This leaves the slab as the only logical form in which the steel could be treated.

In order to determine the effect of homogenizing the steel in the form of slabs, three sections from each of two 6-inch commercial manganese-molybdenum slabs were heated for various lengths of time in a soaking-pit type furnace and then rolled into one-inch plates. Sections from the same slabs were treated in the regular manner for comparison purposes.

In this initial commercial experiment, Steel 23H was heated for periods of 2-1/2, 5, and 10 hours, respectively, at 2300°F. In the second trial, Steel 26H was heated for periods of 3, 8, and 13 hours, respectively, at 2350°F. The chemical analyses of the steels are listed in Table 13. Each steel had previously been rolled from the ingot to 8-inch slabs, reheated, and rolled to 6-inch slabs prior to the time the homogenizing trials were made.

The homogenizing periods in hours are shown in the following data by the suffixes added to the steel number; 23H5, for example, indicates that Steel 23H was homogenized for five hours.

<u>Tensile Properties of the Plate from the Homogenized Slabs</u>

Standard 0.505-inch-diameter threaded-end tensile specimens prepared in duplicate from the center of one-inch plates were used, the

TABLE 14. TENSILE PROPERTIES OF ONE-INCH-THICK PLATES HOT ROLLED FROM HOMOGENIZED COMMERCIAL SLABS

Steel No.	Slab Homogenizing Time, Hrs.	Elong. in 2 Inches, %	Red. of Area, %	Yield* Strength, psi.	Tensile Strength, psi.
23H0	Reg. Practice	22.0	56.0	70,100	103,300
23H2.5	2.5	21.5	56.5	73,600	105,500
23H5	5	21.0	59.5	72,200	102,400
23H10	10	23.5	65.5	68,200	95,100
26H0	Reg. Practice	25.0	63.7	66,200	98,000
26H3	3	23.5	61.2	68,500	104,000
26H8	8	24.0	62.6	69,500	103,300
26H13	13	24.5	62.8	69,500	102,800

* Yield strengths were taken from the stress-strain curve using the load at 0.2 per cent offset.

manner previously described to avoid the possible influence of decarburization. In addition to the test made at 0°F., specimens from Steel 26H were also welded in a water bath at room temperature and in air at room temperature. All the specimens from Steel 23H were welded at 0°F.

Carbon checks were made from chips removed from the plate surface in order to determine if the homogenizing treatment had decarburized the slab sufficiently to influence the crack sensitivity of the plate. These data are listed with the results of the crack-sensitivity tests and indicate that the carbon content had not been affected.

A summary of the cracking data for Steel 23H appears in Table 15 and the complete data are listed in Table 11 of the Appendix. Summary data for Steel 26H will be found in Table 16 and the complete results in Table 12 of the Appendix.

TABLE 15. CRACK SENSITIVITY OF STEEL 23H AFTER HOT ROLLING TO ONE-INCH-THICK PLATES FROM HOMOGENIZED SLABS

Steel No.	Slab Homogenizing Time at 2300°F.	Chemical Analysis, Per Cent C	Mn	Mo	Number of Specimens	Average Cracking, Per Cent
23H0	Direct Rolled	0.19	1.46	0.37	10	79
23H2.5	2-1/2 hours	"	"	"	10	81
23H5	5 hours	"	"	"	10	80
23H10	10 hours	"	"	"	10	79

As shown in Table 15, the four lots of plate from Steel 23H all cracked approximately 80 per cent regardless of the thermal processing, indicating that homogenizing the slab was ineffective in this case.

Examination of microstructure of the annealed plate rolled from the homogenized slabs showed strong evidence of banding and no influence of the homogenizing treatment.

Table 16 also indicates that the homogenizing treatment did not alter the crack sensitivity of Steel 26H, although the temperature was raised from 2300 to 2350°F. and the heating cycle of the fourth lot was increased from 10 to 13 hours. The low crack sensitivity of Steel 26H as compared with Steel 23H was the result of the difference in carbon content which was 0.14 per cent as compared with 0.19 per cent for Steel 23H.

From Table 16 it will be noted that the weld tests which were made in a water bath at room temperature and those welded in air at room temperature cracked to about the same extent or slightly more than those welded at 0°F. There was no indication from these tests that homogenizing the slabs was beneficial.

TABLE 16. CRACK SENSITIVITY OF STEEL 26H AFTER HOT-ROLLING TO ONE-INCH-THICK PLATES FROM HOMOGENIZED SLABS

Steel No.	Slab Homogenizing Time at 2350°F.	Chemical Analysis, % C	Mn	Mo
26H0	Direct rolled to plates	0.14	1.44	0.48
26H3	3 hours	"	"	"
26H8	8 hours	"	"	"
26H13	13 hours	"	"	"

Extent of Underbead Cracking, Per Cent*

Steel No.	Welded at 0°F. Group 1	Group 2	Welded Room Temp. in Water	Welded Room Temp. in Air
26H0	12	8	11	10
26H3	15	16	18	9
26H8	6	7	11	7
26H13	0	6	15	19

* Percentage figures represent average cracking values for ten specimens welded per group.

Because of the ineffectiveness of the homogenizing process when applied to slabs from Steel 23H and 26H, it was decided to determine the influence of homogenizing upon the crack sensitivity of regular hot-rolled one-inch plate from the same heat as Steel 23H, designated as Steel 39. (See Table 17 for chemical analysis.)

TABLE 17. CHEMICAL ANALYSIS OF STEEL 39

Steel	Chemical Composition, Per Cent					
No.	C	Mn	P	S	Si	Mo
39	0.19	1.43	.018	.018	0.28	0.33

Sections sufficiently large to prepare five weld specimens were cut and protector plates were welded to the four edges to prevent decarburization during homogenizing. The sections were then heated to temperatures of 2350°F. and 2400°F. as indicated in Table 18, for periods of ten minutes, 1, 3, and 5 hours, and then normalized at 1650°F. after removal of the protector plates. Weld-cracking tests were run in the usual manner and a summary of the results are listed in Table 18. The data are shown graphically in Figure 16. The complete data are listed in Table 13 of the Appendix.

Figure 16 shows a marked decrease in cracking resulting from heating the specimens to the homogenizing temperature for 10 minutes, the time required to reach temperature being about two hours. Figure 16 also shows that the crack sensitivity decreased progressively with increased holding time with the higher temperature being more effective, as would be expected.

These results, together with those obtained following homogenization of the slabs, indicate this steel will respond to homogenizing, but that the time required to homogenize the slabs would be prohibitive.

TABLE 18. THE CRACK SENSITIVITY OF STEEL 39 AFTER HOT ROLLING TO ONE-INCH PLATE AND HOMOGENIZING AT 2350°F. AND 2400°F., FOLLOWED BY NORMALIZING AT 1650°F.

Condition of Plate	Number of Specimens Welded	Average Cracking, Per Cent
Hot rolled	10	78
Homogenized 10 min. at 2350°F.	5	35
" 1 hr. " "	5	28
" 3 hrs. " "	5	30
" 5 hrs. " "	5	14
" 10 min. at 2400°F.	5	24
" 1 hr. " "	5	12
" 3 hrs. " "	5	14
" 5 hrs. " "	5	10

Notched-Bar Impact Properties

In order to determine the influence of the slab homogenizing treatments upon the notched-bar impact properties of Steels 23H and 26H, longitudinal Charpy bars with V-type notches cut perpendicular to the plate surface from the center of the plates were used. Four duplicate specimens from each lot were broken at each of six temperatures in the range of -75°F. to +210°F. The impact strengths are shown graphically in Figures 17 and 18, and the data for the individual specimens are given in Table 14 of the Appendix.

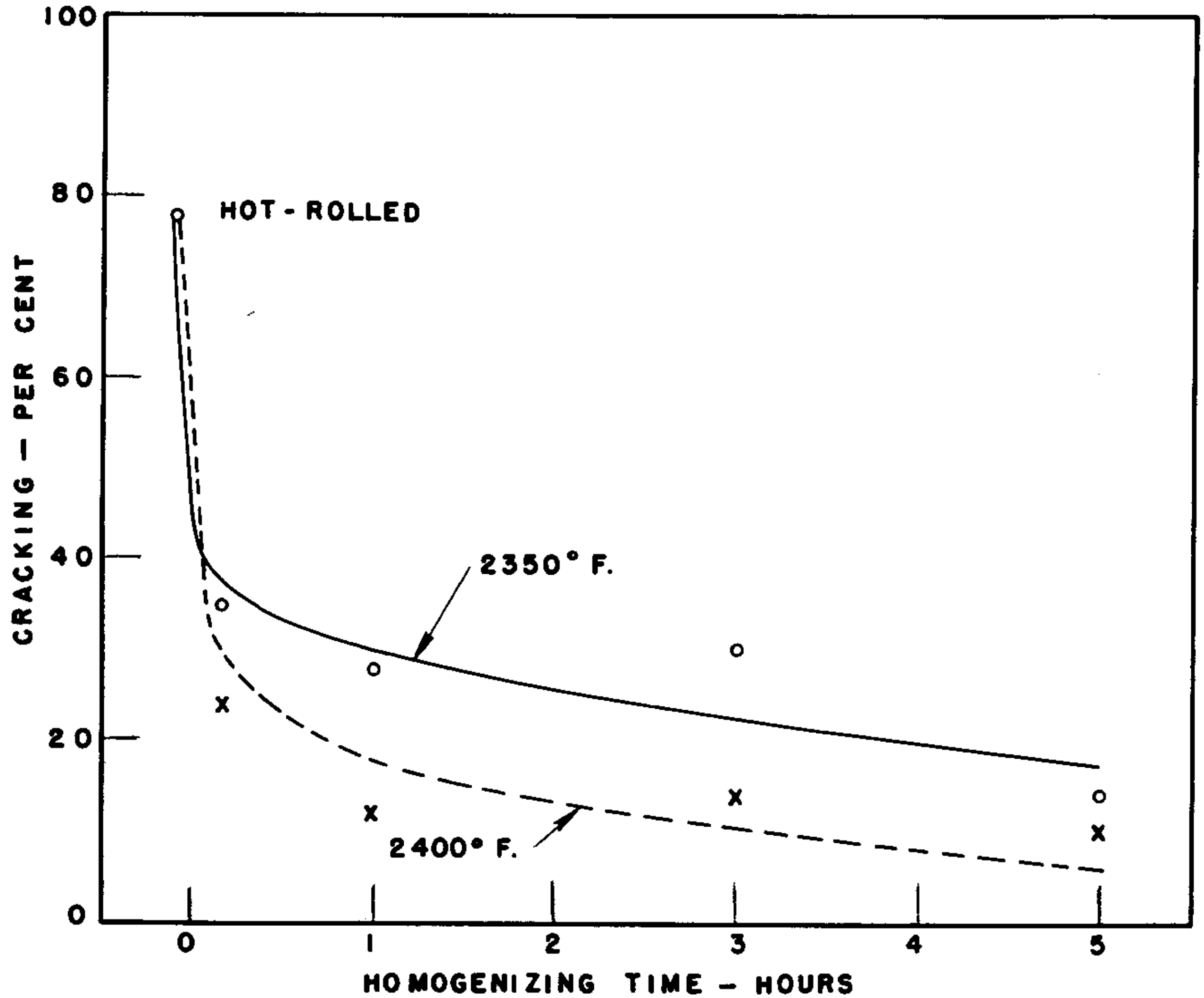

FIGURE 16. RELATIONSHIP OF TIME AT TEMPERATURE TO EXTENT OF UNDERBEAD CRACKING FOR STEEL 39.

