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FINAL AND SUMMARY REPORT

ON

METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

BY

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

Battelle Memorial Institute
Under Bureau of Ships Contract NObs-31219

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

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UNDER

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June 8, 1949

Chief, Bureau of Ships
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Dear Sir:

Attached is Report Serial No. SSC-26 entitled "Metallurgical Quality of Steels Used for Hull Construction." This report has been submitted by the contractor as a Final and Summary 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, Chairman
Division of Engineering and
Industrial Research

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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METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

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

BATTELLE MEMORIAL INSTITUTE

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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

The purpose of this investigation, which concerns high-tensile plate steel (HTS type) used in the construction of welded ship hulls, was twofold, the first part being an investigation of the metallurgical quality with special attention being given to those factors which might influence the welding characteristics and the performance of the welded structure. The second part of the project covers the development of higher strength steels suitable for welded structures.

Since it was decided that the welding characteristics of the HTS type of steel should be evaluated largely on the basis of underbead

cracking, it was first necessary to develop a weld test which would indicate quantitatively the weld crack sensitivity. A single-bead weld test was developed for this purpose.

A study of twenty commercial HTS type steels showed that, in general, the steels with higher chemical composition were the most susceptible to underbead cracking, but frequently the variations in crack sensitivity found in different lots of steel could not be accounted for on the basis of chemical analysis, hardness of the heat-affected zone, hardenability, or the other properties commonly determined.

Further study of these commercial steels showed that thermal processing had a pronounced influence upon the underbead cracking or crack sensitivity, the sensitivity being increased by annealing and decreased by homogenizing. In the case of similar chemical compositions, the level of crack sensitivity was found to increase with the degree of microsegregation. Homogenizing treatments, therefore, which decreased the extent of microsegregation, lowered the crack sensitivity, while annealing, which produced pearlite bands superimposed upon the alloy bands, increased the underbead cracking.

Although the crack sensitivity of plate can be reduced to a marked degree by homogenizing at 2350°F. for a relatively short period, such a treatment is not commercially feasible because of the excessive scaling and warping that would occur to the finished product. Homogenizing the slabs prior to rolling into plate was found to be impractical because of the excessive time required.

A good correlation was found between the crack sensitivity and the depth of complete transformation in the heat-affected zone when expressed as per cent of the total depth of the affected zone under the weld bead.

The steels with relatively deep zones of complete transformation were the most crack sensitive. This correlation was not found when using the standard hardenability test, indicating that the rate of response of the steel to the rapid thermal cycle developed during welding is a factor.

Of the three types of HTS steels, the vanadium-containing steels displayed the best combination of high yield strength and low underbead cracking. A combination of low carbon and moderate manganese contents, together with high aluminum and a fine microstructure, was found to be conducive to high notched-bar impact strength. While increased aluminum content was found to lower the temperature of the transition zone, as would be expected, aluminum additions up to one pound per ton were found to be progressively detrimental to the tensile properties normal to the plate surface.

In the second part of this project in which the influence of chemical composition was investigated, covering a much wider range than found in the commercial HTS steels, it was found that increases in carbon and manganese contents, especially carbon, resulted in marked increases in the crack sensitivity.

Additions of silicon or chromium up to approximately 1.0 per cent had little effect upon underbead cracking but were not attractive because the yield strength of the hot-rolled steel was not increased appreciably. Additions of titanium up to .04 per cent behaved in a similar manner.

Vanadium and molybdenum were found to be the most promising alloy additions since they were quite effective in increasing the yield strength of the hot-rolled steel with no significant increase in underbead cracking.

The use of small or medium amounts of aluminum for deoxidizing the steel was found to be quite detrimental with respect to underbead cracking, the cracking being reduced substantially by either omitting the aluminum or by using large additions, such as four pounds per ton.

By limiting the carbon and manganese contents to 0.13/0.15 and 1.30 per cent, respectively, and adding approximately 0.12 vanadium and 0.50 per cent molybdenum to increase the strength, it was found that a yield strength in excess of 70,000 psi. could be obtained from 1-inch hot-rolled plate accompanied with an extremely low tendency towards underbead cracking. The notched-bar impact strength of this type of steel, however, was relatively low regardless of the aluminum content.

In order to obtain high yield strength and notch-bar toughness, together with low underbead cracking, it was found necessary to resort to quenched and tempered plate made from steel with limited carbon and manganese contents. By using a high-strength electrode, a joint efficiency of practically 100 per cent could be developed in butt welds made in the heat-treated plate.

INTRODUCTION

The earlier part of this investigation was conducted under the auspices of the OSRD (Contract No. OEMsr-1331) for the purpose of investigating the metallurgical quality of high-tensile steels used in the construction of welded ship hulls. The principal assignment was to determine and to study those factors that would influence the welding characteristics of the plate and the performance of the welded structure. This work was supplemented by a study of the welding quality which was conducted by Lehigh University (OSRD Contract No. OEMsr 1323). The OSRD contract was terminated on August 31, 1945, but the work on the project was continued under the Bureau of Ships, U.S.N., Contract No. NObs 31219. This report is a summary of the work conducted under these two contracts.

The work carried out under the OSRD contract was limited to a study of HTS killed carbon-manganese steels which had been treated with titanium or vanadium or both. This part of the program consisted of two parts, one being a study of the steelmaking practices used by the various mills making this grade of steel, and the influence of these different practices upon the behavior of the steel. The second part was a study of both satisfactory and rejected plate from the shipyards.

While wide differences were found in the steelmaking practices used in the different steel mills, the effects appeared to be insignificant with the exception of the deoxidation procedure.

In this investigation, the steels were evaluated on the basis of their tensile properties, especially the yield strength, notched-bar impact strength, and the weldability as determined by the susceptibility to cold cracking in the heat-affected zone under the weld bead. For the type of construction for which this grade of steel is used, any sound steel made in accordance with accepted steelmaking practice displays sufficient strength and ductility in the heat-affected zone to perform its normal functions satisfactorily, provided there are no defects, such as weld cracks, present to act as stress raisers and prevent the inherent ductility from being realized. This line of thought has been given additional support by the recent work of Sachs(1), which showed that the poorest ductility in the heat-affected zone occurs in the area which is only partly transformed. It is significant to note, however, that failures do not originate in this partially transformed area of poor ductility, but start in the harder zone adjacent to the weld deposited metal. This indicates that the failures are initiated by the cracks which may form at the time of welding in the hard heat-affected zone, and not because of the lack of ductility. It is obvious, therefore, that the principal criterion of weldability for this grade of steel is that it be capable of being welded without underbead cracking by methods normally used in production, which excludes the use of preheat in this case. For this reason, considerable effort was expended in the development of a test which would determine the cracking propensities of steel plate.

In studying the steels from both the mills and shipyards, a marked difference was found in their inherent tendencies towards underbead cracking which frequently could not be explained on the basis of chemical analysis, hardenability, or the hardness of the heat-affected zone. It was subsequently found that thermal processing and the microstructure had a pronounced influence upon the crack sensitivity.

The second part of this investigation, which was conducted under the sponsorship of the U. S. Navy Bureau of Ships, deals largely with the effects of thermal processing and the influence of the various elements, including the common alloys, upon underbead cracking and the mechanical properties. This information was used for developing hot-rolled plate with high yield strength (75,000 psi. minimum) which can be welded satisfactorily without preheat.

EXPERIMENTAL WORK

Underbead Cracking Test

Since it was decided to evaluate the welding characteristics of the steel largely on the basis of underbead cracking, it was first necessary to develop a weld test which would determine quantitatively the weld crack sensitivity. Obviously, it was necessary to make the welding conditions sufficiently drastic that even the less sensitive steels would be cracked to a slight extent.

After considerable work(2), a single-bead cracking test was developed which was made by depositing a bead 1-1/2 inches long in a groove 1/16 inch deep by 1/2 inch wide cut in a 2 by 3 by 1-inch specimen as shown in Figure 1. The use of the groove was the only departure from the original procedure and was used to eliminate the possible effect of surface decarburization. The bead was deposited from a 1/8-inch Class E6010-type electrode being D.C. reverse polarity (electrode positive), and a power input of 100 amperes at 24 to 26 volts with a travel speed of 10 inches per minute. Prior to welding, the

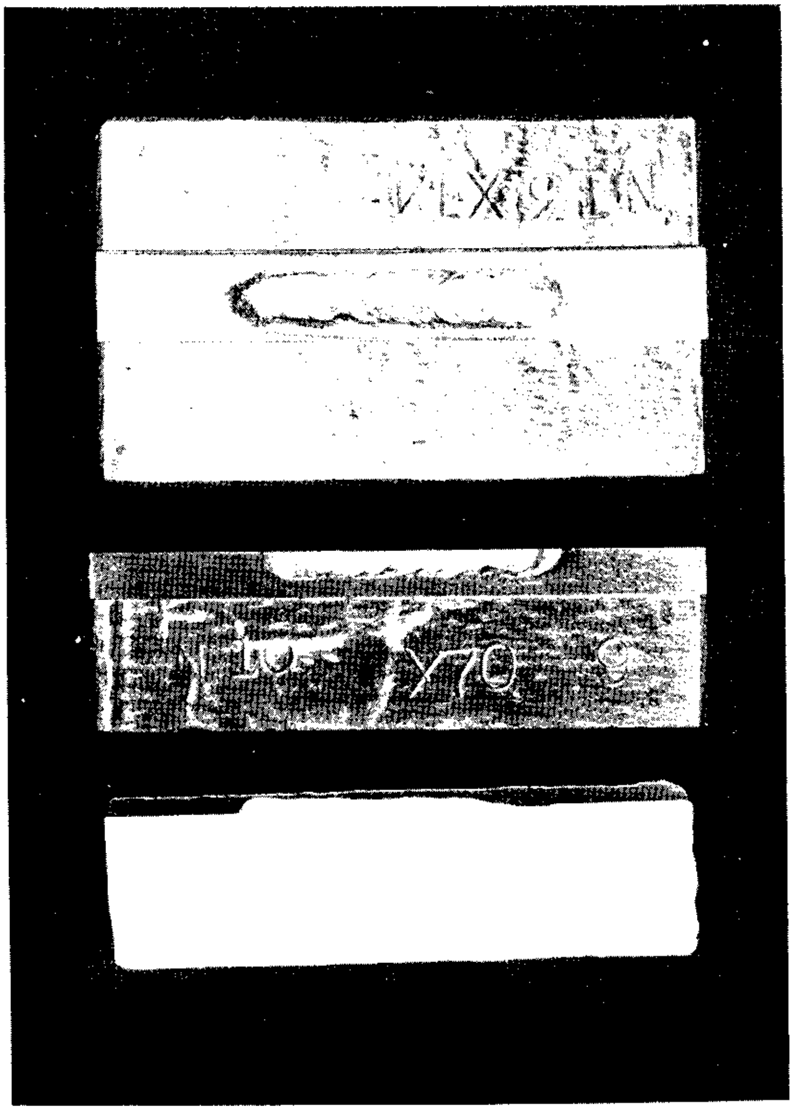

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Figure 1. Weld specimen for single-bead crack-sensitivity test, showing longitudinal section used to expose underbead cracks.

specimens were stored at 0°F., and during welding and for ten seconds afterwards were partially immersed in a liquid bath at 0°F. unless otherwise stated. Following removal from the bath, the specimens were held for 24 hours at 60°F. and then tempered at 1100°F. for one hour. After sectioning and polishing, the specimens were magnafluxed to show the cracks, as shown in Figure 2, and the total length of the cracks in any one specimen was determined and expressed as a percentage of the bead length.

Experience showed that using the above welding conditions would produce up to about 80 per cent cracking in the most sensitive commercial HTS plate steels while only a very few of the least sensitive showed no evidence of cracking. This indicated that the test had sufficient latitude to cover the range of cracking that could be encountered in this type of steel. In most of the work, 10 or 20 duplicate specimens were welded for each steel tested and the average cracking value used. Although the extent of cracking varied considerably in different specimens, the average of 10 specimens was found to be reproducible within about 5 to 10 per cent.

Study of Commercial HTS Steels

The investigation of the steel was started by making a study of 20 commercial HTS heats most of which were 7/8- or 1-inch thick plate and all in the hot-rolled condition. These steels were divided into two groups; the first group, Heats 1 to 13, inclusive, and 17, were steels which had been obtained directly from the five steel mills producing this grade of plate. The melting of Heats 1 to 7, inclusive, and subsequent processing was observed in order to compare the steelmaking practices

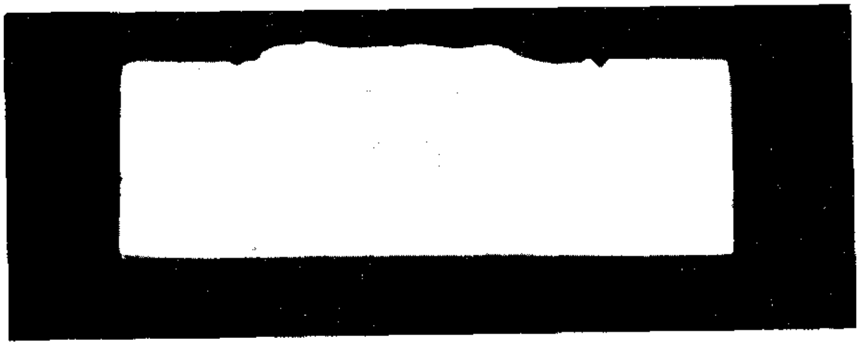

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Figure 2. Longitudinal section of weld specimen showing underbead crack.

used by the different mills and to determine the effect upon the behavior of the plate(3). While the details of the steelmaking and processing varied widely in the different plants, the only significant factor appeared to be the difference in the deoxidation practice. The most marked difference was in the amount of aluminum used, which ranged from 0.38 pound per ton to 1.13 pounds per ton. The influence of this factor will be discussed later.

The second group of steels, Steels 30 to 39, inclusive, were obtained from the various shipyards, part of which had been rejected. Unfortunately, however, the reason for rejection in most cases could not be definitely established(4).