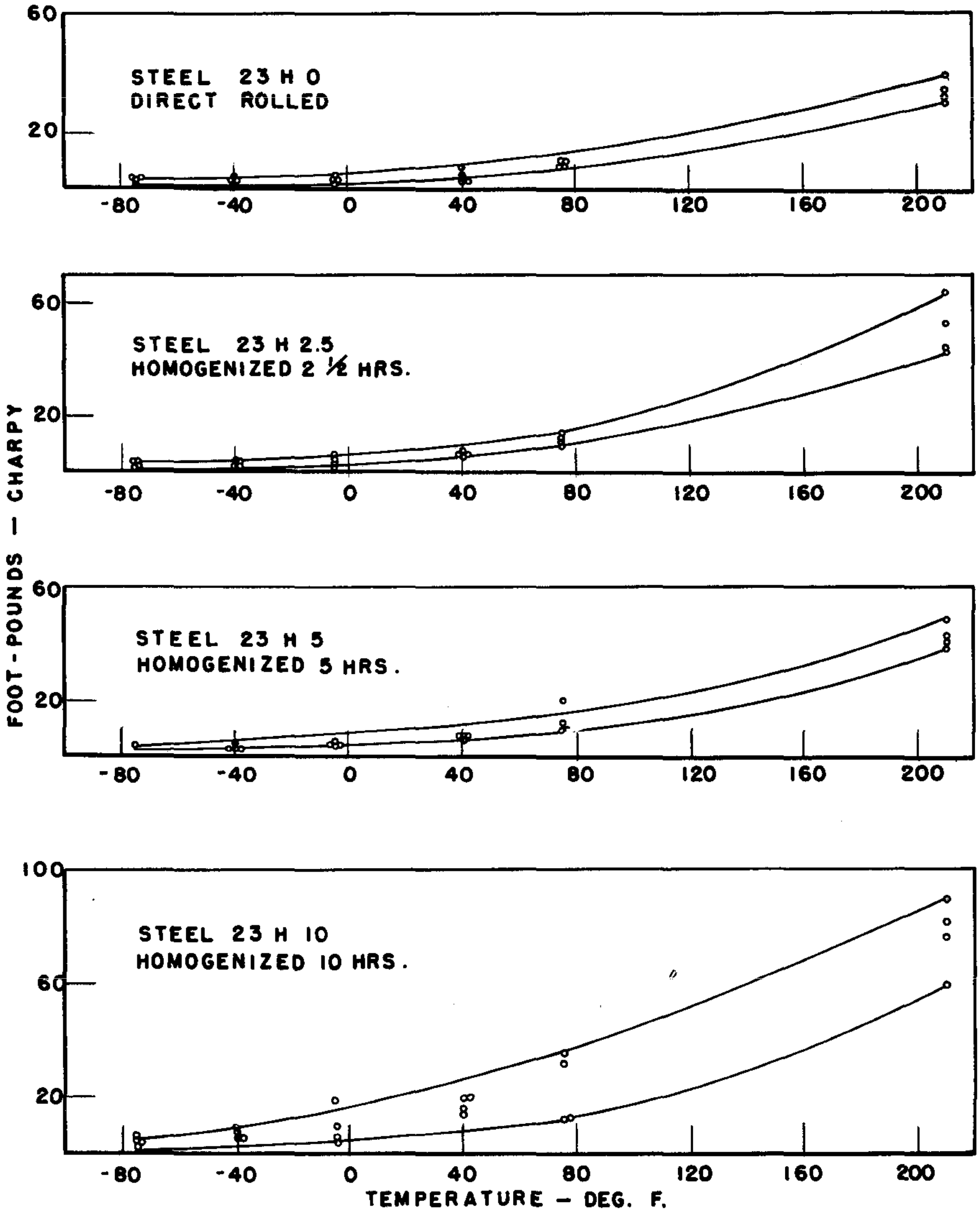

FIGURE 17. NOTCHED-BAR IMPACT PROPERTIES OF HOMOGENIZED STEELS.

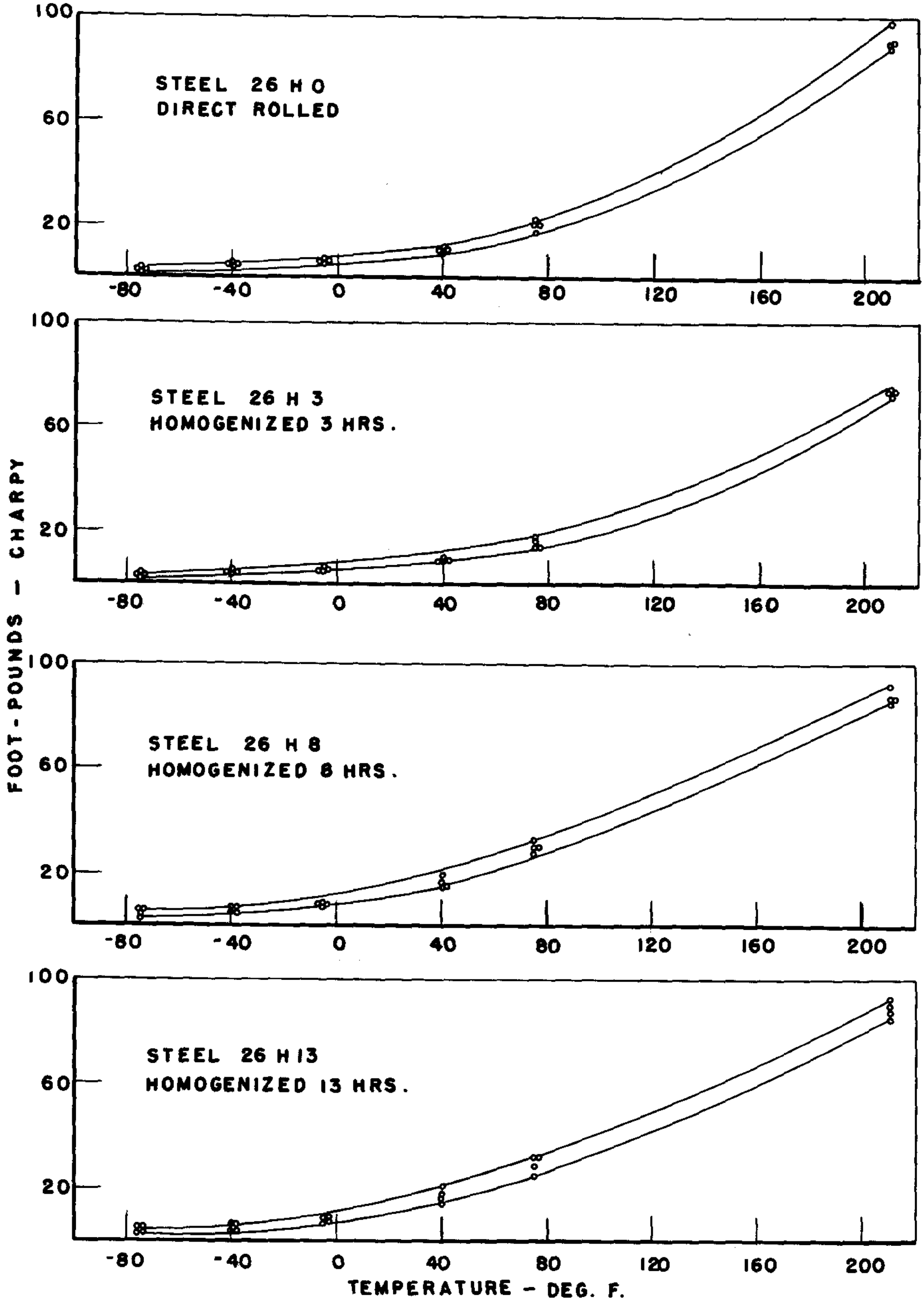

FIGURE 18. NOTCHED-BAR IMPACT PROPERTIES

Figure 17 shows little difference in notched-bar properties of Steels 23H0, 23H2.5, and 23H5, throughout the entire testing temperature range, indicating that the 2-1/2- and 5-hour homogenizing treatments did not improve the notched-bar characteristics. There were some indications that the ten-hour homogenizing cycle was slightly beneficial.

The data in Figure 18 show no indications that the homogenizing has improved the notched-bar impact strength of Steel 26.

Discussion of Homogenizing

Results reported in the previous progress reports have shown that homogenizing one-inch plate at 2350°F. for relatively short periods of time will decrease the crack sensitivity to a marked extent, provided the carbon and manganese contents are not too high, and frequently improves the notched-bar impact characteristics without any sacrifice in tensile properties. Obviously, such a treatment is not commercially feasible because of scaling and warping the finished plate, together with the excessive cost of such an operation.

The above objections could be largely overcome if the slabs from which the plate is rolled could be homogenized in a reasonable length of time. The results shown in this report, however, indicate that the time required would be far in excess of anything that could be considered practical.

An appreciation, however, of the influence of alloy banding and a realization of the effects of homogenization upon underbead cracking has contributed considerably to our understanding of the mechanism of underbead cracking.

Relationship of Hardness Under the Weld Bead to Crack Sensitivity

A study was made in order to determine the relationship of hardness under the weld bead to crack sensitivity, using the steels listed in Table 19. All of the steels in this group were of one-inch-thick plate, with the exception of Z16, which was seven-eighths inch thick. The higher carbon steels, X9, X17, X22, and X61, were tested in the hot-rolled condition and also after being homogenized for four hours at 2350°F., followed by normalizing. The lower carbon steels, X40, 40, and Z16 were tested in the hot-rolled condition only.

The procedure followed for making the weld specimens was the same as that used for crack-sensitivity tests, except that the 1150°F. stress-relief treatment was omitted.

Preparatory to making the hardness survey, sections approximately one-fourth inch thick were cut transversely through the center of the weld bead, wet ground on either side, and polished, the final polish being with 400-grit emery paper. The hardness traverse was made at the point of deepest penetration of the bead using a Vickers Hardness Tester with a one-kilogram load. Impressions were started in weld deposit and carried through the heat-affected zone, the distance between succeeding impressions being .005 inch.

The maximum underbead-hardness values, the crack sensitivity, and the chemical analyses of the steels are listed in Table 19. The complete hardness and cracking data from the individual tests are listed in Tables 15 and 16, respectively, of the Appendix.

TABLE 19. COMPARISON OF UNDERBEAD HARDNESS, CRACK SENSITIVITY, AND CHEMICAL ANALYSES OF VARIOUS STEELS IN THE CONDITIONS LISTED

Steel No.	Chemical Analyses, Per Cent C	Mn	Si	Mo	V	Cr	Condition	Maximum Underbead Hardness (Vickers)	Cracking, Per Cent
X-9	0.21	1.51	0.29	-	-	-	Hot rolled	498	59
"							Homog.	515	11
X-17	0.23	1.32	0.30	0.32	-	-	Hot rolled	551	71
"							Homog.	551	13
X-22	0.21	1.28	0.29	-	0.29	-	Hot rolled	498	74
"							Homog.	533	8
X-61	0.21	1.36	0.34	-	-	0.78	Hot rolled	360	65
"							Homog.	613	14
40	0.14	1.24	0.24	0.43	-	-	Hot rolled	453	2
X-40	0.16	1.32	0.33	-	0.39	-	" "	482	4
Z-16	0.18	1.18	0.28	-	-	-	" "	426	15

From Table 19 it will be noted that the maximum hardness in the heat-affected zone of the hot-rolled steels is essentially the same as in the homogenized plates, although there is a marked difference in the crack sensitivity. A comparison of the chemical analyses of these steels with the maximum underbead hardness indicates there is a relationship between these two factors, but no correlation between the hardness and underbead cracking. These data are in agreement with those included in the August 15, 1945, Progress Report pertaining to this project.

Tensile Properties of Hardened and Untempered Steels

It is still commonly believed that cracks occur in the hard martensitic structure immediately under the bead because this area is hard and devoid of ductility. In order to demonstrate that hard martensite is not necessarily brittle and that underbead cracking is, therefore, not the result of high hardness but is caused by other factors, tensile tests were made on small water-quenched specimens from three heats of HTS steel. The chemical analyses of the steels are listed in Table 20.

TABLE 20. CHEMICAL ANALYSES OF STEELS TESTED IN THE HARDENED AND UNTEMPERED CONDITION

Steel No.	Chemical Analyses, Per Cent					
	C	Mn	P	S	Si	Mo
23HO	0.19	1.46	.020	.018	0.25	0.37
26HO	0.14	1.44	.013	.027	0.25	0.48
34	0.23	1.53	.016	.022	0.24	--

The specimens were prepared by rough turning the one-inch-thick plate to 0.530-inch diameter, water quenching from 1650°F., and wet grinding to 0.500-inch diameter. Precautions were taken to see that the specimens were kept cool during grinding.

In addition to the tests described, 0.247-inch-diameter tensile specimens were made from the same steels and were tested without grinding after water quenching from 1650°F.

A summary of the tensile properties is given in Table 21, and the complete data may be found in Table 17 of the Appendix.

As evidence that the steels were fully quenched, it will be noted that the hardness values obtained, which ranged from 363 Bhn. for the 0.14 per cent carbon steel to 429 Bhn. for the 0.23 per cent carbon steel, represent the highest hardness possible for martensite of these carbon contents.

Although drastically quenched and given no tempering whatever, these steels are far from being brittle. With strengths from 2 to 3 times the hot-rolled values, the ductility ranges from 7.0 per cent elongation and 17.0 per cent reduction of area for the highest carbon steel to 16.0 per cent elongation and 59.0 per cent reduction of area for the lowest carbon steel. It would appear that the explanation for underbead cracking as "martensite being a brittle material cracks under the strain imposed by thermal stresses" is not sufficient.

On the other hand, it has been shown by Herres*, that martensite loaded with hydrogen is a brittle material under slow straining.

Notched-Bar Impact Properties

Impact strength of Steels 23HO and 34 in the quenched and untempered condition was determined from standard V-notch Charpy specimens in the temperature range of -75°F. to +210°F.

Twenty-four longitudinal specimens were rough machined from the center of one-inch plates from each steel, and quenched in water from 1650°F. The specimens were then wet ground to size, notched perpendicular

* Herres, S. A.: Welding Jnl. Research Supplement (1944) 23, 43-s.

TABLE 21. TENSILE PROPERTIES OF STEELS 23HO, 26HO, AND 34 IN THE QUENCHED AND UNTEMPERED CONDITION

Steel No.	Condition*	Test Direction	Elong. in 2", %	Red. of Area, %	Yield** Strength, psi.	Tensile Strength, psi.	Bhn. No.
23HO	Hot rolled ($\frac{1}{2}$"-diam. specimens)	Long.	22.0	56.0	70,800	101,500	202
23HO	Quenched	"	15.0	50.5	145,000	212,200	421
"	Hot rolled	Trans.	21.0	51.5	70,000	101,400	-
"	Quenched	"	13.5	42.5	152,800	210,200	-
26HO	Hot rolled ($\frac{1}{2}$"-diam. specimens)	Long.	24.0	58.5	67,500	98,000	207
26HO	Quenched	"	16.0	59.0	139,100	179,000	363
26HO	Hot rolled	Trans.	23.0	60.0	68,000	96,900	-
"	Quenched	"	14.0	48.5	130,300	178,000	-
34	Hot rolled ($\frac{1}{2}$"-diam. specimens)	Long.	32.0	70.5	53,500	86,100	167
34	Quenched	"	11.5	29.5	155,000	222,100	429
"	Hot rolled	Trans.	27.5	60.0	55,300	85,800	-
"	Quenched	"	7.0	17.0	167,000	217,000	-
23HO	Quenched ($\frac{3}{4}$"-diam. specimen)	Long.	8.5	47.5	-	220,500	-
26HO	Quenched ($\frac{1}{4}$"-diam. specimen)	"	10.5	59.0	-	195,700	-

* Water quenched from 1650°F., not tempered.
** Yield strength at 0.2 per cent offset.

to the plate surface, and four specimens from each steel were broken at each of six temperatures between -75° and 210°F. The impact data from these tests are shown in Figure 19, and the values used in plotting these curves are listed in Table 18 of the Appendix.

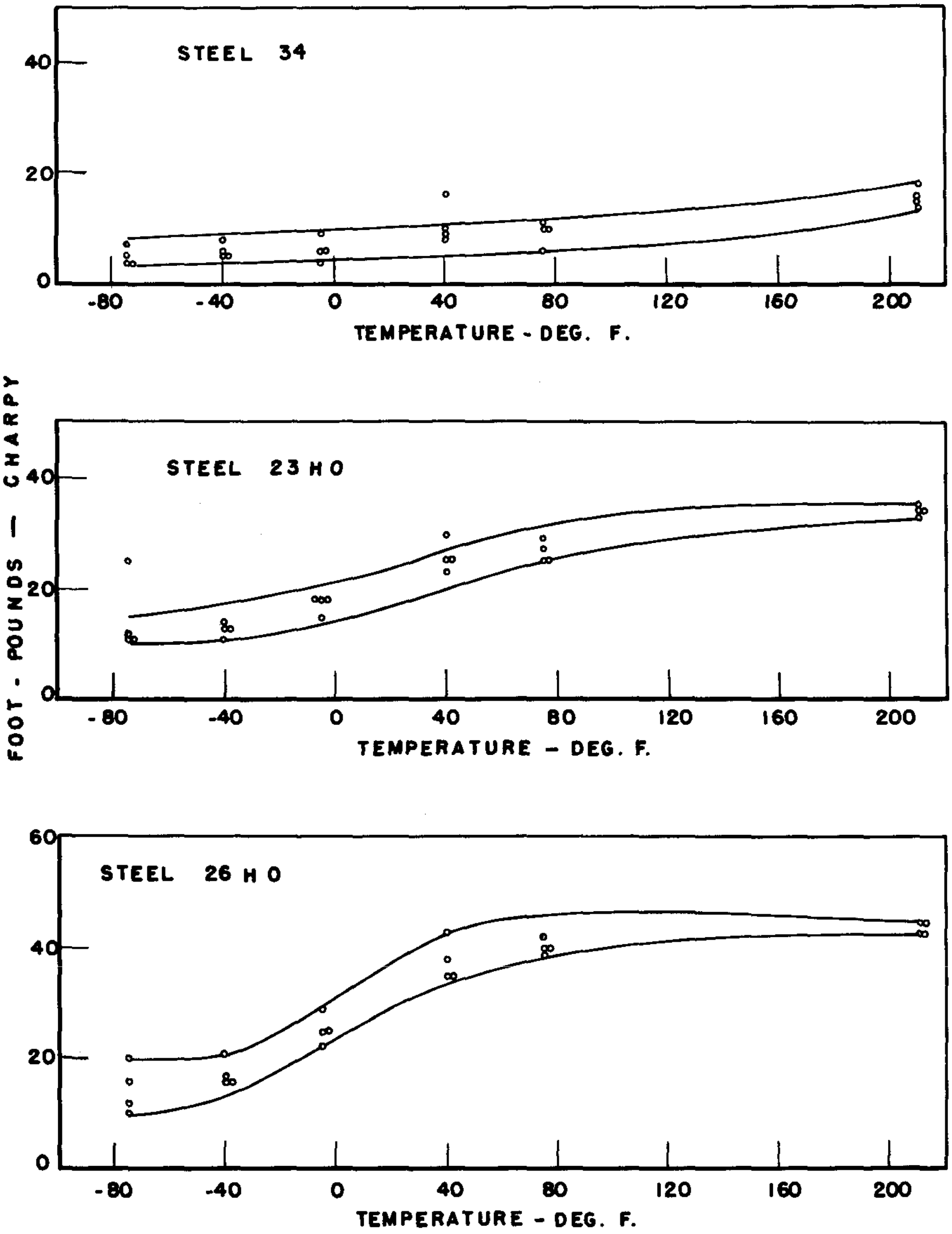

FIGURE 19. NOTCHED-BAR IMPACT PROPERTIES OF QUENCHED AND UNTEMPERED STEELS.

As shown in Figure 19, the notched-bar impact strengths of Steels 23HO and 26HO start at about 10 foot-pounds at -75°F. and increase gradually with increasing temperature, the minimum impact strengths at +210°F. being 33 and 43 foot-pounds, respectively.

The impact properties for Steel 34 were lower than those of the above steels because of the higher carbon content. The results of the above tensile and notched-bar impact tests on fully quenched specimens from the three HTS steels illustrate that hard martensite is not necessarily brittle but can be quite ductile and tough.

Study of Joint Efficiency of Quenched and Tempered Plate

In order to determine the efficiency of butt-welded, quenched and tempered plate, specimens were prepared from two commercial steels, Steel 24 being used in the heat-treated condition as supplied by the mill, while Steel 40 was water quenched from 1600°F. and tempered for one hour at 1200°F. in the laboratory. The chemical analyses of these steels are listed in Table 22.

TABLE 22. CHEMICAL ANALYSES OF STEELS 24 AND 40

Steel No.	Chemical Analyses, Per Cent							
	C	Mn	P	S	Si	Mo	Cr	Zr
24	0.15	0.79	.024	.032	0.73	0.16	0.61	0.14
40	0.14	1.24	.016	.024	0.24	0.43	-	-

The welds were made with 3/16-inch, W59 high-strength lime-coated electrodes (approximately AWS E9015 classification), using the method outlined in Figure 20. Each Vee was welded in four passes, the