In studying these two groups of steels, the following outline was followed:

1. Chemical analysis including residual alloys and the aluminum content.
2. Tensile properties both longitudinal and transverse, and the properties normal to the surface on selected heats.
3. Notched-bar impact strength using both longitudinal and transverse specimens in the temperature range of about 80°F. to 200°F.
4. Underbead crack sensitivity as determined by the single-bead weld test.
5. End-quenched hardenability.
6. Microstructure of the hot-rolled plate.
7. Study of the microstructure of the heat-affected zone under the weld bead.

Chemical Analysis

The chemical analyses of the two groups of steels are shown in Tables 1 and 2. From Table 1 it will be noted that the carbon contents of the steel received from the mills all fell within a very narrow range, 0.14 per cent to 0.17 per cent, with the exception of one heat (Heat 13) which was 0.19 per cent. In most cases, the manganese ranged from 1.11 to 1.29 per cent, with three steels being somewhat lower, 0.81 to 0.98 per cent. All of these steels were made with the addition of either titanium or vanadium, or both. The residual alloys, nickel, chromium, molybdenum, and copper were low in most of these heats, and, although copper ranged from 0.23 to 0.35 per cent in three heats, copper in this range is relatively ineffective. The acid-soluble aluminum content, however, was found to vary from nil to .02 per cent, which is significant in view of the pronounced influence of aluminum as will be shown later.

The chemical analyses of the steels from the shipyards are similar to those from the mills with the exception that some have appreciably higher carbon and manganese contents which undoubtedly explains why they were rejected.

Tensile Properties

The tensile properties were determined in both the longitudinal and transverse directions with respect to the final direction of rolling using a standard 0.505-inch threaded-end type of specimen. The data shown in Tables 3 and 4 are the averages of the results from two test specimens. The yield strength of the steels from Group I ranged from about 41,000 psi. to about 54,000 psi., and the tensile strength from

TABLE 1. CHECK ANALYSES OF ALL THE HEATS OBTAINED FROM FIVE STEEL PRODUCERS, GROUP 1

Heat	Analyses, Per Cent											
No.	C	Mn	P	S	Si	Ti	Cu	Ni	Mo	Cr	V	Al*
2-b	.15	1.29	.023	.020	.29	.014	.10	.06	.014	.05	.002	.015
3	.16	1.23	.030	.032	.21	.016	.007	.02	.006	.03	.003	.012
4	.15	1.16	.032	.040	.20	.010	.23	.11	.014	.03	.003	.007
5	.15	1.28	.024	.021	.28	.009	.24	.15	.040	.05	.003	.006
6-m	.14	1.16	.021	.024	.27	.015	.03	.14	.019	.04	.031	.005
7	.15	1.17	.035	.028	.28	.005	.13	.13	.026	.14	.032	nil
9	.17	1.27	.020	.026	.34	.011	.06	.18	.033	.03	.023	.012
10	.17	.81	.013	.023	.21	nil	.05	.03	.004	.03	.068	.002
11	.17	1.17	.017	.017	.29	.011	.35	.16	.018	.05	.045	.020
12	.17	1.11	.021	.025	.26	.009	.12	.16	.022	.04	.030	.004
13	.19	.98	.011	.027	.22	.015	.03	.03	.005	.07	.050	.012
17	.15	.98	.014	.019	.21	.015	.14	.09	.014	.07	.027	.010

* Acid-soluble aluminum content

TABLE 2. CHECK ANALYSES OF STEELS OBTAINED FROM SHIPYARDS, GROUP 2

Steel No.	Analyses, Per Cent											
	C	Mn	P	S	Si	Ti	Cu	Ni	Mo	Cr	V	Al*
30	.18	1.25	.023	.026	.28	.007	.19	.14	.020	.05	.004	.016
31	.19	1.38	.023	.026	.30	.010	.19	.14	.031	.05	.004	.010
32	.17	1.44	.025	.020	.28	.009	.36	.22	.034	.07	.007	.015
33	.16	1.27	.020	.023	.30	.005	.22	.12	.018	.07	.003	.004
34	.23	1.53	.016	.022	.24	.008	.15	.21	.033	.15	.003	.013
35	.17	1.19	.023	.026	.25	nil	.26	.23	.018	.10	.080	.006
36	.19	1.39	.023	.022	.31	.012	.16	.10	.040	.07	.003	.009
37+	.16	1.21	.017	.033	.28	nil	.07	.01	.030	.03	.120	.020
38	.17	1.50	.029	.018	.32	.013	.14	.09	.011	.02	nil	.017

Note: * Acid-soluble aluminum content.

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

TABLE 3. SUMMARY OF THE TENSILE PROPERTIES OF THE ONE-INCH HOT-ROLLED PLATE OBTAINED FROM THE FIVE STEEL PRODUCERS

Heat No.	Test Direction	Elong. in 2 in., %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
2-b	Long.	29.0	61.4	44,125	73,900
"	Trans.	23.2	58.3	43,000	75,100
3	Long.	34.9	71.2	41,250	67,550
"	Trans.	34.3	60.2	41,750	67,950
4	Long.	34.3	64.4	43,380	71,000
"	Trans.	28.6	57.7	42,000	72,300
5	Long.	35.7	65.7	43,750	72,100
"	Trans.	32.8	62.8	45,500	72,000
6-m	Long.	35.5	71.6	48,130	73,750
"	Trans.	31.6	59.8	48,630	74,310
7	Long.	34.9	72.2	45,630	73,200
"	Trans.	31.0	61.7	46,250	72,800
9	Long.	32.2	70.3	51,500	82,100
"	Trans.	28.2	52.6	52,100	82,000
10	Long.	31.8	67.2	50,000	75,600
"	Trans.	29.5	62.9	48,850	75,000
11	Long.	33.1	72.1	53,250	77,000
"	Trans.	29.7	57.7	54,000	76,750
12	Long.	32.5	70.6	53,100	78,350
"	Trans.	30.9	61.1	54,750	78,000
13	Long.	31.5	67.3	44,750	73,400
"	Trans.	30.0	53.2	43,000	72,250
17	Long.	34.4	69.6	42,810	72,880
"	Trans.	31.5	59.3	40,630	72,630

Note: (1) The above results are the average of two tests.
(2) Standard 0.505-inch threaded-end test specimen used to obtain the above data.
(3) Yield strength determined from the load at 0.2 per cent elongation.

TABLE 4. SUMMARY OF TENSILE PROPERTIES OF STEELS OBTAINED FROM SHIPYARDS

Steel No.	Test Direction	Elong. in 2 in., %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
30	Long.	34.6	64.9	50,350	76,150
"	Trans.	33.4	63.5	49,250	76,650
31	Long.	33.0	67.1	50,500	79,600
"	Trans.	30.6	61.2	47,875	79,350
32	Long.	32.5	66.3	50,250	83,500
"	Trans.	29.4	53.9	53,130	83,600
33	Long.	34.7	70.5	47,130	74,850
"	Trans.	35.6	70.5	47,250	74,800
34	Long.	32.2	71.2	50,630	85,280
"	Trans.	29.0	60.2	50,880	85,600
35	Long.	30.4	67.6	53,000	82,350
"	Trans.	26.5	59.6	53,000	82,000
36	Long.	33.5	65.4	46,250	76,550
"	Trans.	31.8	59.8	46,000	75,800
37	Long.	29.2	67.9	57,000	83,500
"	Trans.	24.4	50.0	57,500	84,880
38	Long.	33.8	72.6	50,630	79,000
"	Trans.	28.4	58.0	50,000	79,000

Note: (1) The standard 0.505-inch threaded type of test specimen was used to obtain the above tensile data.
(2) The above values are the average of two tests.

67,500 psi. to 82,000 psi. The reduction in area of the longitudinal specimens ran from about 61 per cent to 72 per cent, while the transverse specimens frequently indicated slightly less ductility than the longitudinal tests.

The plate from the shipyards had a higher average yield and tensile strength than the steels in Group I, the yield strength ranging from 46,000 psi. to 53,000 psi. and the ultimate strength from about 75,000 psi. to 85,000 psi. The reduction in area in the longitudinal specimens fell between 66 and 70 per cent with the transverse specimens frequently having slightly less ductility.

The most significant information obtained from the study of the tensile properties was the marked influence of vanadium upon the yield strength of these hot-rolled steels as illustrated in Figure 3. In this plot, which shows the relationship of the yield strength to the carbon equivalent (C+ Mn/6), it will be noted that the vanadium and vanadium-titanium steels may be divided from the titanium steels by the line AB.(5) Of these two groups, the vanadium and vanadium-titanium steels have the lower carbon equivalent, but also have the highest yield strength. This illustrates the advantage obtained in strength by the addition of a small amount of vanadium.

Tensile Properties Normal to the Plate Surface

Since structures in welded ship construction are frequently encountered in which the tensile properties of the plate normal to the rolled surface are vitally important, a study of the properties in this third direction was made.

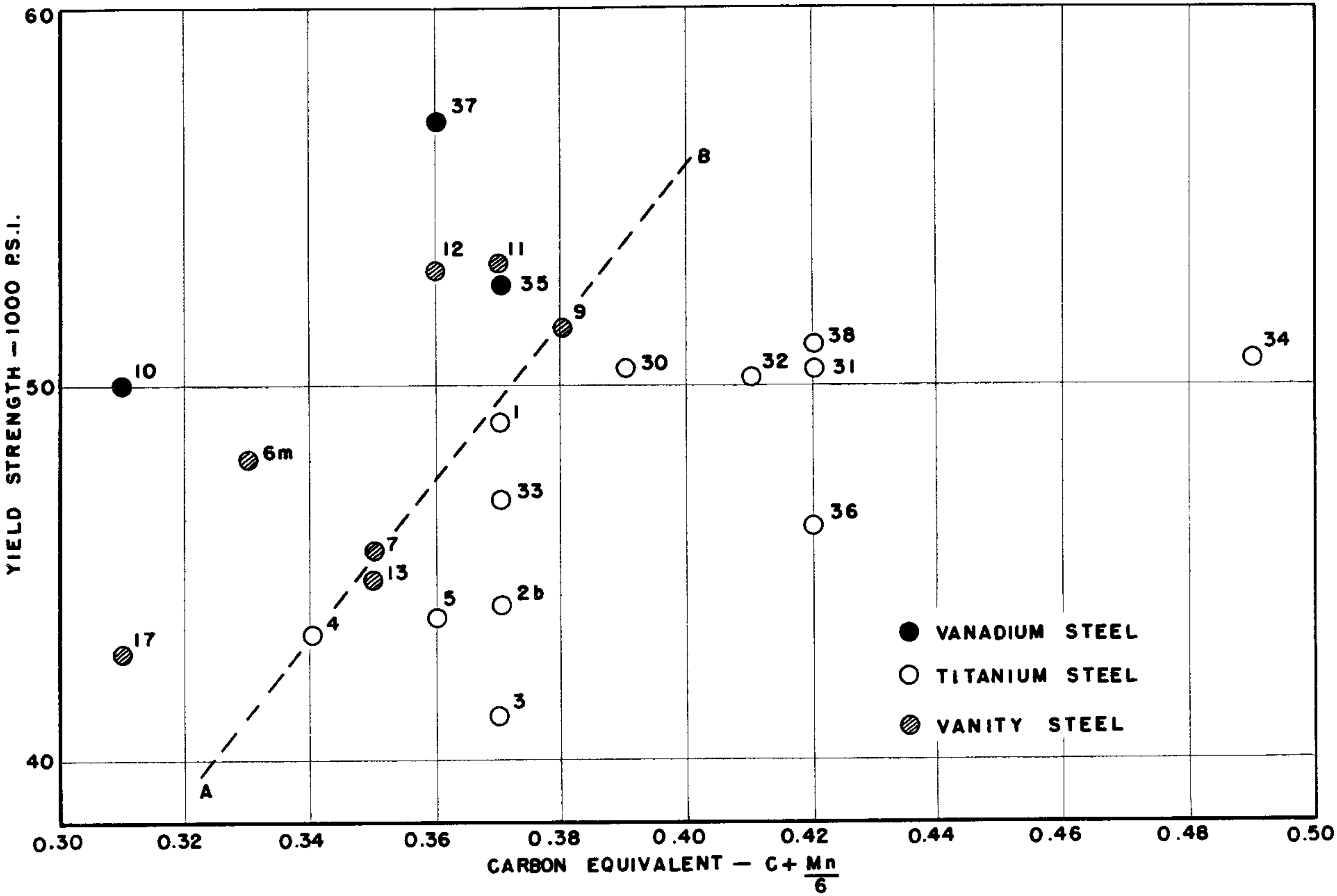

FIGURE 3 . RELATIONSHIP OF THE YIELD STRENGTH TO THE CARBON EQUIVALENT, $C + \frac{Mn}{6}$

Duplicate tensile specimens were prepared by welding and machining as indicated in Figure 4. Specimens, 3 by 6 inches, were cut from each of the following six heats, Heats 2-b, 3, 4, 5, 6-m, and 7. Beveled plates were then welded to these specimens as shown in the above figure. The welds were made with four passes using Shield-Arc 100(AWSE10010) electrodes. The first pass was made with a 3/32-inch electrode and reverse polarity direct current using 130 to 140 amperes and an arc voltage of 27 to 30.(6)

Following rough turning of the tensile specimens, they were given a light etch in order to establish definitely the location of the test plate. After determining the position of the test plate, a 3/4-inch section midway between the extremes of the one-inch test plate was ground to 0.505-inch diameter, leaving the remainder of the bar 0.550 inch. This precaution was taken to insure that the fracture would occur in the desired section.

The results of these tests, as shown in Table 5A, reveal that Heats 2 to 6, inclusive, have very little ductility when tested in the direction normal to the plate surface, the elongation in 3/4 inch being only 1.5 to 4.0 per cent and the reduction in area 4 to 17 per cent. The tensile strength in this third direction is lower than in the longitudinal direction, especially in the case of Heats 2-b and 3.