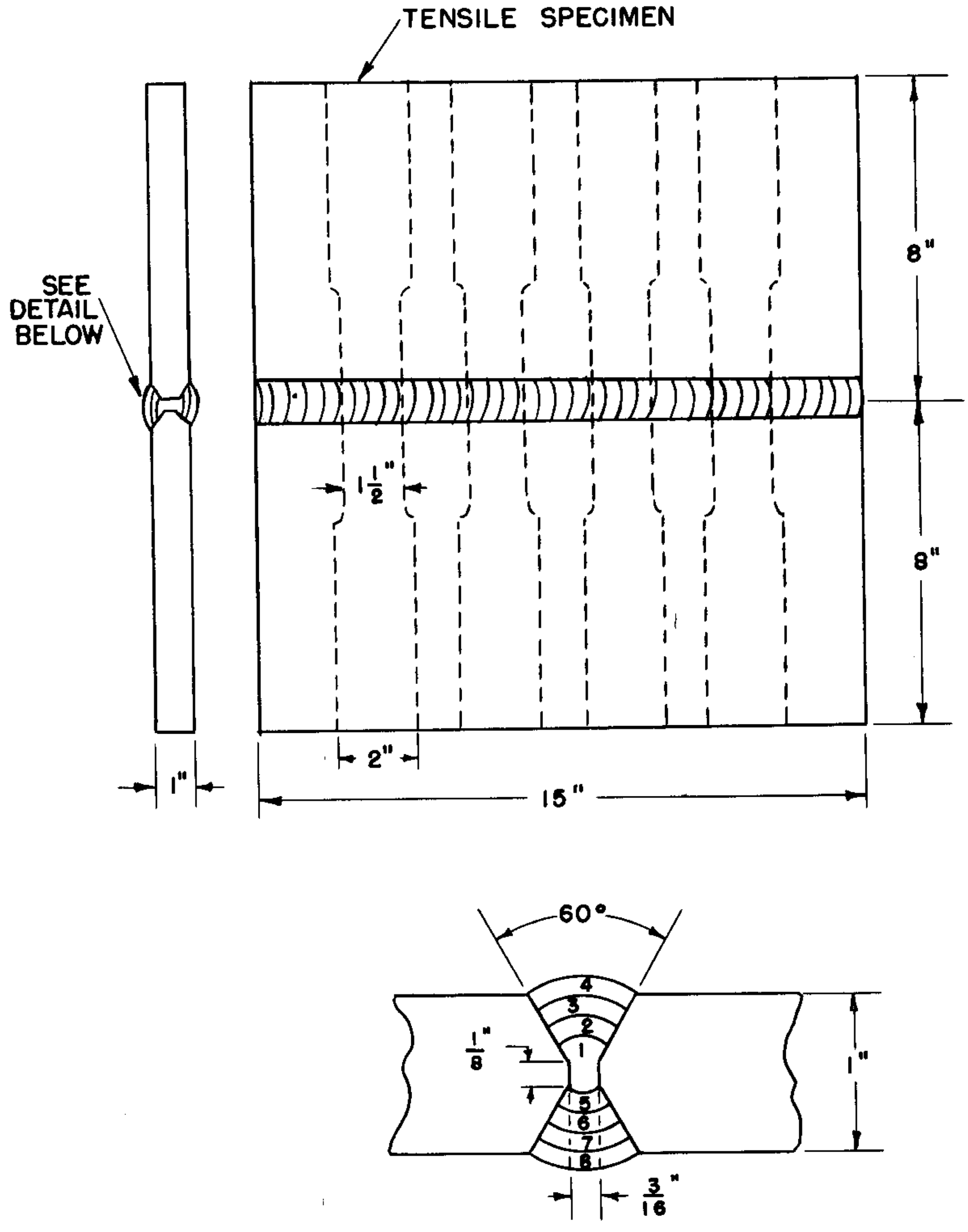

FIGURE 20. METHOD OF PREPARING TENSILE SPECIMENS FOR DETERMINING THE JOINT EFFICIENCY OF QUENCHED AND TEMPERED BUTT-WELDED PLATE.

temperature of the plate being allowed to drop to 200°F. between passes.

Tensile Properties

Tensile bars 1-1/2 inches wide, as shown by Figure 20, were machined from the welded assembly with the weld joint transverse to the testing direction. The direction of rolling was parallel to the 8-inch dimension shown in the drawing.

Full-section tensile specimens were prepared in duplicate from both the as-welded plate and from the plate after machining the bead flush with the surface. The results of these tests were compared with results from similar specimens taken from the unwelded plate. A summary of the test data is given in Table 23, and the results for the individual specimens will be found in Table 19 of the Appendix. Yield strengths were obtained from the stress-strain curve using the load at 0.2 per cent offset.

The data in Table 23 show that, in each case, the strength of the weld and heat-affected zone is equivalent to that of the base plate. All of the specimens failed at least 1-1/2 inches from the weld.

Effect of Electrode Coating, Size of Electrode, and Heat Input Upon Underbead Cracking

In order to determine the effect of the various types of electrode coatings upon underbead cracking, cracking tests were made using two commercial steels which were relatively crack sensitive when welded in accordance with the standard testing procedure. Steel 28 was a one-inch plate furnished in the quenched and tempered condition by the mill. The second steel was a one-inch plate from Steel 39, which was supplied and tested in the hot-rolled condition. Chemical analyses of the plates appear in Table 24.

Crack-sensitivity tests were made on Steel 39, using three types of 1/8-inch electrodes, E6010, E6015, and E6020, the former being the electrode used in the standard crack-sensitivity test. Other than the electrode, these tests were made using the conditions that had been established for the standard sensitivity test. In this case, ten specimens were welded with each type of electrode and a summary of the data from these tests is shown in Table 25. (See Table 20 of the Appendix.)

TABLE 23. TENSILE PROPERTIES OF BUTT-WELDED JOINTS MADE FROM QUENCHED AND TEMPERED PLATE

Steel No.	Description of Specimen	Elong. in 2", %	Yield* Strength, psi.	Tensile Strength, psi.
	(3/4-inch plate thickness)			
24	Base plate only	35.5	79,600	97,100
24	As welded	35.5	78,500	96,700
24	Welded-bead shaped flush to plate	38.0	78,500	96,600
	(1-inch plate thickness)			
40	Base plate only	44.0	86,700	100,700
40	As welded	44.5	82,800	98,200
40	Welded-bead shaped flush to plate	42.5	84,200	98,700

All welded specimens failed in the base plate at least 1-1/2 inches from the weld.

* Yield strength at 0.2 per cent offset.

Note: Steel 24 water quenched from 1650°F., tempered at 1200°F. in a continuous furnace.
Steel 40 water quenched from 1600°F., tempered for one hour at 1200°F., air cooled.

TABLE 24. CHEMICAL ANALYSES OF STEELS 28 AND 39

Steel No.	Chemical Analyses, Per Cent						
	C	Mn	P	S	Si	Mo	B
28	0.15	1.22	.022	.018	0.23	0.17	.001
39	0.19	1.43	.018	.018	0.28	0.33	--

TABLE 25. THE EFFECT OF ELECTRODE COATINGS UPON THE CRACK SENSITIVITY OF STEEL 39

Electrode Type	Electrode Coating	Welding Current		Travel Speed, ipm.	Cracking, Per Cent
		Amperes	Arc Volts		
E6010	Cellulosic	100	25	10	78
E6020	Mineral	"	24	"	20
E6015	Lime	"	26	"	0

Note: The above tests were made using the standard procedure for determining the crack sensitivity with the exception of the type of electrode.

The data in Table 25 show the influence of the electrode coating upon the extent of underbead cracking. Welding with the cellulosic-coated E6010-type electrode, which developes an arc atmosphere high in hydrogen, produced 78 per cent cracking as compared to no cracking when the low-hydrogen, lime-coated E6015-type electrode was used.

While the use of the E6020-type electrode results in considerably less cracking, as compared with the E6010, the explanation for this difference is not too obvious since the arc atmosphere of the E6020 is relatively high in hydrogen. The volume of gas generated per inch of electrode consumed is considerably less, however. Additional study will be necessary in order to obtain a better understanding of the difference in behavior of these two electrodes.

The second group of tests were made on Steel 28, which was quenched and tempered plate. The principal object in this case was to compare the lime-coated type electrodes with the cellulosic-coated E6010 type. Since the lime-coated ferritic electrodes were available only in 3/16-inch size, the welding procedure used in making these tests was altered to accommodate the larger electrode. The welding current was increased from 100 to 200 amperes, while the travel rate was reduced from 10 to 6 inches per minute. Upon completion of the weld bead, the specimens were held in the bath, which was maintained at $0^{o}F.$, for 30 seconds instead of 10 seconds. For comparison purposes, specimens were also welded with both 1/8- and 3/16-inch E6010-type electrodes.

The summary of the data from these tests is shown in Table 26. These results show that no cracking occurred when using the lime-coated ferritic electrodes but that the 3/16-inch E6010 electrode resulted in 95 per cent cracking. The 1/8-inch E6010 electrode, however, produced only 47 per cent cracking. (See Table 20 in the Appendix for complete data.) The difference in results obtained from the two sizes of E6010-type electrodes was somewhat surprising, since it would be expected that the larger electrode, with about twice the power input and slower travel speed, would result in less cracking, but this was not the case. These results indicate the need for additional study covering the effect of the electrode size, travel speed, and power input upon underbead cracking.

TABLE 26. RESULTS OF UNDERBEAD CRACKING TESTS MADE ON STEEL 28 WITH DIFFERENT TYPES OF ELECTRODE COATINGS USING A 3/16-INCH ELECTRODE

Electrode Type	Electrode Coating	Welding Current Amperes	Welding Current Arc Volts	Travel Speed, ipm.	Cracking, Per Cent
E6010	Cellulosic	200	26	6	95
Ferritic	Lime	"	23	"	0
Ferritic	"	"	"	"	0

Cracking for this steel was 47 per cent when welded with 1/8-inch E6010 electrodes and using the standard procedure.

Experimental Heat-Treated Commercial Plate Steels

At the request of the Navy Department, Bureau of Ships, a number of steel producers submitted heat-treated plate having a minimum of 75,000 psi. yield strength and 15 foot-pound Charpy impact strength at -40°F., which was to be suitable for welded construction. As part of the program for investigating these steels, Battelle was assigned the problem of determining the crack sensitivity.

Plates from each of the six heats in this group have been received and tested with the exception of Heat X-15044. In the case of Heat 21242, only hot-rolled plate was obtained, but this material was heat treated in the Battelle laboratory, by normalizing and tempering in the same manner used to treat the plate which was shipped to the Navy.

The chemical analyses of these steels, both the ladle and check analyses on the plate tested, are listed in Table 27 and the heat treatment in Table 28.

TABLE 27. LADLE AND PLATE CHECK ANALYSES OF COMMERCIAL HEAT-TREATED STEELS SUPPLIED BY THE VARIOUS STEEL MILLS

Heat No.	Type of Analysis	Analyses, Per Cent													
		C	Mn	P	S	Si	Mo	V	Ni	Cr	Cu	B	Zr	Al*	Ti
5M16076	Ladle	0.14	0.76	.022	.025	0.79	0.16	-	-	0.61	-	-	0.08	-	-
"	Check	0.15	0.79	.024	.032	0.73	0.16	-	-	0.61	-	-	0.14	.025	-
19M519	Ladle	0.16	0.27	.014	.021	0.17	0.20	-	2.32	-	0.04	-	-	-	-
"	Check	0.15	0.26	.010	.021	0.17	0.17	-	2.39	1.28	-	-	-	.055	-
35M319	Ladle	0.16	1.45	.017	.038	0.21	0.48	0.08	0.53	-	0.08	-	-	-	-
	Check	0.17	1.36	.019	.035	0.19	0.41	0.09	0.59	-	-	-	-	.035	-
164969	Ladle	0.15	1.22	.022	.019	0.24	0.16	-	-	-	-	-	-	-	-
	Check	0.15	1.22	.022	.018	0.23	0.17	-	-	-	-	.001	-	.016	-
21242	Ladle	0.16	1.30	.013	.024	0.25	0.21	0.11	1.68	-	0.23	-	-	-	.006
	Check	0.15	1.32	.012	.026	0.25	0.22	0.13	1.62	-	0.31	-	-	.020	.005

* Acid-soluble aluminum content

TABLE 28. METHODS OF HEAT TREATMENT USED IN PRODUCING THE COMMERCIAL PLATES

Heat No.	Thickness of Plate	Type of Treatment
5M16076	3/4 inch	Spray quenched (water) from 1650°F., tempered at 1200°F. in a continuous furnace, and air cooled from the tempering temperature.
5M16076	1 inch	Same as for 3/4-inch plate.
19M519	3/4 inch	Heated in 1-1/4 hours to 1605°F.(875°C.), maintained at temperature one hour, water quenched(dipped) 2-1/2 minutes, heated in 1-1/2 hours to 1215°F. (655°C.), maintained at temperature 4 hours, water quenched (dipped) until cold.
19M519	1 inch	Heated in 1-1/2 hours to 1610°F.(875°C.), maintained at temperature 1-1/2 hours, water quenched(dipped) 3-1/2 minutes, heated in 1-3/4 hours to 1205°F.(650°C.), maintained at temperature 4 hours, water quenched(dipped) until cold.
35M319	3/4 inch	Heated to 1605°F.(875°C.) and maintained 1 hour, water quenched cold and reheated to 1238°F.(670°C.), maintained 1 hour and floor cooled. 1st redraw Heated to 1238°F.(670°C.), maintained 2 hours and floor cooled. 2nd redraw Heated to 1248°F.(675°C.), maintained 4 hours and floor cooled.
164969	1 inch	Water quenched 1625°-1650°F. Tempered 1215°F. for 4 hours, air cooled from tempering temperature.
21242	1 inch	Hot-rolled plates heat treated at Battelle by normalizing for one hour at 1650°F., tempered one hour at 1200°F. and air cooled from tempering temperature.