A marked contrast will be noted in the tensile properties of Heat 7 as compared with the above-mentioned heats, Heat 7 having much better ductility and tensile strength, the latter exceeding the strength shown in the longitudinal direction. The photograph of the tensile fractures shown in Figure 5 reveals a woody structure in all of the steels with the exception of Heat 7 which approaches a typical tensile fracture.

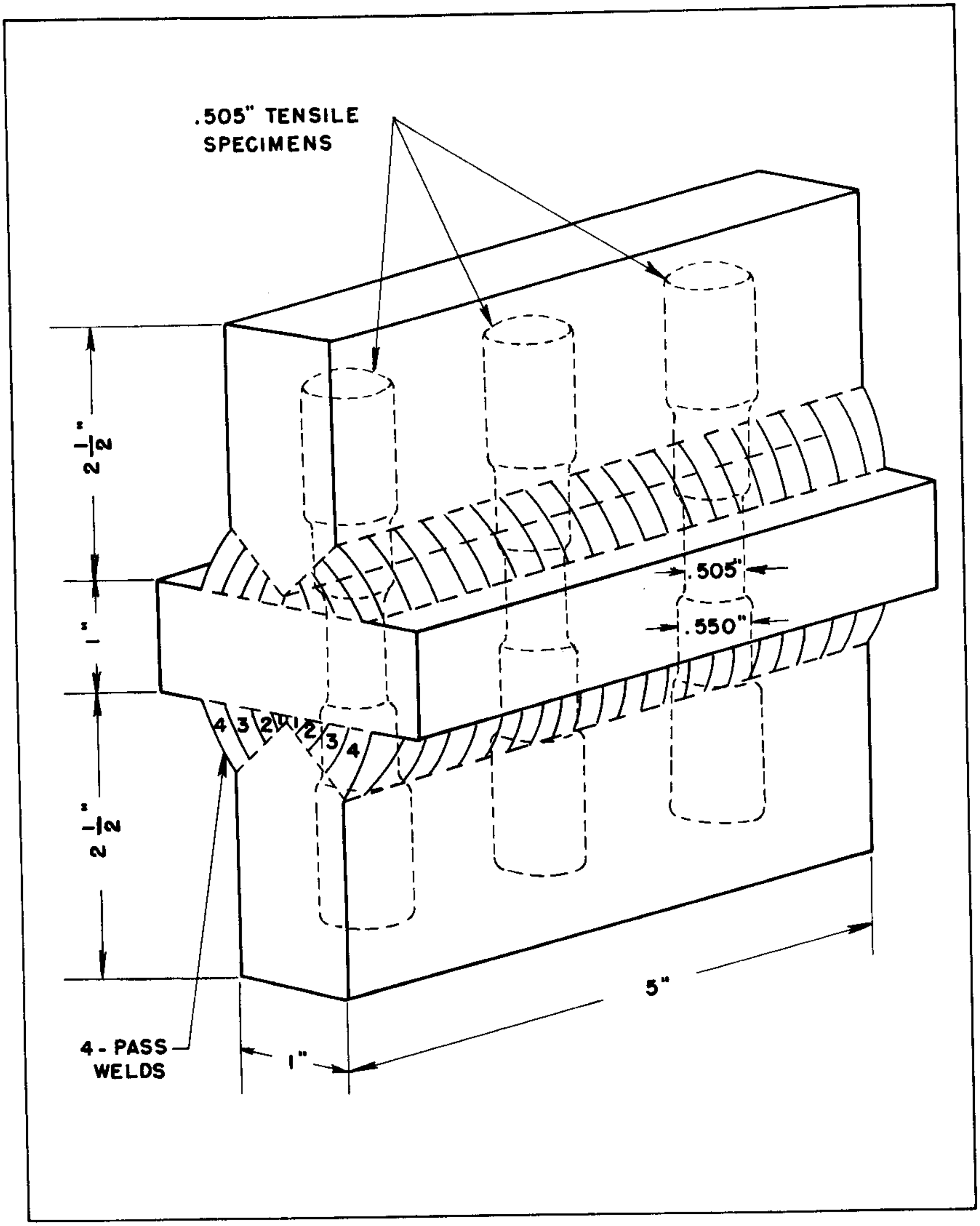

FIGURE 4 . PROCEDURE USED FOR MAKING THE SPECIMENS TO DETERMINE THE TENSILE PROPERTIES NORMAL TO THE PLATE SURFACE.

TABLE 5A. TENSILE PROPERTIES NORMAL TO THE PLATE SURFACE AND THE TENSILE STRENGTH IN THE LONGITUDINAL DIRECTION

	Properties Normal to the Plate Surface					Longitudinal Properties
Heat No.	Specimen No.	Aluminum* Content, %	Red. of‡ Area, %	Elong. in 3/4", %	Tensile Strength, psi.	Tensile + Strength, psi.
2-b	1	.015	6.0	1.5	63,500	73,900
	2		4.0	-	55,000	
3	1	.012	6.0	1.5	60,250	67,550
	2		4.0	1.5	62,750	
4	1	.007	6.0	2.0	69,000	71,000
	2		8.0	2.0	68,600	
5	1	.006	-	2.0	67,500	72,000
	2		13.0	3.5	70,500	
6-m	1	.005	15.0	-	71,250	73,750
	2		17.0	4.0	72,500	
7	1	Nil	46.0	9.0	76,000	73,200
	2		40.0	11.0	75,500	

* Acid-soluble aluminum content.

\+ Tensile strength from Table 11, page 25 of the February 15, 1945, report.

‡ Not all of the reduced sections could be measured as a result of the type of fractures.

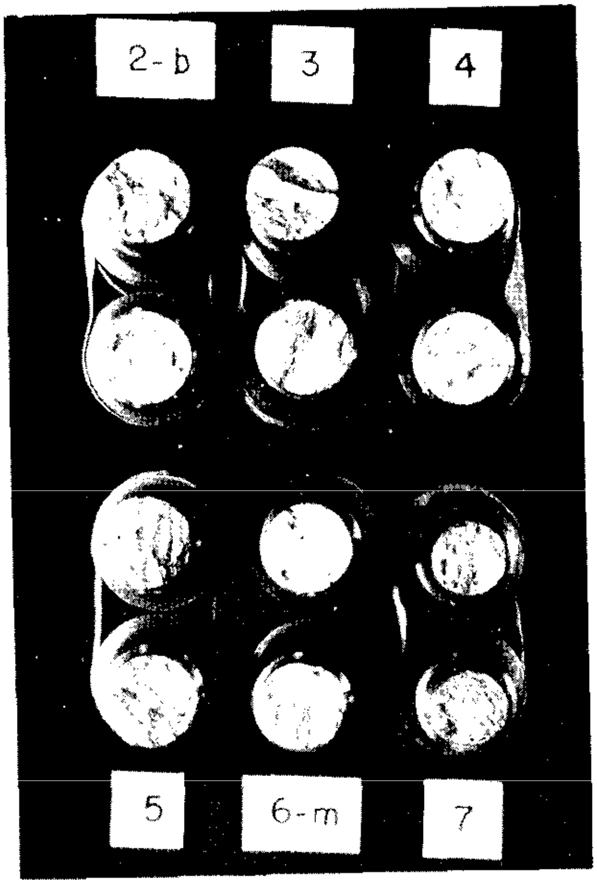

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Figure 5. Tensile fractures of Heats 2 to 7, inclusive, tested normal to the plate surface.

Note the difference between the fracture of Heat 7 as compared with the remainder of the steels in this group.

In looking for an explanation for the difference in the behavior of Heat 7, as compared with the other heats in this group, it was observed that the acid-soluble aluminum content of Heat 7 was nil as compared with aluminum contents of .005 to .015 per cent in the other heats (see Table 5A). It was also noted that the two heats with the highest aluminum contents, Heats 2-b and 3, displayed the poorest properties in the third-dimensional direction, the lowest reduction in area and elongation together with the lowest tensile strength.

Therefore, from these data, it appears that aluminum content is an extremely influential factor with respect to the tensile properties normal to the plate surface, the presence of small amounts of

aluminum lowering the tensile strength and the ductility to a marked extent.

Notched-Bar Impact Properties

The notched-bar impact properties were determined in the temperature range of -75°F. to 210°F., using the standard Charpy test specimen with a V-type Izod notch cut parallel with the plate surface.(7) Four specimens were broken at each of six different temperatures in the above-mentioned range. The results of these tests showed there was a pronounced difference in the longitudinal and transverse properties. While the data from the longitudinal specimens indicated that part of these steels had a definite transition temperature zone, in no case was there any indications from the transverse data of a transition temperature. This difference in the directional properties is illustrated in Figure 6. An example of a steel which did not show any indications of a transition zone in the temperature range studied, -75°F. to 210°F.,

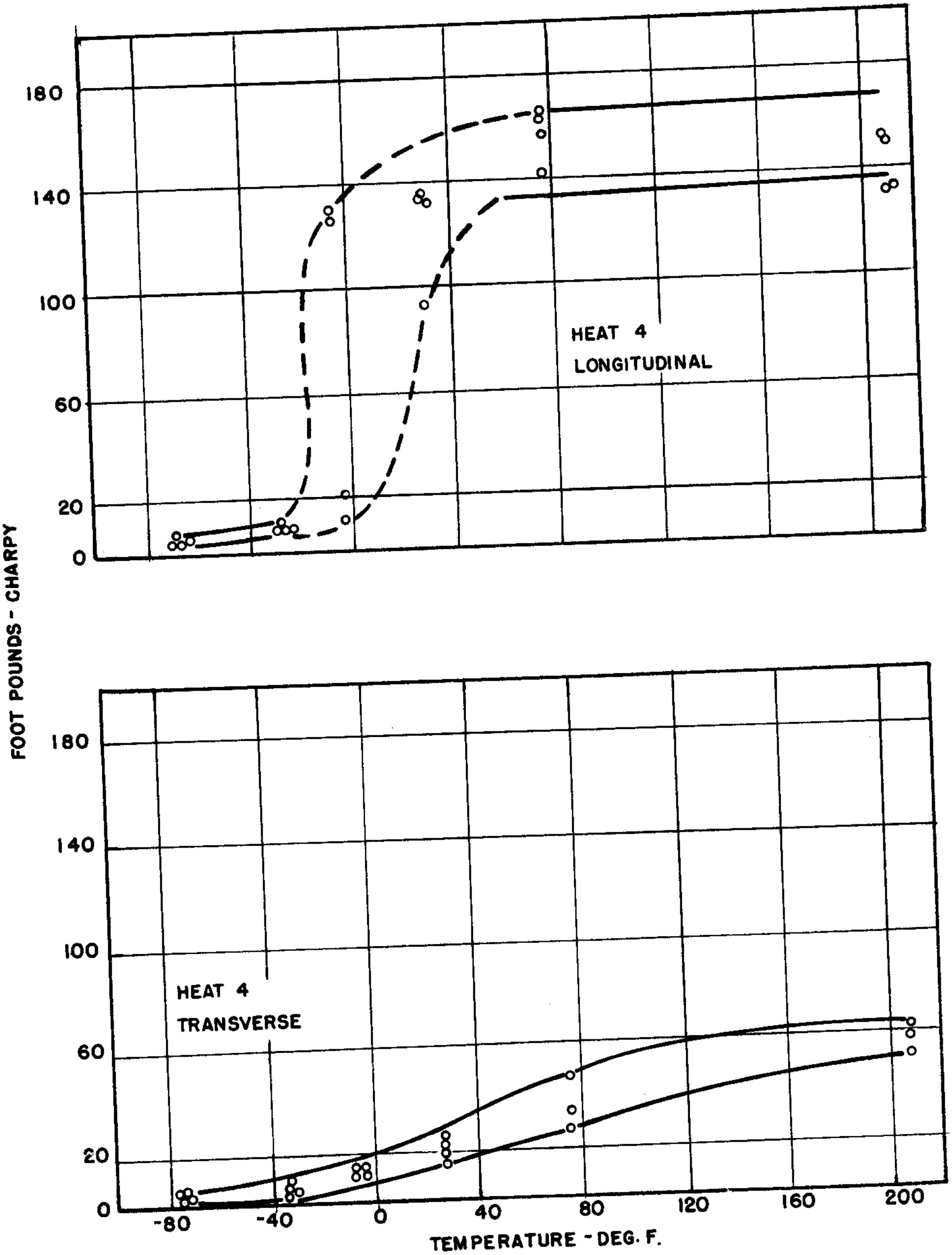

FIGURE 6. LOW TEMPERATURE NOTCH-BAR IMPACT PROPERTIES

in either direction of testing is illustrated in Figure 7. The reason for the behavior of this steel, Steel 34, is not obvious, especially in view of the high aluminum content.

The results obtained from this study of the notched-bar impact properties indicate that low carbon and manganese, and high aluminum contents, together with a fine microstructure, are conducive to high notched-bar impact strength. High aluminum content appears to be especially effective with respect to lowering the transition-zone temperature, as would be expected. In addition, however, high aluminum content appears to increase the difference in the longitudinal and transverse notched-bar characteristics. The influence of the acid-soluble(8) aluminum content upon the transition temperature in the case of the six steels from the steel mills, which were selected for this purpose because of their similarity in chemical analysis, is shown in Table 5B. The data in this table show that the transition temperature decreases with increased aluminum content.

The above summary of the notched-bar impact study is obviously rather vague as is usually the case in attempting to evaluate this type of data, indicating the need for more fundamental knowledge of this subject.

TABLE 5B. TRANSITION ZONES AND ALUMINUM CONTENTS OF HEATS 2 TO 7, INCLUSIVE

Heat No.	Approximate Transition Zone, Degrees F.	Aluminum Content
2-b	-40 to -10	.015
3	-20 to +10	.012
4	-10 to +30	.007
5	-10 to +30	.006
6-m	+30 to +80 or above	.005
7	No transition zone*	nil

* No indications of a transition zone in the temperature range investigated, -75°F. to 210°F.