Crack-Sensitivity Tests

The crack sensitivity of these steels was determined using the standard procedure, 10 specimens from each heat being welded while held in a bath at 0°F. A summary of the results of these tests will be found in Table 29, and the data from each individual specimen are listed in Table 21 of the Appendix.

As shown in Table 29, the crack-sensitivity tests on both 3/4- and 1-inch plate from Heat 5M16076 showed no evidence of cracking, which can be explained by the low carbon and manganese contents, the check analysis on the plate showing 0.15 per cent carbon and 0.79 per cent manganese. While the silicon content of this steel is relatively high, 0.73 per cent, and it also contains small amounts of molybdenum and chromium, it has previously been shown that these alloys in the amount present are not detrimental to the crack sensitivity.

TABLE 29. CRACK SENSITIVITY OF THE COMMERCIAL HEAT-TREATED STEELS

Heat No.	Condition of Plate	Thickness of Plate	Number of Specimens Welded	Underbead Cracking, Per Cent
5M16076	Quenched and	3/4 inch	10	0
"	tempered	1 inch	10	0
19M519	Ditto	3/4 inch	10	0
"	"	1 inch	10	0
35M319	"	3/4 inch	10	64
"	"	1 inch	10	51
164969	"	1 inch	10	47
21242	Normalized and tempered	1 inch	10	52

The results of the tests from Heat 19M519 also appear to indicate a low degree of crack sensitivity. While this heat has low carbon and manganese contents, 0.15 and 0.26 per cent, respectively, it also contains 2.39 per cent nickel. Because of the high nickel content, it now appears that the crack-sensitivity results in this case are misleading because very recent work on another project has shown that low-carbon 2 or 3 per cent nickel steels do not crack when welded at 0°F. but will crack extensively when the specimens are welded at a higher initial temperature, such as 180°F. In view of these results, it would be necessary to make crack-sensitivity tests on the steel from Heat 19M519, using several initial temperatures between 0°F. and about 250°F. in order to definitely establish the crack sensitivity.

The remaining three steels in this group are all quite crack sensitive, cracking from 47 to 64 per cent. Since these heats are all appreciably higher in manganese than Heat 5M16C76 which showed no signs of cracking, these results appear to indicate the necessity of keeping the manganese content low in order to reduce underbead cracking.

HMB/CES/ALW:abn
September 30, 1948

APPENDIX

TABLE 1. LONGITUDINAL TENSILE PROPERTIES OF MANGANESE-MOLYBDENUM-VANADIUM LABORATORY HEATS FOR CONDITIONS INDICATED

Heat No.	Condition**	Elong. in 2 Inches, %	Red. of Area, %	Yield* Strength, psi.	Tensile Strength, psi.
X-51	HR	23.0	60.0	67,500	98,000
"	"	"	62.0	70,000	100,500
X-51	Homog.	23.0	63.5	69,800	99,500
"	"	"	64.0	72,800	101,500
X-51A	HR	21.5	56.5	75,500	107,000
"	"	"	59.0	77,500	108,500
X-51A	Homog.	21.0	60.0	78,000	109,500
"	"	20.5	59.5	76,000	109,000
X-53	HR	21.5	60.5	72,500	105,000
"	"	22.0	58.0	69,500	102,800
X-53	Homog.	20.0	55.0	79,000	109,500
"	"	"	"	75,000	106,000
X-53A	HR	19.0	52.0	84,500	115,500
"	"	"	55.5	84,000	113,800
X-53A	Homog.	19.0	50.5	84,300	115,500
"	"	18.5	51.0	88,500	118,500
X-55	HR	19.0	54.5	86,000	118,300
"	"	17.5	54.0	87,000	119,500
X-55A	HR	19.0	51.0	89,200	121,500
"	"	"	52.0	87,500	119,000
X-56	HR	20.0	59.0	84,000	112,500
"	"	19.0	59.0	84,000	112,000
X-56	Temp.	19.0	58.0	90,500	113,500
"	"	21.0	"	96,000	113,300
X-56A	HR	19.5	57.5	85,500	116,500
"	"	20.0	58.5	87,500	115,800
X-56A	Temp.	18.5	53.0	90,500	115,800
"	"	19.5	56.0	92,000	117,300

TABLE 1. Continued

Heat No.	Condition**	Elong. in 2 Inches, %	Red. of Area, %	Yield* Strength, psi.	Tensile Strength, psi.
X-57	HR	19.0	54.5	84,500	115,000
"	"	19.5	59.0	83,750	113,800
X-57	Temp.	21.0	57.0	91,000	115,800
"	"	20.0	55.0	90,500	114,500
X-57A	HR	16.0	42.0	88,000	116,300
"	"	"	39.0	86,500	115,300
X-57A	Temp.	19.0	52.5	91,000	116,300
"	"	18.5	52.5	91,500	117,300
X-58	HR	16.5	41.5	84,000	111,800
"	"	17.5	45.0	84,500	111,300
X-58	Temp.	19.0	53.5	91,500	113,500
"	"	"	57.5	93,500	112,700
X-58A	HR	18.5	55.5	87,000	116,500
"	"	19.0	56.0	88,500	118,300
X-58A	Temp.	18.0	53.5	93,500	116,300
"	"	20.0	54.5	93,000	117,000

* Yield strength at 0.2 per cent offset.

** Conditions as follows:

HR: Hot rolled

Homog.: 6-5/8-inch-square ingots were forged to 2-inch-thick slabs. Slabs were heated at 2350° for 4 hours, then hot rolled to one-inch-thick plates.

Temp.: Hot-rolled plates were tempered by heating at 1000°F. for one hour, then air cooled to room temperature.

TABLE 2. UNDERBEAD CRACKING RESULTS FOR MANGANESE-MOLYBDENUM-VANADIUM LABORATORY HEATS FOR CONDITIONS LISTED

Heat No.	Condition	Specimen Number	Underbead Cracking, Per Cent	
X-51	Hot rolled	1	16	
		2	31	
		3	11	
		4	24	
		5	34	
		6	30	
		7	10	
		8	40	
		9	20	
		10	23	Avg. 24
X-51	Homogenized*	1	5	
		2	5	
		3	5	
		4	5	
		5	7	
		6	0	
		7	9	
		8	10	
		9	10	
		10	5	Avg. 6
X-51A	Hot rolled	1	15	
		2	9	
		3	15	
		4	7	
		5	14	
		6	15	
		7	14	
		8	0	
		9	15	
		10	12	Avg. 12
X-51A	Homogenized*	1	5	
		2	0	
		3	0	
		4	6	
		5	0	
		6	9	
		7	0	
		8	0	
		9	2	
		10	0	Avg. 2

TABLE 2. Continued

Heat No.	Condition	Specimen Number	Underbead Cracking, Per Cent
X-53	Hot rolled	1	16
		2	36
		3	10
		4	30
		5	12
		6	15
		7	15
		8	12
		9	19
		10	17 Avg. 18
X-53	Homogenized*	1	12
		2	11
		3	6
		4	12
		5	18
		6	5
		7	12
		8	16
		9	5
		10	25 Avg. 12
X-53A	Hot rolled	1	14
		2	15
		3	24
		4	0
		5	40
		6	22
		7	5
		8	27
		9	10
		10	20 Avg. 18.0
X-53A	Homogenized*	1	4
		2	4
		3	15
		4	10
		5	0
		6	7
		7	5
		8	0
		9	4
		10	2 Avg. 5

TABLE 2. Continued

Heat No.	Condition	Specimen Number	Underbead Cracking, Per Cent
X-55	Hot rolled	1	73
		2	77
		3	79
		4	57
		5	54
		6	77
		7	63
		8	55
		9	49
		10	73 Avg. 66
X-55A	Hot rolled	1	30
		2	36
		3	15
		4	31
		5	35
		6	39
		7	18
		8	39
		9	26
		10	20 Avg. 29
X-56	Hot rolled	1	81
		2	73
		3	58
		4	-
		5	29
		6	34
		7	-
		8	30
		9	73
		10	73 Avg. 56
X-56A	Hot rolled	1	65
		2	53
		3	65
		4	47
		5	70
		6	58
		7	51
		8	36
		9	40
		10	64 Avg. 55

TABLE 2. Continued

Heat No.	Condition	Specimen Number	Underbead Cracking, Per Cent	
X-57	Hot rolled	1	97	
		2	84	
		3	81	
		4	72	
		5	63	
		6	55	
		7	79	
		8	57	
		9	75	
		10	71	Avg. 73
X-57A	Hot rolled	1	88	
		2	70	
		3	65	
		4	57	
		5	67	
		6	76	
		7	88	
		8	82	
		9	84	
		10	73	Avg. 75
X-58	Hot rolled	1	51	
		2	65	
		3	42	
		4	65	
		5	66	
		6	43	
		7	23	
		8	49	
		9	61	
		10	-	Avg. 52
X-58A	Hot rolled	1	49	
		2	61	
		3	66	
		4	52	
		5	36	
		6	73	
		7	60	
		8	67	
		9	73	
		10	73	Avg. 61

* Two-inch-thick slabs were forged from 6-5/8-inch square ingots, heated at 2350°F. for four hours, and hot rolled into one-inch plates.

TABLE 3. NOTCHED-BAR IMPACT PROPERTIES (CHARPY V-NOTCH) OF MANGANESE-MOLYBDENUM-VANADIUM LABORATORY HEATS FOR THE CONDITIONS INDICATED. LENGTH OF SPECIMENS IN DIRECTION OF ROLLING. SPECIMENS NOTCHED PERPENDICULAR TO PLATE SURFACE

Heat No.	Condition*	Testing Temperature, Degrees F.					
		-75	-40	-5	+40	+75	+210
X-51	Hot rolled	2-2-3-4	2-3-3-3	2-3-3-3	3-3-3-4	5-5-5-5	25-26-34-38
"	Homog.	2-2-2-3	2-2-2-2	2-2-2-2	3-3-3-4	5-6-6-6	28-30-34-35
X-51A	Hot rolled	3-5-6-7	5-6-6-8	5-5-5-6	6-7-8-10	8-10-13-14	31-34-36-37
"	Homog.	3-4-4-5	3-4-5-6	3-5-6-7	8-9-9-10	12-13-14-15	28-45-54-62
X-53	Hot rolled	2-2-2-2	3-3-3-3	2-2-2-2	3-3-3-3	4-4-4-5	16-17-20-24
"	Homog.	2-2-2-3	2-2-2-2	2-2-2-2	3-3-3-3	4-4-4-4	17-21-22-23
X-53A	Hot rolled	2-3-3-4	4-5-5-19	3-5-6-6	5-5-5-5	5-6-8-8	18-21-22-26
"	Homog.	3-3-3-4	2-3-4-4	3-4-4-4	4-5-6-6	5-6-9-11	16-20-22-40
X-56	Hot rolled	5-6-6-10	5-6-6-10	6-7-7-10	8-10-12-12	11-20-21-22	33-41-57-63
X56A	Hot rolled	3-3-3-3	3-3-4-4	3-4-5-6	5-5-6-7	7-8-8-11	14-14-22-22
X-57	Hot rolled	4-4-6-6	6-6-6-7	8-8-9-13	8-12-15-19	11-13-16-16	35-35-43-43
X-57A	Hot rolled	3-3-3-3	3-3-4-4	2-3-4-6	3-3-6-8	5-6-7-9	19-23-26-26
X-58	Hot rolled	3-3-4-4	3-4-4-5	4-4-5-6	5-6-6-8	6-8-8-13	21-21-24-24
X-58A	Hot rolled	3-3-3-3	2-2-2-3	2-2-2-5	3-4-5-6	3-4-6-8	12-13-19-20

* Homog. = Two-inch-thick slabs were forged from 6-5/8 inch square ingots. Slabs were heated for 4 hours at 2350°F. and hot rolled into one-inch-thick plates.

TABLE 4. LONGITUDINAL TENSILE PROPERTIES OF MANGANESE-MOLYBDENUM-VANADIUM-NICKEL-COPPER LABORATORY HEATS IN VARIOUS CONDITIONS

Heat No.	Condition*	Elong. in 2 Inches, %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
X-63	A	19.0	39.5	72,500	115,300
		21.0	44.5	75,500	114,800
"	B	20.0	55.5	84,000	126,000
		20.0	55.5	84,000	126,200
"	C	23.5	60.5	80,000	107,500
		24.5	61.5	79,500	107,500
X-64	A	20.5	44.5	77,800	117,800
		20.5	45.0	80,000	118,500
"	B	21.5	53.5	82,000	128,300
		21.5	50.0	82,000	128,800
"	C	20.5	59.0	108,500	131,000
		21.0	59.0	111,000	130,500
X-65	A	22.0	55.0	78,000	108,300
		21.0	53.5	80,500	108,500
"	B	21.5	57.0	78,000	119,500
		21.5	56.5	78,000	120,000
"	C	21.5	59.5	103,500	125,500
		21.5	61.0	104,000	125,000
X-66	A	16.0	29.0	85,300	119,000
		18.0	38.0	82,000	115,500
"	B	20.0	50.5	92,000	136,300
		19.5	48.5	93,000	136,300
X-66	C	20.0	55.0	118,500	135,500
		20.5	56.0	112,000	137,100
"	D	20.0	54.0	111,800	137,300
		20.0	53.5	111,000	136,500
"	E	19.0	51.0	97,500	132,500
		19.0	50.5	94,500	132,800

* Condition: A = Hot rolled
B = Normalized 1650°F. for 1 hour
C = Normalized 1650°F., tempered 1200°F. for 1 hour
D = " " " 1300°F. " " "
E = " " " 1000°F. " " "

TABLE 5. UNDERBEAD CRACKING RESULTS FOR THE MANGANESE-MOLYBDENUM-VANADIUM-NICKEL-COPPER LABORATORY HEATS FOR THE CONDITIONS LISTED

Heat No.	Condition	Specimen No.	Per Cent Cracking* When Welded at 0°F.	+75°F.	+210°F.
X-63	Hot rolled	1	20	6	0
		2	3	0	7
		3	0	6	14
		4	0	13	10
		5	9	6	13
		6	6	-	-
		7	6	-	-
		8	0	-	-
		9	0	-	-
		10	9	-	-
		Average	5	7	9
X-63	Norm. 1650°F., not tempered	1	0	-	-
		2	0	-	-
		3	0	-	-
		4	0	-	-
		5	0	-	-
		6	0	-	-
		7	0	-	-
		8	0	-	-
		9	0	-	-
		10	0	-	-
		Average	0	-	-
X-64	Hot rolled	1	39	-	-
		2	13	-	-
		3	13	-	-
		4	15	-	-
		5	14	-	-
		6	20	-	-
		7	28	-	-
		8	38	-	-
		9	40	-	-
		10	16	-	-
		Average	24	-	-
X-64	Norm. 1650°F., tempered 1 hr. at 1200°F.	1	0	-	-
		2	0	-	-
		3	0	-	-
		4	0	-	-
		5	0	-	-
		6	0	-	-
		7-	0	-	-
		8	0	-	-
		9	10	-	-
		10	0	-	-
		Average	1	-	-

TABLE 5. (Continued)

Heat No.	Condition	Specimen No.	Per Cent Cracking* When Welded at 0°F.	+75°F.	+210°F.
X-65	Hot rolled	1	14	7	43
		2	21	14	12
		3	9	22	30
		4	34	5	0
		5	8	45	0
		6	18	-	-
		7	15	-	-
		8	5	-	-
		9	11	-	-
		10	6	-	-
		Average	14	19	17
X-65	Norm. 1650°F., tempered 1 hr. at 1200°F.	1	0	-	-
		2	0	-	-
		3	0	-	-
		4	0	-	-
		5	0	-	-
		6	0	-	-
		7	0	-	-
		8	0	-	-
		9	0	-	-
		10	0	-	-
		Average	0	-	-
X-66	Hot rolled	1	11	-	-
		2	12	-	-
		3	10	-	-
		4	-	-	-
		5	18	-	-
		6	0	-	-
		7	16	-	-
		8	5	-	-
		9	0	-	-
		10	10	-	-
		Average	9	-	-
X-66	Norm. 1650°F.	1	4	-	-
		2	4	-	-
		3	8	-	-
		4	6	-	-
		5	17	-	-
		Average	8	-	-

Heat No.	Condition	Specimen No.	Per Cent Cracking* When Welded at 0°F.	+75°F.	+210°F.
X-66	Norm. 1650°F., tempered 1 hr. at 1200°F.	1	10	-	-
		2	0	-	-
		3	10	-	-
		4	30	-	-
		5	13	-	-
		Average	13	-	-

* All specimens were welded according to the standard procedure excepting those at +75° and +210°F. Water was used at these temperatures and the specimens were partially immersed in it.

TABLE 6. NOTCHED-BAR IMPACT PROPERTIES (CHARPY V-NOTCH AND KEYHOLD TESTS) OF MANGANESE-MOLYBDENUM-VANADIUM-NICKEL-COPPER LABORATORY HEATS FOR THE CONDITIONS INDICATED. LENGTH OF SPECIMENS IN DIRECTION OF ROLLING. SPECIMENS NOTCHED PERPENDICULAR TO PLATE SURFACE.

Heat No.	Condition	Type of Test	Testing Temperature, Degrees F.					
			-75	-40	-5	+40	+75	+210
X-63	Hot rolled	V-notch	3-4-4-4	4-4-5-5	6-6-6-6	9-9-10-10	19-19-19-20	55-55-56-56
"	" "	Keyhole		4-6-6-6				
"	Normalized*	"		21-25-26-26				
X-64	Hot rolled	V-notch	3-3-4-4	4-5-5-6	6-6-6-7	8-9-10-10	13-14-15-16	40-40-41-44
"	" "	Keyhole		7-7-7-8				
"	Norm.& drawn**	"		10-12-15-16				
X-65	Hot rolled	V-notch	4-4-5-6	6-6-7-8	6-7-10-12	9-13-17-19	18-25-26-27	76-76-78-79
"	" "	Keyhole		5-6-9-12				
"	Norm.& drawn**	"		9-13-13-17				
X-66	Hot rolled	V-notch		5-6-6-7	7-8-9-10		17-19-20-21	
"	" "	Keyhole		7-7-8-8				
"	Normalized*	V-notch		6-6-6-6	7-7-8-8		15-17-17-19	
"	"	Keyhole		7-7-8-8				
"	Norm.& drawn**	V-notch		3-3-4-5	3-4-5-6		7-8-9-9	
"	" "	Keyhole		5-6-7-8				
"	" "***	V-notch		6-8-9-10	9-10-13-15		6-10-11-14	

* Normalized at 1650°F.
** Normalized at 1650°F., drawn 1200°F. for 1 hour, air cooled.
*** Normalized at 1650°F., drawn 1100°F. for 1 hour, air cooled.

TABLE 7. LONGITUDINAL TENSILE PROPERTIES OF MANGANESE-CHROMIUM AND STANDARD COMPOSITION LABORATORY HEATS FOR THE CONDITIONS LISTED

Heat No.	Condition	Elong. in 2 Inches, %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
		(Standard Composition Heats)			
X-45	Hot rolled	34.5	69.0	51,750	78,900
"	" "	33.0	65.4	52,500	79,250
X-46	" "	35.0	70.1	49,750	79,900
"	" "	35.0	70.1	51,750	80,750
		(Manganese-Chromium Heats)			
X-59	" "	34.0	69.0	48,000	79,500
"	" "	33.0	70.0	48,800	80,500
X-60	" "	31.5	69.0	50,000	81,800
"	" "	31.5	71.0	49,500	82,000
X-61	" "	28.0	66.0	52,500	89,500
"	" "	28.0	64.0	50,500	87,000
X-62	" "	27.0	65.5	55,000	92,800
"	" "	27.0	66.0	54,000	91,000
"	Homog. & Norm.*	24.5	61.0	61,500	102,300
"	" "	24.5	61.5	60,900	100,300

* One-inch-thick plates were homogenized for 4 hours at 2350°F. and then normalized at 1650°F.

TABLE 8. UNDERBEAD CRACKING RESULTS FOR MANGANESE-CHROMIUM AND STANDARD COMPOSITION LABORATORY HEATS FOR THE CONDITIONS LISTED

Heat No.	Specimen No.	Per Cent Cracking	
		Hot Rolled	Homog.-Norm.*
	(Standard Composition Heats)		
X-45	1	14	10
	2	40	2
	3	99	4
	4	70	4
	5	64	4
	6	25	0
	7	91	5
	8	46	11
	9	36	12
	10	83	5
	Average	57	6
X-46	1	64	19
	2	75	27
	3	90	25
	4	86	7
	5	29	5
	6	53	6
	7	68	27
	8	75	7
	9	9	9
	10	53	6
	Average	60	14
	(Manganese-Chromium Heats)		
X-59	1	33	-
	2	46	-
	3	45	-
	4	23	-
	5	32	-
	6	16	-
	7	29	-
	8	4	-
	9	22	-
	10	29	-
	Average	28	-
X-60	1	21	-
	2	16	-
	3	17	-
	4	41	-
	5	23	-

TABLE 8. Continued

Heat No.	Specimen No.	Per Cent Cracking	
		Hot Rolled	Homog.-Norm.*
X-60	6	4	-
	7	7	-
	8	35	-
	9	10	-
	10	27	-
	Average	20	-
X-61	1	68	-
	2	74	-
	3	62	-
	4	64	-
	5	40	-
	6	70	-
	7	85	-
	8	50	-
	9	65	-
	10	70	-
	Average	65	-
X-62	1	49	2
	2	34	11
	3	30	5
	4	68	0
	5	70	7
	6	78	7
	7	55	9
	8	60	8
	9	38	0
	10	55	10
	Average	54	5

* Plate homogenized 4 hours at 2350°F. and then normalized 1650°F.