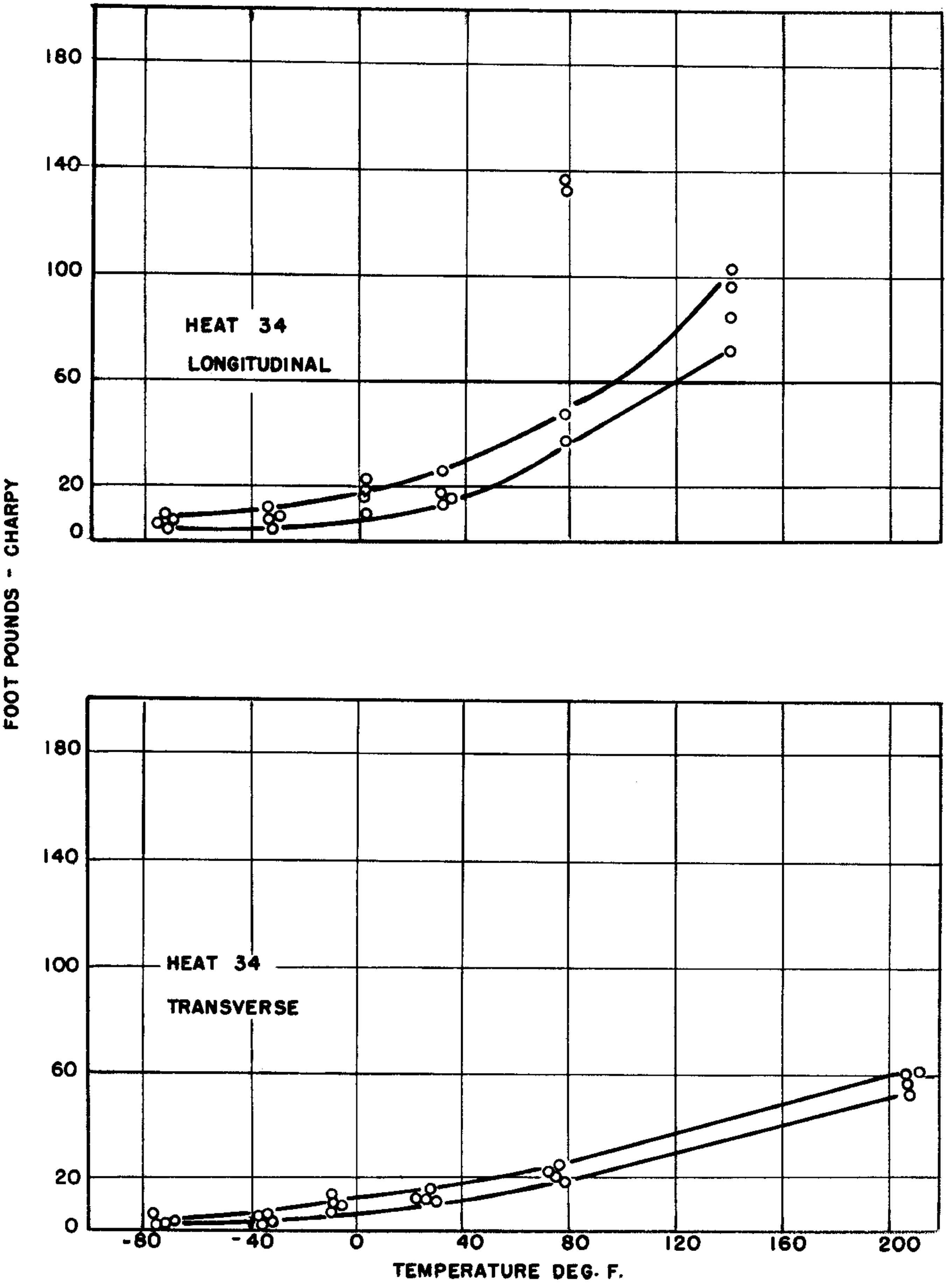

FIGURE 7. LOW TEMPERATURE NOTCH-BAR IMPACT PROPERTIES

Underbead Cracking

Underbead cracking tests were made using the single-bead weld test, as previously described, with twenty specimens being welded from each steel(9). A summary of the results from these tests is shown in Tables 6 and 7.

Table 6 shows that the heats received directly from the mills had a wide range of crack sensitivity, the underbead cracking ranging from 0 to 59 per cent with three of the heats cracking more than 20 per cent, while the remaining 9 heats cracked between 0 and 5 per cent. These results indicated that the 9 heats which cracked 5 per cent or less would be quite insensitive when welded under normal conditions, while Heat 2-b, which cracked 59 per cent, was relatively sensitive and might require special attention to eliminate the possibility of cracking during fabrication. Heat 11, which cracked 28 per cent, was probably a borderline case.

From Table 7 it will be noted that the nine steels from the shipyards were appreciably more crack sensitive than the steels in the preceding group. Five of the steels listed in Table 7 cracked 65 per cent or more. Out of the remaining four steels, three cracked between 21 and 28 per cent, while the fourth cracked only 12 per cent. These results indicated that underbead cracking might be a problem in the welding of the five steels which cracked 65 per cent or more unless special precautions were taken.

TABLE 6. UNDERBEAD CRACKING IN THE STEELS FROM THE FIVE STEEL PRODUCERS

Heat No.	Plate Gage, Inches	Type of Steel	Underbead* Cracking, Per.Cent
2b	1	Ti	59
3	1	Ti	0
4	1	Ti	3
5	1	Ti	5
6M	1	Ti & V	1
7	1	Ti & V	0
9	1	Ti & V	21
10	1	V	1
11	1	Ti & V	28
12	1	Ti & V	3
13	1	Ti & V	2
17	1	Ti & V	4

* Average cracking of 20 specimens.

TABLE 7. UNDERBEAD CRACKING IN THE STEELS OBTAINED FROM SHIPYARDS

Heat No.	Plate Gage, Inches	Type of Steel	Underbead+ Cracking, Per Cent
30	7/8	Ti	28
31	7/8	Ti	65
32	7/8	Ti	76
33	7/8	Ti	24
34	1	Ti	71
35	2-1/2*	V(.08)	21
36	7/8	Ti	81
37	7/8	V(.12)	12
38	1	Ti	66

* Machined to 1-inch gage for weld testing.

\+ Average of 20 specimens.

Influence of Chemical Analysis Upon Underbead Cracking

In looking for an explanation for this wide difference in the underbead cracking characteristics of these hull steels, the first factor considered was the chemical analysis. Since it is difficult to make a correlation, using for one of the terms such a complicated expression as a complete chemical analysis, the analyses have been reduced to simpler terms by using the carbon content plus one-sixth of the manganese, the other elements being ignored for the present, since these two appear to be the most influential in this particular grade of steel. However, the effect of the other elements will be considered later. The carbon equivalent and other pertinent data, which will be referred to later, are shown in Tables 8 and 9A(10),

A comparison of the degree of underbead cracking, or the crack sensitivity, and the carbon equivalent is shown in Figure 8. These data reveal there is a broad trend between the carbon equivalent and the crack sensitivity as would be expected, the extent of cracking increasing as the carbon and manganese contents are increased. However, it also shows that the crack sensitivity is not entirely a function of the C plus Mn, but there are other factors of great significance. To illustrate the trend between the analysis and crack sensitivity, it will be noted that the steels with a carbon equivalent of 0.35 per cent and less display a very low degree of crack sensitivity, while the steels with 0.40 per cent or more equivalent carbon crack 60 to 80 per cent. However, in the intermediate range of 0.35 to 0.40 per cent equivalent carbon, the degree of cracking was found to range all the way from 0 to 65 per cent, indicating there is some factor other than chemical

TABLE 8. UNDERBEAD CRACKING, CARBON EQUIVALENT, AND LONGITUDINAL TENSILE PROPERTIES OF THE HEATS FROM THE FIVE STEEL PRODUCERS

Heat No.	Underbead Cracking, Per Cent	Carbon Equivalent C + Mn/6	Yield Strength psi.	Tensile Strength, psi.
3	0	.37	41,250	67,550
4	3	.34	43,380	71,000
5	5	.36	43,750	72,100
6-m	1	.33	48,130	73,750
7	0	.35	45,630	73,200
9	21	.38	51,500	82,100
10	1	.31	50,000	75,600
11	28	.37	53,250	77,000
12	3	.36	53,100	78,350
13	2	.35	44,750	73,400
17	7	.31	42,810	72,880

TABLE 9A. UNDERBEAD CRACKING, CARBON EQUIVALENT, AND LONGITUDINAL TENSILE PROPERTIES OF THE STEELS OBTAINED FROM SHIPYARDS

Heat No.	Underbead Cracking, Per Cent	Carbon Equivalent, C + Mn/6	Yield Strength, psi.	Tensile Strength, psi.
30	28	.39	50,350	76,150
31	65	.42	50,500	79,600
32	76	.41	50,250	83,500
33	24	.37	47,130	74,850
34	71	.49	50,630	85,280
35	21	.37	53,000	82,350
36	81	.42	46,250	76,550
37	12	.36	57,000	83,500
38	66	.42	50,630	79,000

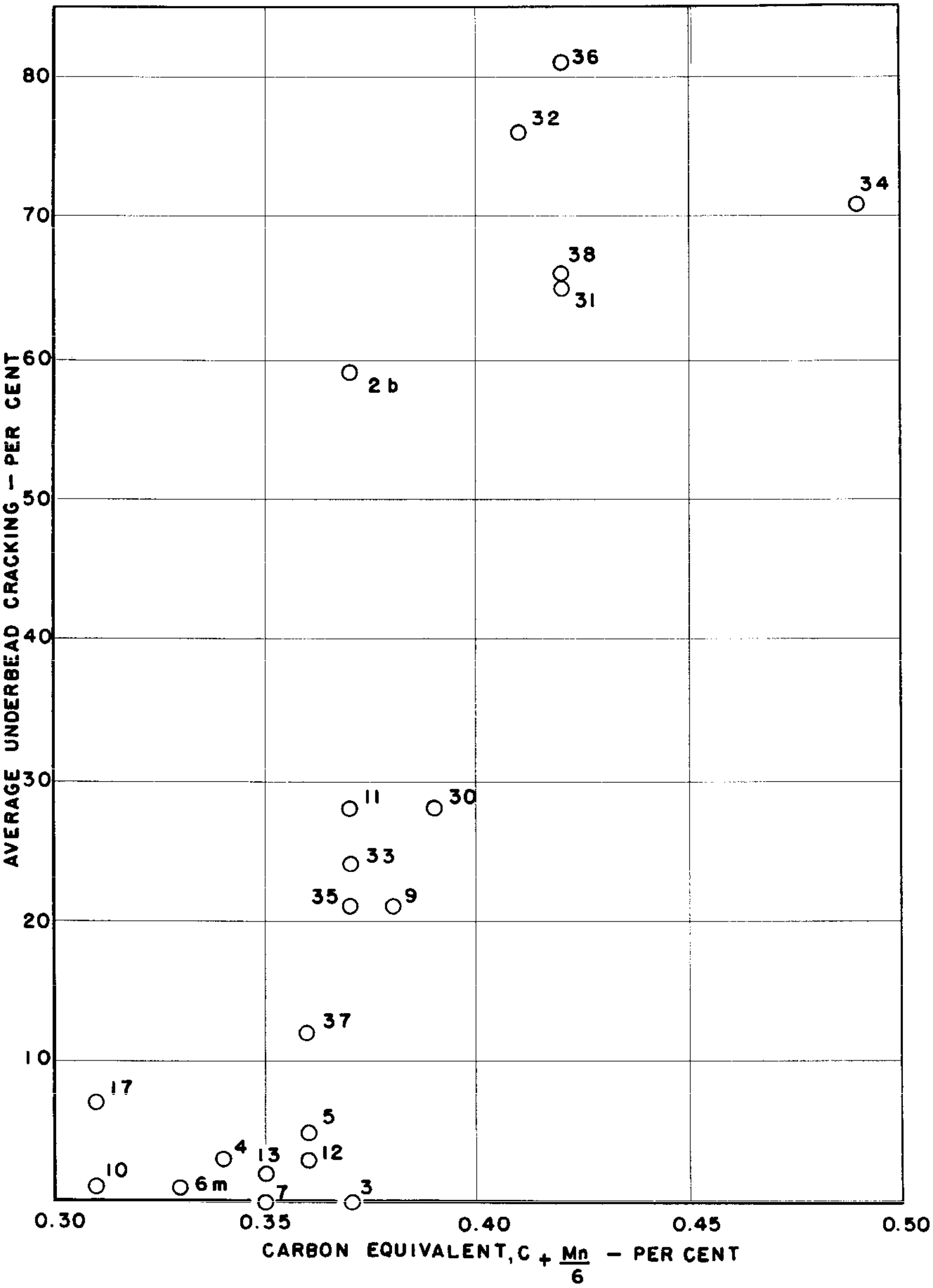

FIGURE 8. RELATION BETWEEN CRACK SENSITIVITY AND CARBON EQUIVALENT.

composition which has a very marked effect. It is this latter factor which is of especial interest in this investigation.

Comparison of Tensile Properties and Underbead Cracking

The tensile properties of a steel are established to a large degree by the summation of effects of all of the chemical elements present. Therefore, it appeared that the tensile and yield strength might be used as terms representing the complete chemical analysis of the steel. While it was recognized that the microstructure has an influence upon the tensile properties, it was believed that the structure of these steels was sufficiently similar so that any effects arising from this factor would be insignificant.

The relationship between the yield strength and the degree of underbead cracking is shown graphically in Figure 9. This figure reveals there is no correlation between the yield strength and the extent of underbead cracking(11). It is of interest to note, and it may be significant, that Heats 6, 10, and 12, which have high yield strength, also have a notably low crack sensitivity.

A comparison of the tensile strength and underbead cracking also failed to indicate any evidence of a relationship. These results, therefore, indicate that there is not a good correlation between the chemical composition, as reflected by the tensile strength, and the crack sensitivity.

End-Quenched Hardenability

Since hardenability has frequently been used as a measure of weldability, Jominy end-quenched tests were made on these two groups of

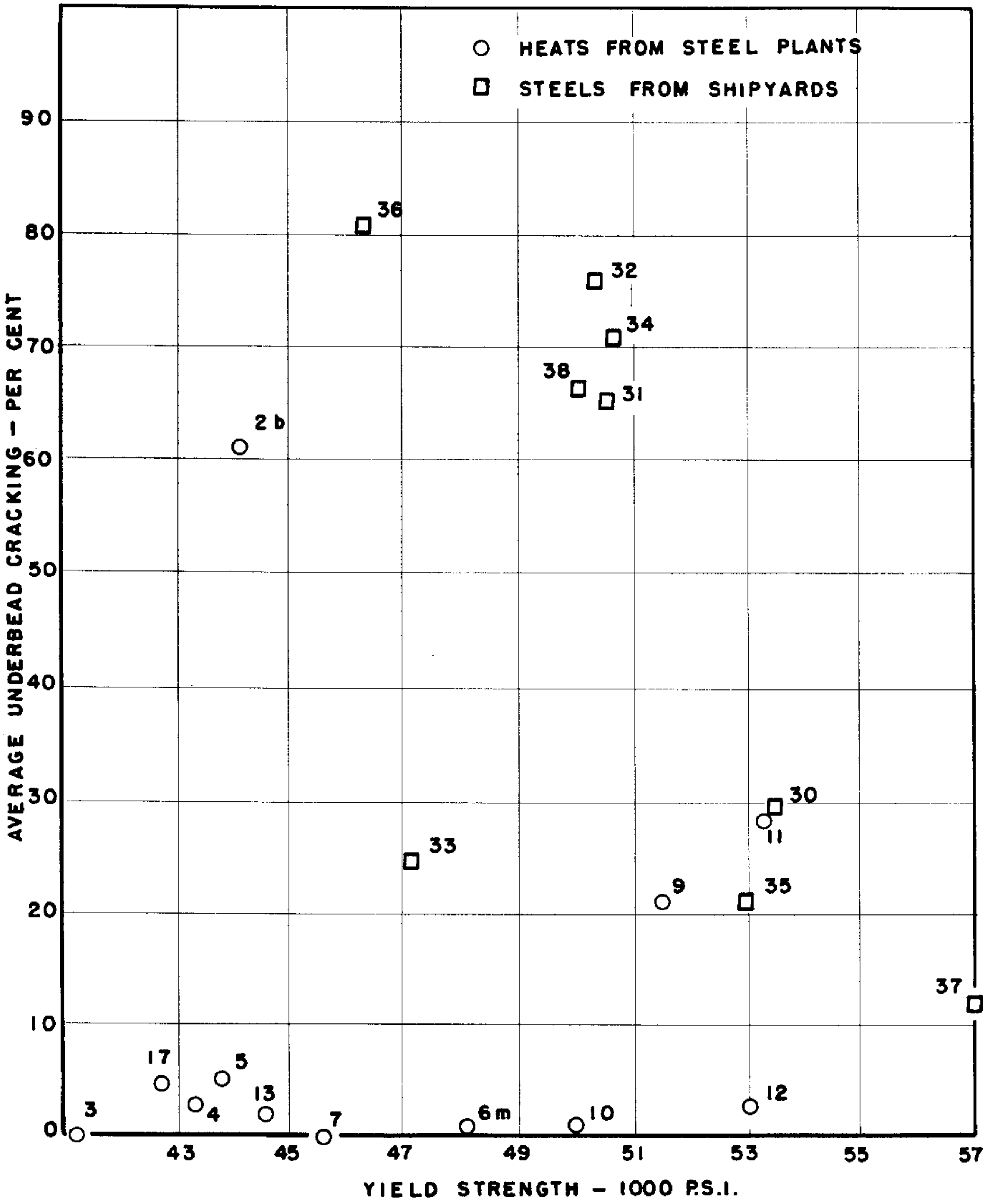

FIGURE 9. COMPARISON OF UNDERBEAD CRACKING AND YIELD STRENGTH.

steels using the standard L-bar specimen because of the shallow-hardening characteristics of these steels(12).

Duplicate specimens were heated in protective containers for one hour at 1600°F. prior to quenching in the conventional manner. A summary of the results of these tests is shown in Figure 10. It will be noted from this figure that the group of steels from the shipyards had an appreciably higher hardenability than the heats received from the steel mills. This difference would be expected in view of the higher chemistry of the shipyard steels. Thus, the higher hardenability of this group appears to be in agreement with the generally higher level of crack sensitivity found in these steels.

The most significant information, however, obtained from this study, was that steels of similar hardenability could differ widely in crack sensitivity. For example, Heats 2-b, 5, 6, and 7 had essentially the same hardenability as shown in Figure 11, but these steels differed widely in crack sensitivity, Heat 2-b cracking 59 per cent, while Steels 5, 6, and 7 cracked 5, 1, and 0 per cent, respectively. Additional tests were made in which the specimens were quenched from 1800°F. but these indicated a slightly higher hardenability for Heats 5, 6, and 7 as compared with Heat 2-b.

These results indicate, therefore, that the standard hardenability test is not a reliable measure of crack sensitivity, although, in general, the more hardenable steels are more susceptible to underbead cracking.

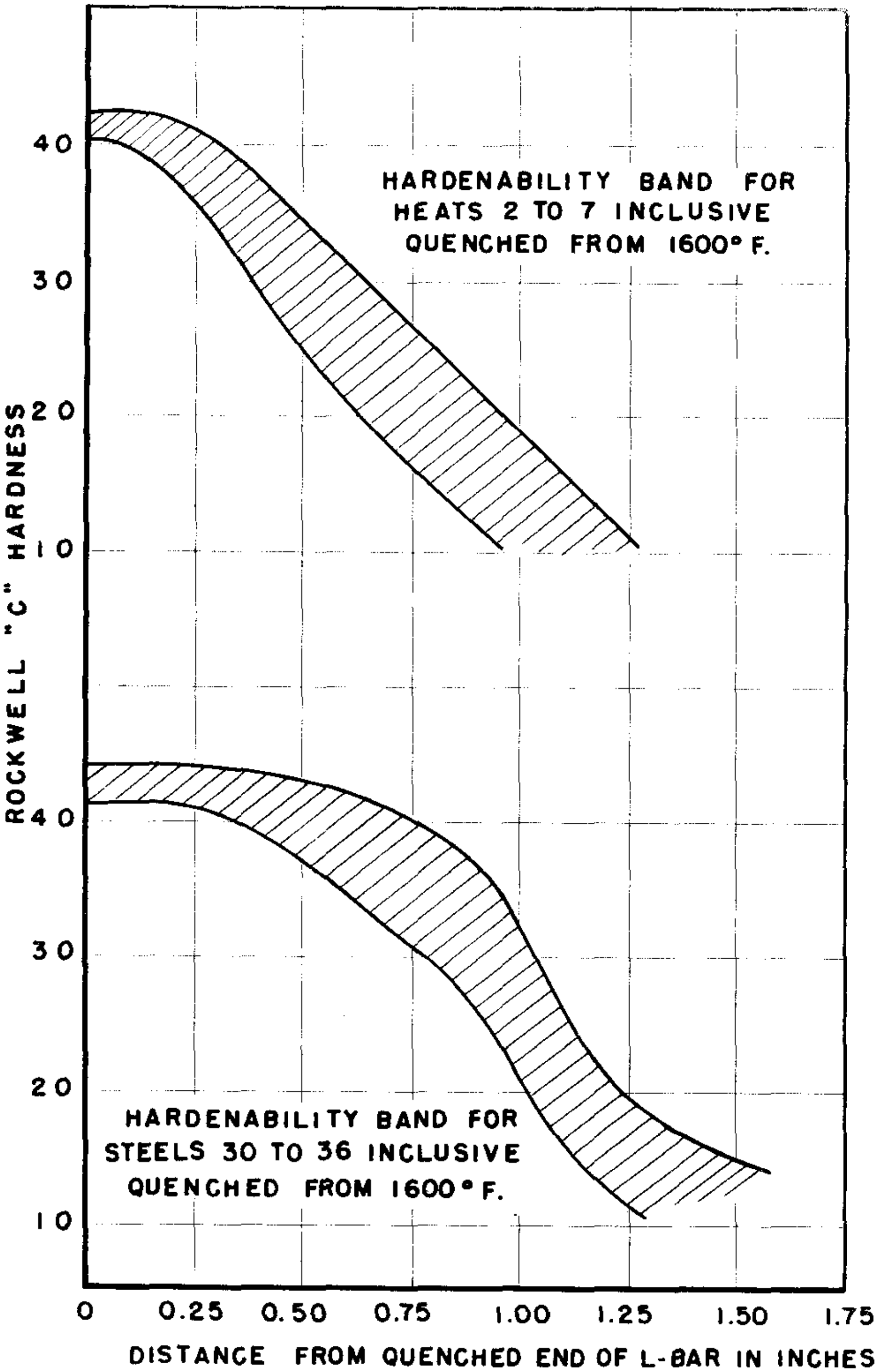

FIGURE 10. HARDENABILITY BANDS FOR THE HEATS FROM THE STEEL PLANTS AND SHIPYARDS.

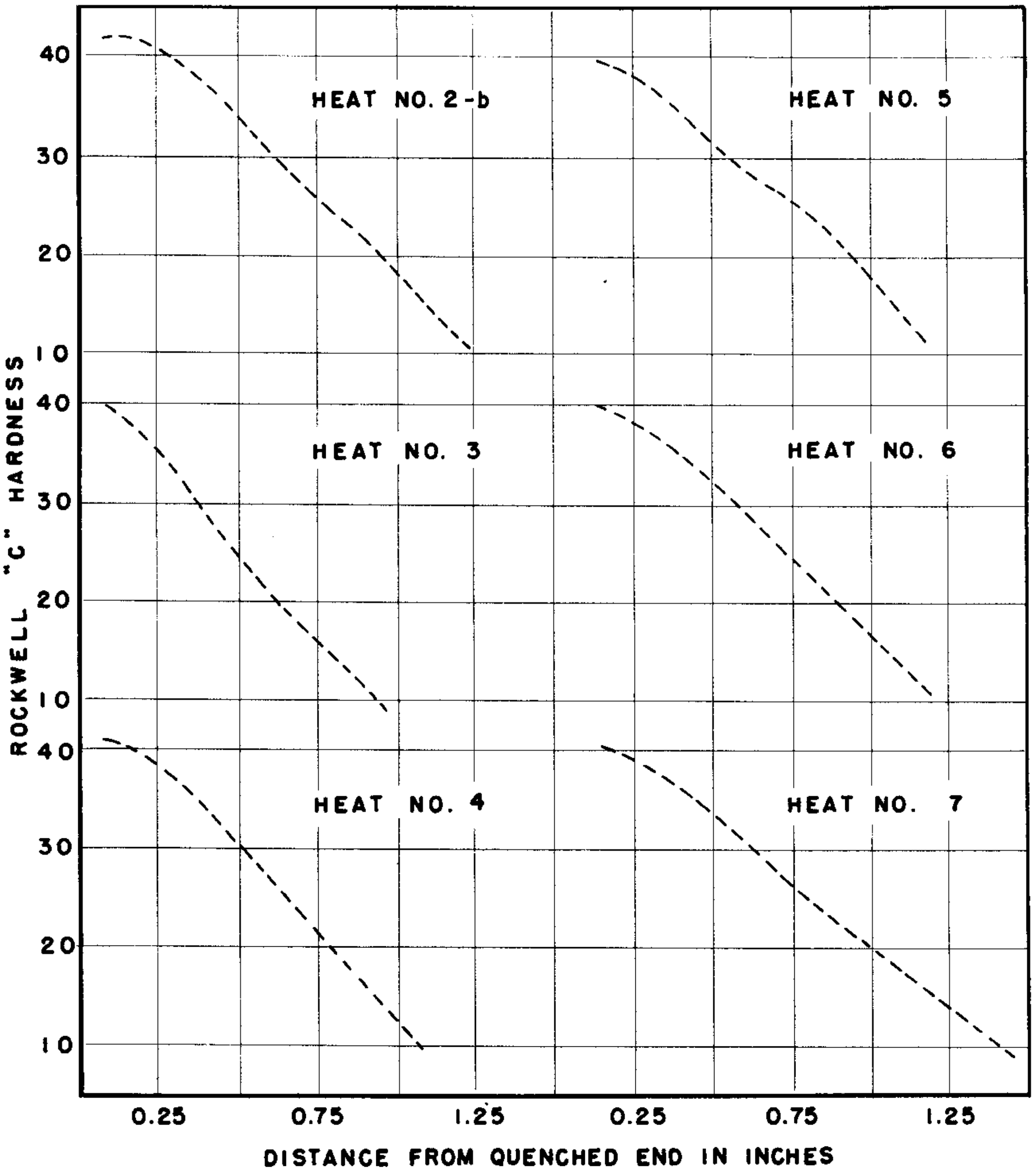

FIGURE 11. END-QUENCHED HARDENABILITY CURVES FOR HEATS 2b TO 7, INCLUSIVE. DATA FROM L-BAR SPECIMENS QUENCHED FROM 1600° F.

Hot-Rolled Microstructure

An examination of the microstructures of these steels showed the normal types of structures expected in this grade of hot-rolled steel(13). While there were differences in grain size resulting from variations in the deoxidation practice used in making the steel, and from differences in the finishing temperature upon completion of hot rolling which also influenced the degree of pearlite banding, there was no correlation between these structures and underbead cracking.

It was later found, however, that pearlitic banding did influence the crack sensitivity of a steel. For example, the crack sensitivity of a hot-rolled steel, which had been cooled sufficiently rapidly so that there was little or no evidence of banding, could be increased by an annealing treatment which would develop strong pearlitic banding. A comparison of the banding in the original hot-rolled structures, however, could not be used as a guide to indicate the relative crack sensitivity of a group of steels.