TABLE 9. CHARPY NOTCHED-BAR IMPACT PROPERTIES OF MANGANESE-CHROMIUM LABORATORY HEATS FOR CONDITIONS LISTED. SPECIMENS PREPARED LONGITUDINAL TO DIRECTION OF ROLLING AND V-TYPE NOTCHES CUT PERPENDICULAR AND PARALLEL TO THE PLATE SURFACE

Heat No.	Condition	Notched	Testing Temperature, Degrees F. -75	-40	-5	+40	+75	+210
			(Standard Composition Heats)					
X-45	Hot Rolled	Parallel	22-4-6-6	105-19-14-46	45-112-132-126 27-111-102-125	107-132-106-119	121-121-116-113	104-116-116-111
X-46	Hot Rolled	"	8-6-9-9	75-20-30-41	30-121-115-100 110-111-102-92	117-149-111-117	129-123-115-116	110-100-133-110
X-59	Hot rolled (1" plate)	Perp.	3-3-7-9	4-5-6-25	25-27-28-30	38-41-43-48	43-58-60-61	77-80-80-84
"	Ditto	Parallel	3-3-3-5	4-6-8-20	4-14-21-38	42-46-48-90	88-104-113-130	109-115-117-118
X-60	"	Perp.	3-3-8-8	4-4-7-20	18-29-34-37	36-46-51-56	47-49-52-61	78-80-80-80
"	"	Parallel	3-4-5-6	3-5-5-8	7-11-24-25	36-40-46-50	45-46-94-103	90-91-110-113
X-61	"	Perp.	2-3-3-3	4-4-6-11	6-10-11-14	23-23-30-32	28-36-39-40	70-70-72-75
"	"	Parallel	2-3-3-3	3-3-6-7	3-8-9-15	9-13-13-28	26-29-43-102	81-82-88-104
X-62	"	Perp.	2-2-2-3	3-4-5-12	3-4-9-10	11-19-20-28	26-28-31-31	68-68-68-69
"	"	Parallel	2-2-3-5	2-2-3-3	3-4-9-16	7-7-9-22	30-30-33-37	77-80-93-108
"	Plate homog. 2350°F. for 4 hrs. then normalized	"	3-5-6-7	4-5-8-11	11-28-33-119	40-50-110-145	98-128-135-164	90-98-117-120

Note: The above impact values are given in foot-pounds. The specimens used were the standard V-notch Charpy bars which were broken on a Riehle impact machine having an initial energy of 220 foot-pounds.

TABLE 10. LONGITUDINAL TENSILE PROPERTIES OF ONE-INCH-THICK PLATES HOT ROLLED FROM HOMOGENIZED COMMERCIAL SLABS

Steel No.	Slab Homog, Time, Hrs.	Elong. in 2 Inches, %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
23H0	Reg. Practice*	21.0	56.0	69,700	103,300
"	" "	23.0	55.5	70,500	103,300
23H2.5	2.5	20.0	55.5	72,500	105,500
"	"	21.0	57.5	74,700	105,500
23H5	5	21.0	59.5	73,200	102,300
"	"	21.0	59.5	71,200	102,500
23H10	10	23.5	65.0	68,200	95,000
"	"	23.5	66.0	68,200	95,200
26H0	Reg Practice*	24.5	65.1	66,800	98,000
"	" "	25.0	62.3	65,500	98,000
26H3	3	23.5	61.8	68,500	103,500
"	"	23.5	60.6	68,500	104,500
26H8	8	24.0	62.6	69,000	103,500
"	"	24.0	62.6	69,500	103,000
26H13	13	24.5	63.3	69,500	103,000
"	"	24.5	62.3	69,000	102,600

* The regular practice consisted of heating the slabs to the rolling temperature and holding for about 1/2 - 1 1/2 hours before rolling.

TABLE 11. UNDERBEAD CRACKING RESULTS FOR STEEL 23H AFTER HOT ROLLING FROM SLABS HOMOGENIZED AT 2300°F. TO ONE-INCH PLATES

Steel No.	Homogenizing Time, Hrs.	Specimen No.	Per Cent Cracking
23H0	Regular practice*	1	64
		2	81
		3	79
		4	81
		5	80
		6	79
		7	80
		8	74
		9	83
		10	86 Avg. 79
23H2.5	2-1/2	1	78
		2	94
		3	83
		4	79
		5	80
		6	75
		7	94
		8	80
		9	98
		10	56 Avg. 81
23H5	5	1	65
		2	84
		3	84
		4	73
		5	86
		6	90
		7	83
		8	86
		9	75
		10	74 Avg. 80
23H10	10	1	81
		2	83
		3	100
		4	83
		5	70
		6	60
		7	85
		8	78
		9	65
		10	88 Avg. 79

* The regular practice consisted of heating the slabs to the rolling temperature and holding for about 1/2 - 1 1/2 hours before rolling.

TABLE 12. UNDERBEAD CRACKING RESULTS FOR STEEL 26H AFTER HOT ROLLING FROM SLABS HOMOGENIZED AT 2350°F. TO ONE-INCH PLATES

Steel No.	Homog. Time, Hrs.	Spec. No.	Extent of Cracking, Per Cent: Welded at 0°F. Group 1	Gr. 2	Gr. 3	Welded Room Temp. in Water	Welded Room Temp. in Air
26H0	Reg. pract.*	1	6	4	2	15	12
		2	0	9	2	0	10
		3	25	15	0	4	5
		4	7	5	0	13	10
		5	5	7	0	7	0
		6	13	0	10	22	13
		7	25	18	0	5	5
		8	17	10	0	26	12
		9	15	6	0	6	11
		10	7	5	0	10	26
		Average	12	8	1	11	10
26H3	3	1	15	11	5	15	16
		2	17	13	13	20	11
		3	6	13	0	21	12
		4	0	16	0	18	15
		5	24	26	7	12	12
		6	10	17	5	21	5
		7	25	17	2	11	7
		8	10	16	0	26	5
		9	30	30	10	5	4
		10	13	11	0	34	5
		Average	15	16	4	18	9
26H8	8	1	5	4	5	10	10
		2	10	0	0	10	11
		3	5	5	0	12	0
		4	7	0	0	12	10
		5	0	6	7	6	5
		6	11	0	5	20	2
		7	9	30	8	15	5
		8	10	0	9	10	15
		9	2	6	5	0	4
		10	4	20	0	16	12
		Average	6	7	4	11	7
26H13	13	1	0	8	0	20	4
		2	0	14	0	11	2
		3	0	5	0	15	9
		4	0	7	0	10	19
		5	0	6	0	9	9
		6	0	0	5	16	10
		7	0	6	0	14	10
		8	0	0	5	15	6
		9	0	9	6	25	6
		10	0	3	0	20	16
		Average	0	6	2	15	9

* The regular practice consisted of heating the slabs to the rolling temperature and holding for about 1/2 - 1 1/2 hours before rolling.

TABLE 13. UNDERBEAD CRACKING RESULTS FOR ONE-INCH PLATE FROM STEEL 39 IN THE HOT-ROLLED CONDITION AND AFTER HOMOGENIZING AT 2350°F. AND 2400°F. FOLLOWED BY NORMALIZING AT 1650°F.

Condition of Plate	Specimen No.	Underbead Cracking, %
Hot rolled	1	95
	2	75
	3	63
	4	76
	5	93
	6	80
	7	71
	8	84
	9	75
	10	70 Avg. 78
Homogenized 10 min. at 2350°F.	1	48
	2	34
	3	12
	4	25
	5	55 Avg. 35
Homogenized 1 hr. at 2350°F.	1	39
	2	19
	3	23
	4	25
	5	33 Avg. 28
Homogenized 3 hrs. at 2350°F.	1	23
	2	23
	3	28
	4	34
	5	40 Avg. 30
Homogenized 5 hrs. at 2350°F.	1	8
	2	6
	3	23
	4	20
	5	13 Avg. 14
Homogenized 10 min. at 2400°F.	1	28
	2	0
	3	30
	4	20
	5	40 Avg. 24

TABLE 13. Continued

Condition of Plate	Specimen No.	Underbead Cracking, %
Homogenized 1 hr. at 2400°F.	1	14
	2	10
	3	8
	4	5
	5	25 Avg. 12
Homogenized 3 hrs. at 2400°F.	1	13
	2	20
	3	10
	4	10
	5	13 Avg. 14
Homogenized 5 hrs. at 2400°F.	1	11
	2	9
	3	6
	4	8
	5	16 Avg. 10

TABLE 14. NOTCHED-BAR IMPACT PROPERTIES OF ONE-INCH-THICK PLATES HOT ROLLED FROM HOMOGENIZED SLABS (STEEL 26H) STANDARD CHARPY BARS WITH V-TYPE NOTCH CUT PERPENDICULAR TO PLATE SURFACE USED. LENGTH OF SPECIMENS IN DIRECTION OF ROLLING

Steel No.	Testing Temperature, Degrees F.					
	-75	-40	-5	+40	+75	+210
23H0	2-3-5-3	2-3-3-4	4-4-4-5	5-5-6-8	8-8-9-10	32-34-36-41
23H2.5	3-3-4-4	3-3-4-5	4-5-6-7	6-7-7-8	10-12-13-14	43-44-53-64
23H5	3-3-4-4	4-4-4-5	4-4-4-5	6-7-7-7	10-10-13-20	39-41-43-49
23H10	3-4-6-7	6-6-8-9	4-6-10-19	15-16-20-20	12-12-32-36	60-77-82-90
26H0	3-3-3-4	5-5-5-5	5-6-6-7	10-10-10-11	18-21-21-23	89-91-91-99
26H3	3-3-3-4	4-5-5-6	5-6-6-6	9-9-9-10	15-15-17-18	73-75-75-76
26H8	4-5-6-6	6-6-7-7	8-8-8-9	15-15-16-19	28-30-30-33	86-87-87-92
26H13	4-4-5-5	5-5-6-6	7-7-8-8	15-17-18-21	25-29-33-32	86-87-90-93

Note: The above impact values are given in foot-pounds. The specimens used were the standard V-notch Charpy bars which were broken on a Riehle impact machine having an initial energy of 220 foot-pounds.

TABLE 15. HARDNESS TRAVERSES OF THE HEAT-AFFECTED ZONE UNDER THE WELD BEAD OF UNTEMPERED CRACK-SENSITIVITY SPECIMENS. VALUES EXPRESSED AS VICKERS HARDNESS NUMBERS. ONE KILOGRAM LOAD USED. IMPRESSIONS SPACED .005-INCH APART

	Heat X-9							
	Hot Rolled				Homog. 2350°F.-4 Hrs.-Norm.			
	Specimen Number				Specimen Number			
Traverse	1	2	3	4	1	2	3	5
Weld metal	283	305	297	283	283	263	269	263
" "	283	297	305	305	305	290	263	283
Heat-affected zone	378	348	358	368	439	401	413	453
" " "	358	439	426	467	482	413	515	467
" " "	467	453	467	439	453	415	467	426
" " "	498	453	467	467	426	368	426	453
" " "	426	467	482	426	426	348	413	467
" " "	413	439	482	439	390	338	413	426
" " "	401	426	453	401	368	358	368	401
" " "	348	413	482	348	313	321	358	356
" " "	339	313	378	330	321	297	313	330
" " "	330	339	373	378	305	283	297	330
Base metal	197	197	224	205	205	205	189	197
	Heat X-17							
	Hot Rolled				Homog. 2350°F.-4 Hrs.-Norm.			
	Specimen Number				Specimen Number			
	1	2	3	4	1	2	3	4
Weld metal	297	283	297	313	239	368	297	269
" "	313	283	290	290	257	348	321	305
Heat-affected zone	401	339	426	378	348	467	482	439
" " "	439	498	378	439	348	467	482	467
" " "	482	498	467	515	378	498	482	467
" " "	439	467	467	551	390	498	515	467
" " "	533	482	413	515	426	498	551	439
" " "	482	453	439	515	426	482	498	467
" " "	498	498	439	390	358	515	498	515
" " "	533	401	426	498	330	453	498	498
" " "	439	439	358	498	358	453	467	498
" " "	339	339	368	378	313	378	426	439
Base metal	197	197	205	197	186	197	189	201