Microstructure of the Heat-Affected Zone

While studying the structure under the weld bead in the crack-sensitivity specimens, it was observed that there was an appreciable difference in the depth to which complete transformation extended as compared to the total depth of the heat-affected zone(14). A comparison of a number of crack-sensitive and insensitive steels indicated that the zone of complete transformation was relatively shallow in the insensitive steels. This difference is illustrated by Figures 12 and 13, showing the structures under the bead in specimens from Heat 2-b and 5 which

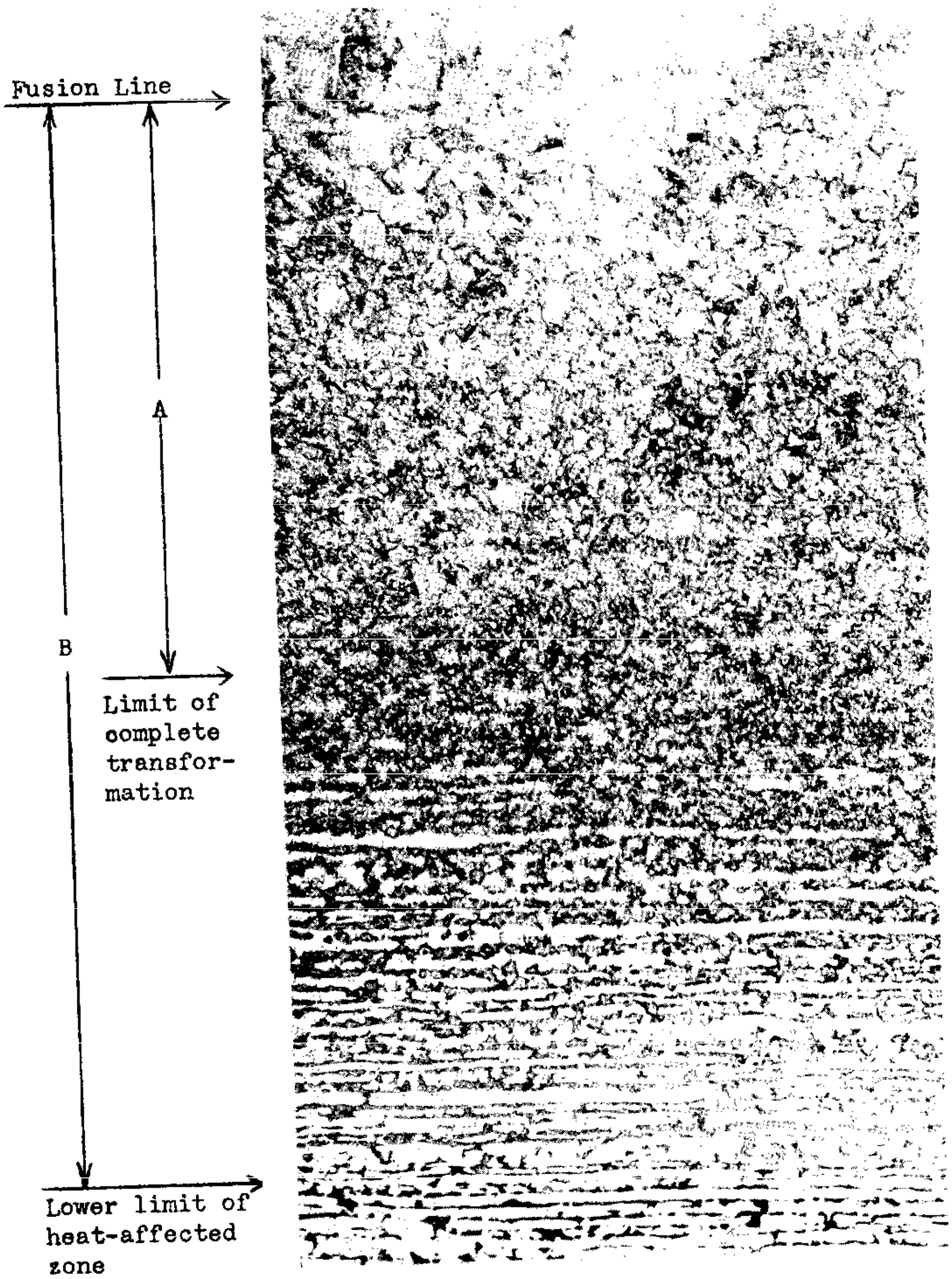

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Figure 12. Heat-affected zone beneath weld bead in specimen from Heat 2-b which cracked 59 per cent. Transverse section. 100X

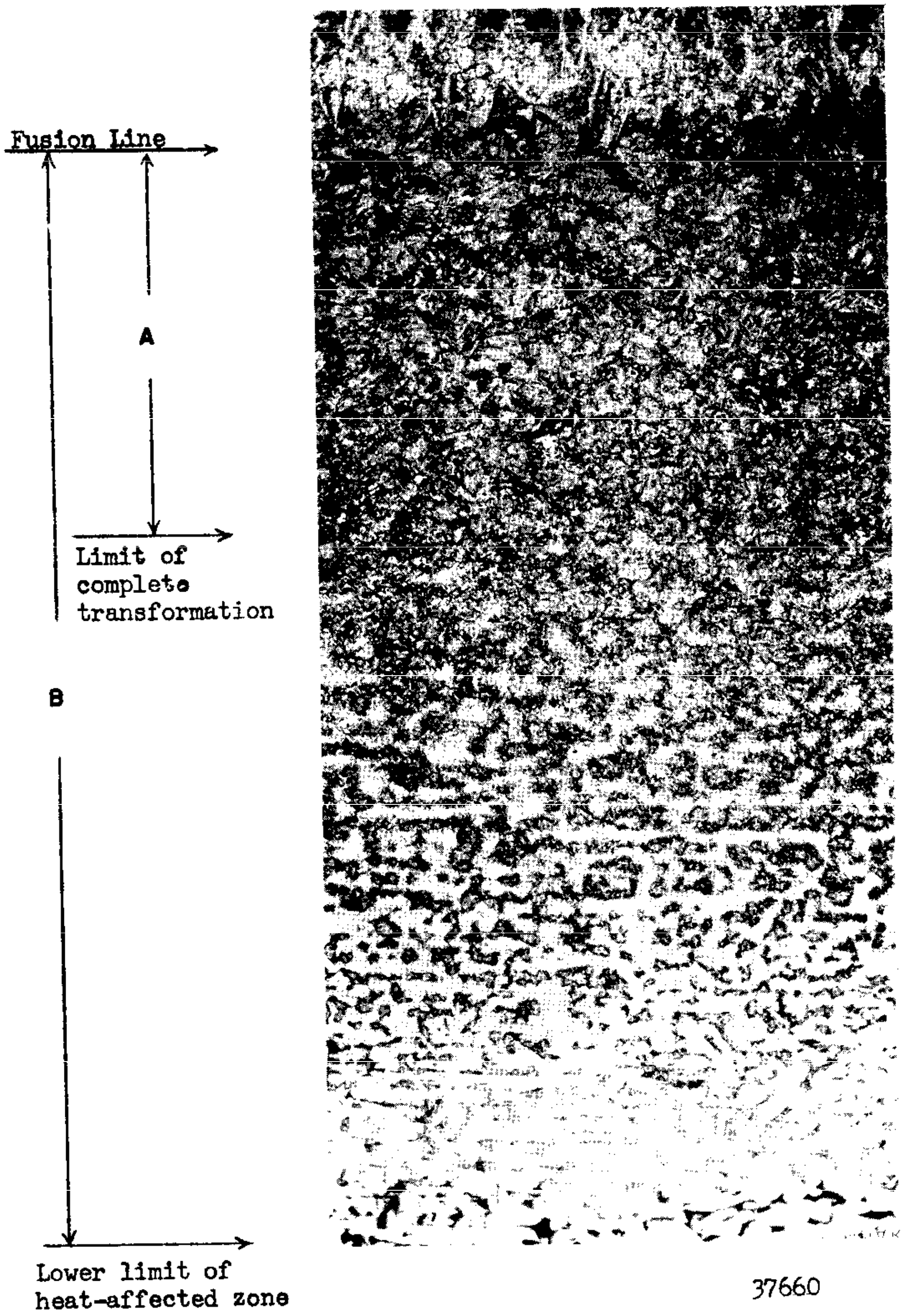


Figure 13. Heat-affected zone beneath weld bead in specimen from Heat 5 which cracked 5 per cent. Transverse section. 100X

cracked 59 and 5 per cent, respectively.

In order to investigate further this difference in structure under the weld bead, duplicate crack-sensitivity test specimens were made from each heat of both groups of steels. For this particular purpose, the 1100°F. draw was omitted because the draw treatment partially obliterated the line of demarcation between the different structures.

After measuring the distances A and B as indicated in Figures 12 and 13, the depth of the zone of complete transformation was expressed as a per cent of the total depth of the heat-affected zone; that is, A/B x 100. These data for the two groups of steels are shown in Tables 9B and 10.

The relationship of the above data, that is, the depth of the zone of complete transformation expressed as A/B x 100, to the underbead, cracking is shown graphically in Figure 14. This figure shows a good correlation between these two factors, the relationship being a straight line when plotted on a semilog scale as illustrated.

Probably the most significant feature of these data is that they indicate there is a marked difference in the response of the crack-sensitive and insensitive steels to the rapid thermal cycle developed during the welding operation.

The Influence of Thermal History

The Effect of Homogenizing

While looking for means of explaining the difference in underbead cracking in steels of similar chemical composition and hardenability, it

TABLE 9B. UNDERBEAD CRACKING AND THE PER CENT OF COMPLETE TRANSFORMATION IN THE HEAT-AFFECTED ZONE FOR THE HEATS FROM THE STEEL PRODUCERS

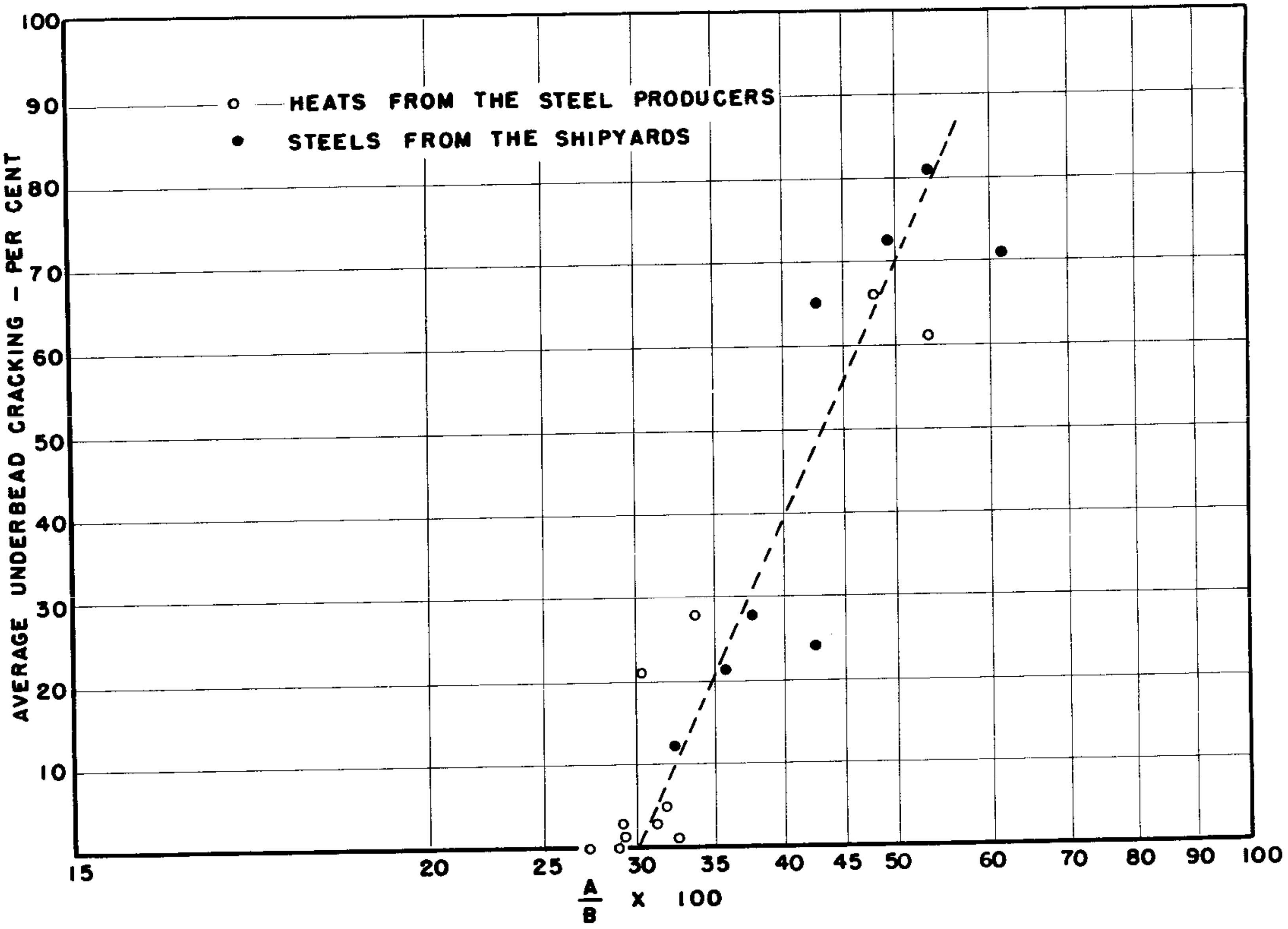
Heat No.	Type of Steel	Underbead Cracking, Per Cent	Ratio* A/B, Per Cent
2b	Ti	59	53
3	Ti	0	29
4	Ti	3	29
5	Ti	5	32
6-m	Ti & V	1	32
7	Ti & V	0	27
9	Ti & V	21	30
10	V	1	29
11	Ti & V	28	34
12	Ti & V	3	31

* The factor A/B x 100 is a measure of the depth of complete transformation expressed as a per cent of the total depth of the heat-affected zone. Heats 13 and 17 were not available at the time this study was made.