TABLE 15. Continued

Traverse	Heat X-22							
	Hot Rolled				Homog. 2350°F.-4 Hrs.-Norm.			
	Specimen Number				Specimen Number			
	1	2	3	5	1	2	3	4
Weld metal	305	305	297	297	313	321	330	348
" "	313	269	290	297	305	313	358	330
Heat-affected zone	426	453	467	358	348	482	533	401
" " "	401	426	413	453	413	453	498	498
" " "	401	467	467	453	467	453	482	533
" " "	482	467	453	453	439	453	482	498
" " "	482	467	413	482	439	426	439	482
" " "	426	439	401	498	413	413	426	453
" " "	426	498	413	401	401	401	401	467
" " "	439	321	378	413	378	401	401	426
" " "	390	348	368	368	358	330	401	368
" " "	339	348	263	330	321	321	348	358
Base metal	245	239	239	257	214	219	219	219

Traverse	Heat X-61							
	As Rolled				Homog. 2350°F.-4 Hrs.-Norm.			
	Specimen Number				Specimen Number			
	11	12	13	14	6	8	9	10
Weld metal	330	330	339	368	358	368	330	439
" "	348	321	368	368	358	390	413	426
Heat-affected zone	426	498	482	390	348	413	482	551
" " "	498	498	498	482	439	515	498	591
" " "	571	571	515	453	571	551	467	515
" " "	482	571	591	533	613	551	439	591
" " "	551	551	591	533	571	551	467	533
" " "	482	571	613	515	515	591	515	571
" " "	533	591	551	515	515	591	533	613
" " "	551	660	591	571	551	613	498	591
" " "	571	613	551	482	571	591	482	533
Base metal	234	239	224	219	229	224	224	224

Traverse	Heat X-40			Heat 40		
	Hot Rolled			Hot Rolled		
	Specimen Number			Specimen Number		
	1	2	3	1	2	3
Weld metal	297	290	297	290	283	283
" "	339	348	297	290	290	269
Heat-affected zone	467	426	467	390	348	413
" " "	426	467	482	426	453	426
" " "	453	467	453	426	439	413
" " "	467	413	439	453	439	401
" " "	368	339	368	426	439	439
" " "	358	297	313	453	453	453
" " "	330	297	321	439	413	413
" " "	269	290	321	413	413	401
" " "	251	245	269	413	426	378
" " "	257	234	245	390	413	297
Base metal	229	229	229	229	229	234

TABLE 15. Continued

Traverse	Heat Z16, Hot Rolled Specimen Number 11	 12	 13
Weld metal	276	245	269
" "	276	263	276
Heat-affected zone	413	368	401
" " "	390	390	426
" " "	358	390	413
" " "	368	339	339
" " "	358	313	339
" " "	321	305	321
" " "	305	290	305
" " "	297	251	283
" " "	269	269	269
" " "	263	276	276
Base metal	205	210	219

TABLE 16. UNDERBEAD WELD CRACKING INDEXES FOR THE VARIOUS STEELS USED TO DETERMINE THE HARDNESS UNDER THE WELD BEAD

Steel No.	Specimen No.	Cracking, Per Cent	
		Hot Rolled	Homog.-Norm.*
X-9	1	71	9
	2	74	14
	3	76	3
	4	68	23
	5	60	10
	6	34	8
	7	58	8
	8	70	20
	9	6	10
	10	71	10
	Average	59	11
X-17	1	71	21
	2	74	10
	3	54	4
	4	74	17
	5	71	7
	6	71	20
	7	63	-
	8	81	-
	9	84	-
	10	64	-
	Average	71	13
X-22	1	74	6
	2	80	15
	3	78	9
	4	70	11
	5	71	9
	6	65	12
	7	95	-
	8	79	-
	9	70	-
	10	54	-
	Average	74	10
X-61	1	68	32
	2	74	0
	3	62	15
	4	64	10
	5	40	14
	6	70	-
	7	85	-
	8	50	-
	9	65	-
	10	70	-
	Average	65	14

TABLE 16. Continued

Steel No.	Specimen No.	Cracking, Per Cent Hot Rolled	Cracking, Per Cent Homog.-Norm.*
X-40	1	5	-
	2	0	-
	3	4	-
	4	8	-
	5	4	-
	Average	4	-
40	1	0	-
	2	0	-
	3	5	-
	4	0	-
	5	7	-
	Average	2	-
Z16	1	6	-
	2	19	-
	3	12	-
	4	5	-
	5	15	-
	6	12	-
	7	20	-
	8	15	-
	9	21	-
	10	21	-
	Average	15	-

* One-inch-thick plates were homogenized for 4 hours at 2350°F. and then normalized at 1650°F.

TABLE 17. TENSILE PROPERTIES OF STEELS 23HO, 26HO, AND 34 IN THE HOT-ROLLED CONDITION AND AFTER WATER QUENCHING FROM 1650°F.

Steel No.	Direction of Test	Condition	Elong. in 2", %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
		(1/2-inch-diameter tensile specimens)				
23HO	Long.	Hot rolled	22.5	56.5	70,500	101,200
			21.5	55.5	71,000	101,700
"	Trans.	" "	22.0	51.5	70,500	101,500
			20.0	51.5	69,500	101,200
"	Long.	Quenched	15.0	49.0	143,500	212,200
			15.5	52.0	146,500	212,200
"	Trans.	"	13.5	41.5	152,800	209,600
			14.0	43.5	152,800	210,300
26HO	Long.	Hot rolled	22.5	52.5	68,700	99,000
			25.0	64.5	66,300	96,600
"	Trans.	" "	22.0	59.5	68,700	97,500
			24.0	60.5	67,200	96,800
"	Long.	Quenched	17.0	61.0	138,800	178,000
			15.0	57.0	139,400	180,000
"	Trans.	"	14.0	48.5	129,000	178,000
			14.0	48.5	131,500	178,000
34	Long.	Hot rolled	32.0	70.0	53,000	86,000
			31.5	71.5	54,000	86,200
"	Trans.	" "	28.0	60.0	55,500	85,500
			27.0	60.0	55,000	86,100
"	Long.	Quenched	11.0	28.0	154,800	221,200
			12.0	30.5	157,200	223,000
"	Trans.	"	6.0	16.0	165,000	213,000
			8.0	18.0	169,000	221,000
23HO	Long.	Quenched	8.5	46.5	--	221,300
			8.5	48.5	--	219,700
26H	Long.	"	10.5	59.0	--	195,200
			11.0	59.0	--	196,200

TABLE 18. CHARPY NOTCHED-BAR IMPACT PROPERTIES OF STEELS 23HO, 26HO, AND 34 AFTER WATER QUENCHING FROM 1650°F. SPECIMENS WITH V-TYPE NOTCHES CUT PERPENDICULAR TO THE PLATE SURFACE WERE USED. THE LENGTH OF THE SPECIMENS WAS IN THE DIRECTION OF ROLLING.

Steel No.	Testing Temperature, Degrees F.					
	-75	-40	-5	+40	+75	+210
23HO	11-11-12-25	11-13-13-14	15-18-18-18	23-25-25-30	25-25-27-29	33-34-34-35
26HO	10-12-16-20	16-16-17-21	22-25-25-29	35-35-38-43	39-40-40-42	43-43-45-45
34	4-4-5-7	5-5-6-8	4-6-6-9	8-9-10-16	6-10-10-11	14-15-16-18

Note: The above impact values are given in foot-pounds. The specimens used were the standard V-notch Charpy bars which were broken on a Riehle impact machine having an initial energy of 220 foot-pounds.

TABLE 19. TENSILE PROPERTIES OF BUTT-WELDED SPECIMENS FROM STEELS 24 AND 40. BOTH STEELS HEAT TREATED* PRIOR TO WELDING.

Steel No.	Description of Specimen	Elong. in 2", %	Yield Strength, psi.	Tensile Strength, psi.
24	Base plate only	35.0	79,300	96,400
		36.0	79,900	97,800
"	As welded	36.0	78,200	96,500
		35.0	78,700	96,800
"	Welded bead machined flush to plate	38.0	77,500	96,100
		38.0	79,400	97,000
40	Base plate only	43.0	86,000	100,300
		45.0	87,300	101,000
"	As welded	45.0	83,100	98,300
		44.0	82,400	98,000
"	Welded bead machined flush to plate	43.0	84,200	98,900
		42.0	84,100	98,400

* Steel 24 was heat treated in a continuous furnace by the Great Lakes Steel Corporation by water quenching from 1650°F. and tempering at 1200°F. Plate was 3/4" thick.

Steel 40 was water quenched from 1600°F. and tempered for one hour at 1200°F. Plate thickness was one inch.

TABLE 20. UNDERBEAD CRACKING RESULTS FOR STEELS 28 AND 39 WHEN WELDED WITH VARIOUS TYPES OF ELECTRODES. TESTS RUN AT 0°F.

Steel No.	Type of Electrode	Size of Electrode	Specimen No.	Cracking, Per Cent
39	E 6010	1/8 inch	1	95
			2	75
			3	63
			4	76
			5	93
			6	80
			7	71
			8	84
			9	75
			10	70 Avg.78
39	E 6015	1/8 inch	1	0
			2	0
			3	0
			4	0
			5	0
			6	0
			7	0
			8	0
			9	0
			10	0 Avg.0
39	E 6020	1/8 inch	1	16
			2	11
			3	25
			4	17
			5	31
			6	24
			7	24
			8	10
			9	33
			10	8 Avg.20
28	E 6010	1/8 inch	1	47
			2	45
			3	46
			4	59
			5	44
			6	45
			7	31
			8	46
			9	62
			10	40 Avg.47

TABLE 20. Continued

Steel No.	Type of Electrode	Size of Electrode	Specimen No.	Cracking, Per Cent
28	E 6010	3/16 inch	1	94
			2	115
			3	68
			4	85
			5	91
			6	104
			7	85
			8	75
			9	103
			10	130 Avg.95
28	Lime Ferritic	3/16 inch	1	0
			2	0
			3	0
			4	0
			5	0
			6	0
			7	0
			8	0
			9	0
			10	0 Avg 0
28	Lime Ferritic	3/16 inch	1	0
			2	0
			3	0
			4	0
			5	0
			6	0
			7	0
			8	0
			9	0
			10	0 Avg.0

TABLE 21. UNDERBEAD CRACKING RESULTS FOR SPECIAL TREATED COMMERCIAL STEELS AS RECEIVED

Heat No.	Thickness of Plate	Specimen No.	Cracking, Per Cent
5M16076	3/4 inch	1-10	None showed cracking
"	1 inch	1-10	" " "
19M519	3/4 inch	1-10	" " "
"	1 inch	1-10	" " "
35M319	3/4 inch	1	65
		2	66
		3	--
		4	54
		5	70
		6	74
		7	65
		8	64
		9	74
		10	48 Avg. 64
35M319	1 inch	1	61
		2	61
		3	35
		4	50
		5	57
		6	49
		7	38
		8	53
		9	58
		10	-- Avg. 51
164969	1 inch	1	47
		2	45
		3	46
		4	59
		5	44
		6	45
		7	31
		8	46
		9	62
		10	40 Avg. 47

TABLE 21. Continued

Heat No.	Thickness of Plate	Specimen No.	Cracking, Per Cent
21242	1 inch	1	52
		2	60
		3	44
		4	57
		5	48
		6	45
		7	40
		8	59
		9	57
		10	60 Avg. 52