TABLE 10. UNDERBEAD CRACKING AND THE PER CENT OF COMPLETE TRANSFORMATION IN THE HEAT-AFFECTED ZONE FOR THE STEELS FROM THE SHIPYARDS

Heat No.	Type of Steel	Underbead Cracking, Per Cent	Ratio* A/B, Per Cent
30	Ti	28	38
31	Ti	65	43
32	Ti	76	49
33	Ti	24	43
34	Ti	71	62
35	V	21	36
36	Ti	81	53
37	V	12	32
38	Ti	66	48

* The factor A/B x 100 is a measure of the depth of complete transformation expressed as a per cent of the total depth of the heat-affected zone.



COMPLETE TRANSFORMATION IN HEAT-AFFECTED ZONE — PER CENT

FIGURE 14. RELATIONSHIP BETWEEN UNDERBEAD CRACKING AND STRUCTURE IN THE HEAT-AFFECTED ZONE.

was found that 3/4-inch and 1-1/4-inch hot-rolled plate from Heat 2, as supplied by the mill, cracked 65 and 35 per cent, respectively, as compared with 59 per cent for the 1-inch plate, 2-b[15]. Since these three steels were from the same heat and were practically identical in chemical analyses as shown in Table 11, it appeared that differences in the processing of these lots, which could not be detected from the microstructure, may have been a factor contributing to the variation in the crack sensitivity. If this were the case, it appeared that the differences could be obliterated by the proper thermal treatment.

TABLE 11. ANALYSES OF PLATE FROM HEAT 2

Heat No.	Plate Gage in Inches	Analyses, Per Cent C	Mn	P	S	Si	Ti	Cu	Ni	Mo	Cr	V
2-a	3/4	.16	1.23	.023	.020	.21	.011	.08	.05	.010	.06	.003
2-b	1	.15	1.29	.023	.020	.29	.014	.10	.06	.014	.05	.002
2-c	1-1/4	.16	1.29	.021	.020	.29	.013	.10	.08	.013	.06	.002

After machining the 1-inch and 1-1/4-inch plate to 3/4 inch in order to eliminate the possible effect of gage, the three steels were homogenized by heating to 2350°F. for four hours followed by normalizing at 1650°F. for one hour. The homogenizing was carried out in an atmosphere-controlled furnace to prevent decarburization. In this particular case, the surfaces of the specimens were very slightly carburized.

The results of tensile tests following the above treatment, as listed in Table 12, show that the properties of the hot-rolled and homogenized-normalized steels were essentially the same, with the exception of Steel 2-a which was slightly lower in strength following the heat treatment.

TABLE 12. TENSILE PROPERTIES OF PLATES FROM HEAT 2 IN THE HOT-ROLLED CONDITION AND AFTER HOMOGENIZING FOLLOWED BY NORMALIZING

Heat No.	Gage in Inches	Treatment	Elong. in 2", %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
2-a	3/4	Homogenized & normalized	39.0	75.9	44,000	67,630
2-b	1	Ditto	37.3	76.3	46,500	72,100
2-c	1-1/4	"	37.3	76.3	45,500	70,400
2-a	3/4	Hot rolled	36.4	73.9	47,500	70,200
2-b	1	" "	29.0	61.4	44,130	73,900
2-c	1-1/4	" "	34.0	73.4	44,000	72,600

Twenty weld specimens were made on each of the three steels, and a summary of the data together with the hot-rolled crack sensitivity is shown in Table 13. From these data it will be noted that the homogenizing treatment followed by normalizing had a pronounced effect, the under-bead cracking being practically eliminated in all three steels. These results, therefore, indicated that the difference in crack sensitivity of these three lots of steel, 2-a, 2-b, and 2-c, was not an inherent difference but was most probably the result of variations in the processing, since it could be eliminated by thermal treatment. It is also equally significant to note that the crack sensitivity was reduced to a marked extent by the homogenizing and normalizing treatment without any loss in tensile or yield strength.

TABLE 13. UNDERBEAD CRACKING OF STEEL FROM HEATS 2-a, b, AND c AFTER HOMOGENIZING* AND NORMALIZING+

Heat No.	Plate Gage, Inch	Underbead Cracking, Per Cent
2-a	3/4	Less than 1
2-b	3/4	2
2-c	3/4	2

Note: * The homogenizing treatment consisted of heating to 2350°F. for four hours.

\+ The steels were normalized by heating to 1650°F. for one hour.

The Influence of Various Thermal Treatments Upon Underbead Cracking

In order to obtain more information concerning the effect of thermal treatments upon underbead cracking, plates from Heat 11 and Steel 30 were treated in the following three ways:(16)

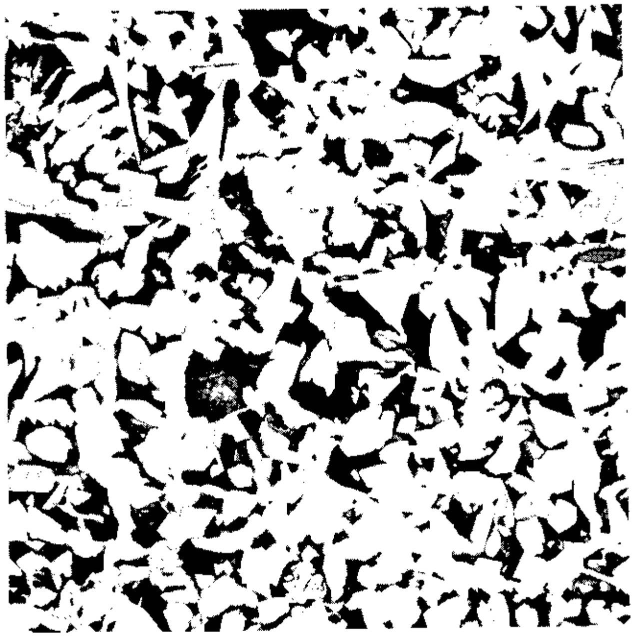
1. Normalized at 1650°F. for one hour.
2. Water quenched from 1650°F. followed by a 1000°F. draw for one hour.
3. Annealed at 1650°F. for one hour followed by furnace cooling.

A summary of the tensile data and the results of crack-sensitivity tests are shown in Table 14. These data show that the annealing treatment, which resulted in the lowest tensile strength, produced the highest crack sensitivity, practically doubling the cracking as compared with the hot-rolled steel. While both the other two treatments, normalizing and quenching and drawing, increased the cracking somewhat, their effect was much less than that of annealing.

TABLE 14. TENSILE PROPERTIES OF PLATE FROM HEATS 11 AND 30 FOLLOWING HEAT TREATMENT

Heat No.	Treatment	Elong. in 2", %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.	Underbead Cracking, Per Cent
11	Hot rolled	33.1	72.1	53,250	77,000	28
11	Annealed	36.0	68.0	51,250	71,250	57
11	Normalized	35.9	71.0	54,250	74,380	37
11	Quenched & drawn	25.0	67.9	81,880	100,630	35
30	Hot rolled	34.6	64.9	50,350	76,150	28
30	Annealed	35.3	63.4	48,750	71,880	48
30	Normalized	35.6	67.7	52,500	76,250	32
30	Quenched & drawn	23.4	62.8	90,880	108,200	38

An examination of the microstructures of these steels showed that the annealing treatment produced a strongly banded structure. (See Figure 15.) This phenomenon can be explained on the basis of heterogeneous alloy distribution resulting from dendritic segregation during the freezing of the ingot. Since manganese, the principal alloy in this steel, diffuses very slowly at temperatures normally used during rolling or heat treating, the manganese segregation persists throughout processing. While this segregation is on a microscale, it results in areas both much lower or higher in alloy content than that of the average analysis. On the other hand, carbon diffuses very readily so that during the slow cooling of the annealing cycle, the carbon



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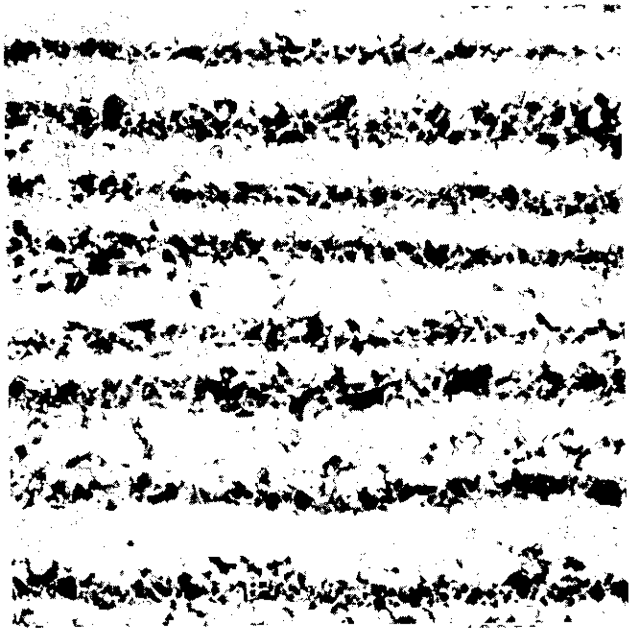
Aircooled from about 1750°F. following hot rolling. 100X



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Furnace cooled from 1600°F. 100X

Figure 15. Comparison of hot-rolled and annealed structures. The above photographs show how the presence of alloy banding is revealed by annealing.

segregates to the high-manganese areas, which remain austenitic for the longest period. This finally results in the formation of pearlite in the high-manganese bands.

Microscopic examination of the cracks in the annealed crack-sensitivity specimens revealed pertinent information regarding the phenomenon of underbead cracking(17). In transverse sections through the weld bead, the underbead cracks are normally found running concentric with the fusion line forming a segment of a circle as shown in Figure 16. However, in the annealed steel, the cracks did not follow this normal pattern. One end of the crack started in the region where the cracks usually occur, but instead of continuing along the circular path, they extended inward along lines parallel with the banding in the microstructure of the plate. This type of crack is shown in Figure 17, the specimens being annealed steel from Heat 11.

The above observations, together with the fact that underbead cracking can be eliminated, or greatly reduced, by an homogenizing treatment, indicate that alloy banding is an important factor influencing underbead cracking.

Underbead Hardness in Heat-Treated Steels

In order to determine if there was any relationship between the underbead hardness developed in the heat-treated steels and the crack sensitivity, Steel 31 was studied in the following four conditions(18):

1. As-received hot-rolled plate.
2. Water quenched from 1650°F. and drawn at 1000°F. for one hour.
3. Annealed at 1650°F. for one hour followed by furnace cooling.
4. Homogenized at 2350°F. for four hours followed by normalizing at 1650°F.

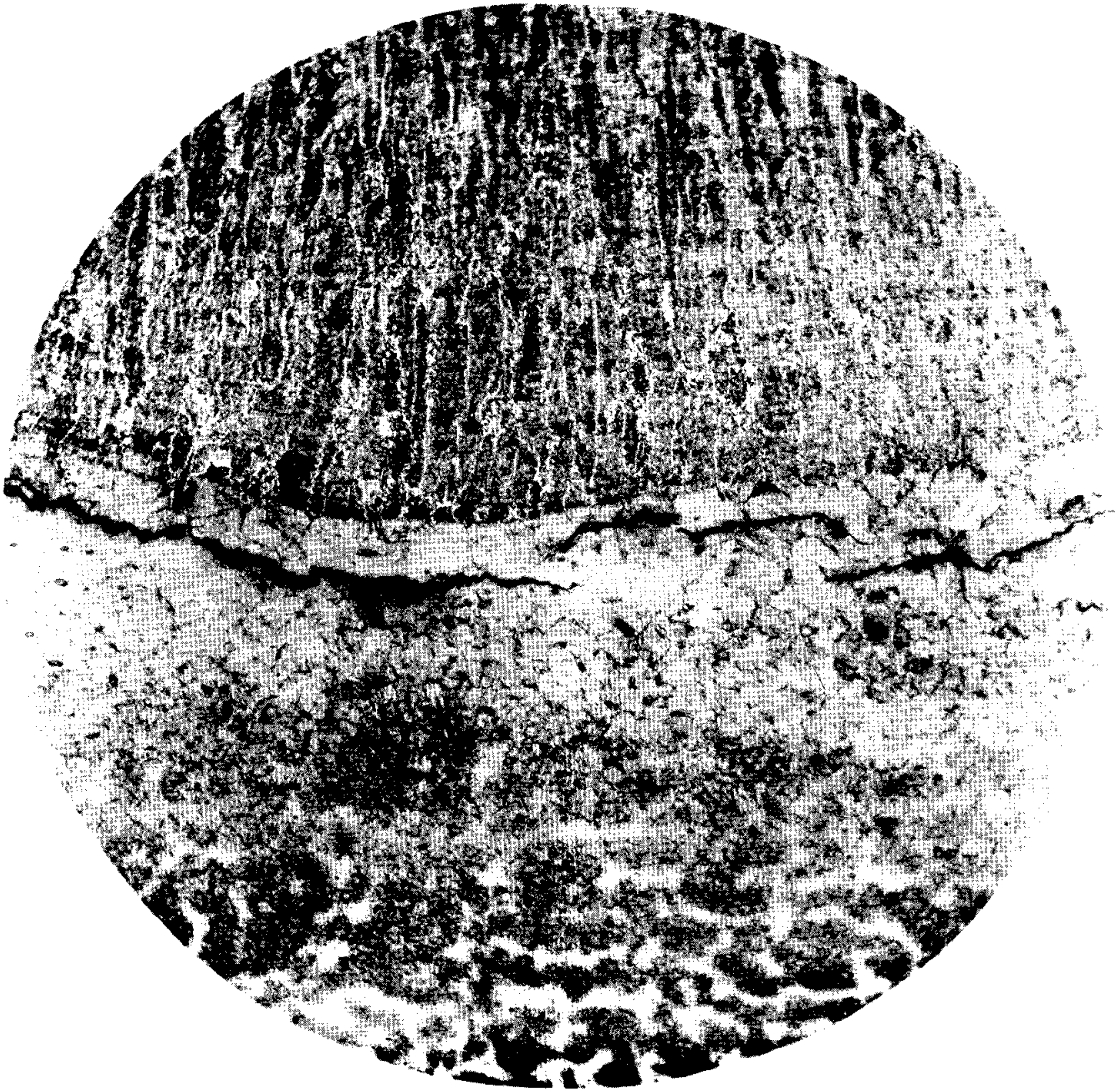

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Figure 16. Photograph of typical underbead crack. Note that the cracks in the above transverse section follow the circular contour of the fusion line. 100X

38253

Figure 17. Transverse section through annealed specimen showing underbead cracks running parallel with the banded structure. 100X

The crack sensitivities of these four steels and the maximum hardness developed in the heat-affected zone are shown in Table 15.

TABLE 15. COMPARISON OF UNDERBEAD CRACKING AND THE MAXIMUM HARDNESS IN THE HEAT-AFFECTED ZONE

Condition of Plate	Underbead Cracking, Per Cent	Vickers Hardness Number
Hot rolled	76	437
Quenched & tempered	70	434
Annealed	72	430
Homogenized & normalized	1	443

While the hot-rolled, quenched and drawn, and the annealed steels all cracked between 70 and 76 per cent, the homogenized and normalized steel cracked only one per cent. The maximum hardness in the heat-affected zone of these four steels was essentially the same showing there is no correlation between the underbead cracking and hardness.

A Study of Homogenizing Time-Temperature Cycles

In order to determine the effectiveness of various homogenizing cycles for reducing the crack sensitivity of 1-inch hot-rolled plate, steel from Heat 31 was homogenized at temperatures of 2250°F. and 2350°F. for periods of time ranging from 1/2 hour to 6 hours.(19) Following the high-temperature treatment, the steel was normalized at 1650°F. for one hour.

The results of the crack-sensitivity tests made on these steels are shown in Figure 18, each datum point being the average of five tests.

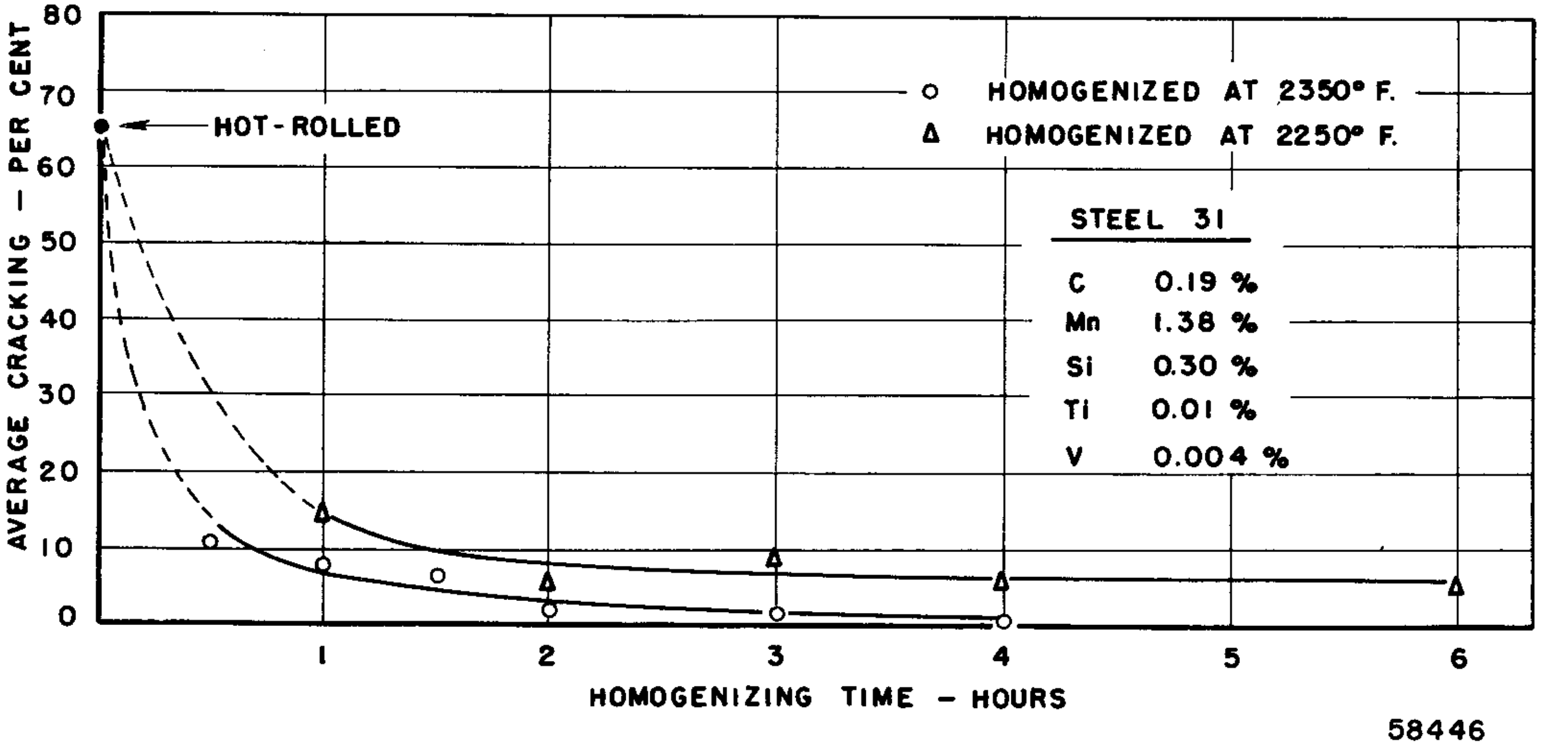

FIGURE 18. THE INFLUENCE OF HOMOGENIZING TIME AND TEMPERATURE UPON UNDERBEAD CRACKING.

These results show that even 1/2 hour at 2350°F. or one hour at 2250°F. had a pronounced effect, the underbead cracking being reduced from 65 to less than 15 per cent. Increasing the homogenizing time beyond the abovementioned times resulted in only slight additional reductions in the underbead cracking.

Since there was some reason to suspect that the higher carbon and manganese steels would not respond so readily to the homogenizing treatment as the steels of lower chemical composition, a study was made of the effect of various time-temperature cycles upon the crack sensitivity of Steel No. 34, which had a carbon content of 0.23 per cent and a manganese content of 1.53 per cent. The results of this study are shown in Figure 19. Each value shown in this figure is the average of five weld tests.

The data in Figure 19 show that homogenizing treatments of three hours or less at 2350°F. had little effect upon the crack sensitivity of Steel No. 34, four hours being required to reduce the cracking from 71 to 47 per cent. This slow response to homogenizing appears to be typical of the steels with higher carbon and manganese contents.

The Effect of Hot Reduction on the Rate of Homogenization

In order to obtain some idea of the influence of hot reduction upon the response to the homogenizing treatment, a study was made of the time required to eliminate microsegregation in steels from a 6 by 6-inch laboratory ingot after various degrees of hot reduction. The results of this study are shown in Table 16, which indicates that the homogenizing time is reduced rapidly with increased hot reduction.

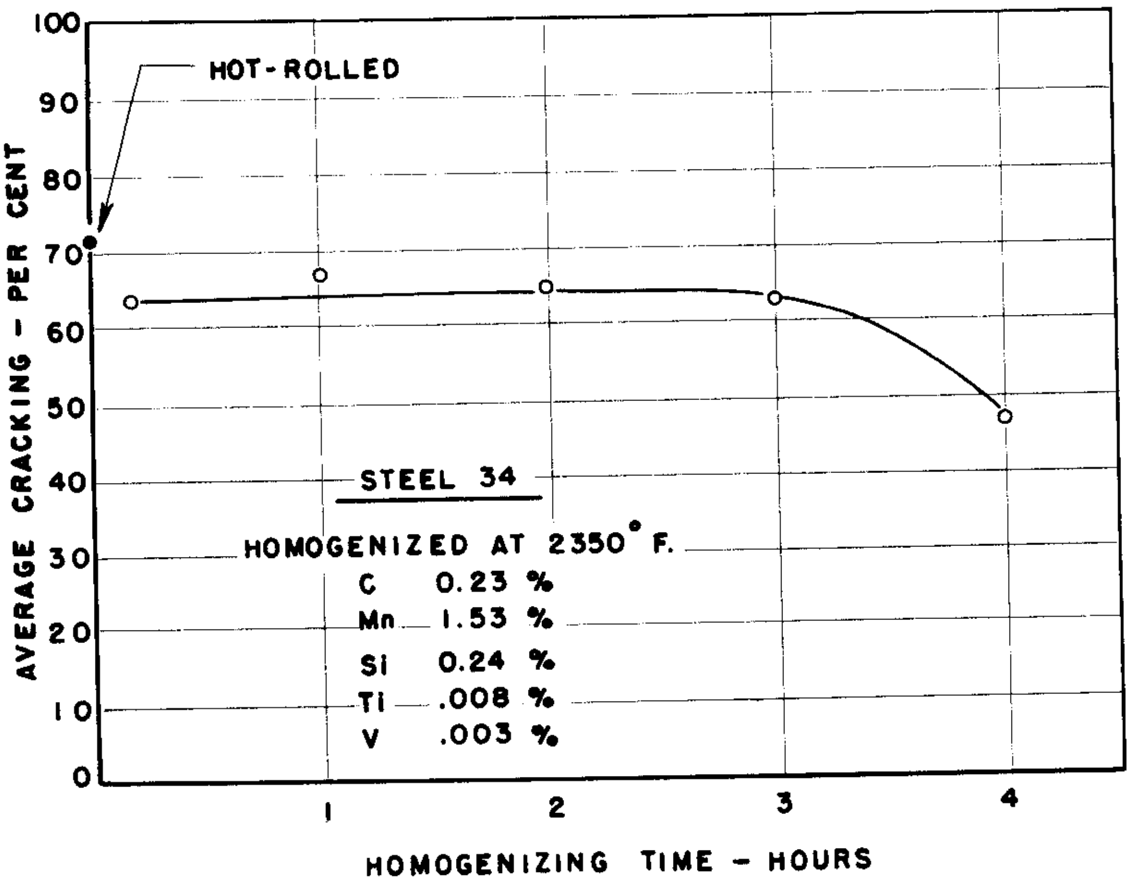

FIGURE 19. THE INFLUENCE OF HOMOGENIZING UPON UNDERBEAD CRACKING IN A STEEL OF HIGHER CHEMICAL ANALYSIS.

TABLE 16. THE EFFECT OF HOT-REDUCTION UPON THE TIME REQUIRED FOR HOMOGENIZING

Per Cent Reduction	Time at 2350°F. to Homogenize
0	11 hours
12.5	7 "
21.5	3 "
37.5	1 "
50	Less than 1 hour

Homogenizing Tests on Commercial Slabs

While the underbead cracking of 1-inch plate could be drastically reduced by homogenizing, it was obvious that such a high-temperature treatment would not be commercially practicable because of excessive scaling and warping of the plate. It did appear, however, that it might be feasible to homogenize the slabs in the slab heating furnace or soaking pits prior to rolling to plate(20).

In order to determine the effectiveness of such a procedure, 6-inch-thick slabs from a commercial heat (Steel No. 23) were homogenized for 2-1/2, 5, and 10 hours at 2350°F. in a standard ingot-soaking pit prior to rolling into 1-inch plate. The chemical analysis and the results of underbead cracking tests made on plate from the homogenized slabs are shown in Table 17. This table also includes the results of underbead cracking tests made on regular hot-rolled plate from Steel 23, after the plate was homogenized at 2350°F. for various lengths of time under conditions precluding decarburization and scaling.

TABLE 17. CHEMICAL ANALYSES AND DATA ON HOMOGENIZED SLABS AND PLATES FROM STEEL 23

Steel No.	C	Mn	P	S	Si	Mo
23	0.19	1.46	.020	.018	0.25	0.37

Steel No.	Homogenizing* Time, Hours	Underbead Weld Cracking, %
23 six-inch slab	0 (Direct rolled)	79
23 " " "	2-1/2	81
23 " " "	5	80
23 " " "	10	79
23 one-inch plate	0 (As rolled)	78
23 " " "	1/6	35
23 " " "	1	28
23 " " "	3	30
23 " " "	5	14

* Homogenized at 2350°F.

From Table 17 it will be noted that homogenizing the slabs at 2350°F. for periods of time extending up to 10 hours did not reduce the cracking in the plates subsequently rolled from them. When the plate, itself, was homogenized, however, at 2350°F. for only 10 minutes, followed by normalizing at 1600°F., the cracking was reduced from 78 per cent to 35 per cent, while homogenizing for 5 hours reduced the cracking to 14 per cent. These results showed that the time required to obtain sufficient diffusion of the high-alloy areas in the coarse slab structure to reduce cracking would be entirely too long for practical purposes.

The Influence of the Electrode Coating and Preheat Upon Underbead Cracking

For the crack-sensitivity test used in this investigation, the E6010-type electrode was selected because of its wide use in ship construction and because of its strong tendency to produce underbead cracks. It is well known, however, that there are other types of electrodes which are less prone to develop underbead cracks, and efforts are being made to perfect such an electrode which will be universally acceptable for all types of work. Considerable progress has been made, and the realization of this goal would solve the underbead cracking problem very well. Since the object of this investigation was to study the metallurgical factors influencing underbead cracking, the E 6010 type of electrode was the obvious type to use.

To show the effect of the electrode coating, crack-sensitivity tests were made using three different types of electrodes with coatings which varied widely in hydrogen content(21). For this test, a hot-rolled commercial steel was selected (Steel 39, 0.19% C, 1.43% Mn, and 0.33% Mo) which was prone to crack. Ten specimens were welded with each type of electrode, and the summary of the results is shown in Table 18.

The data in Table 18 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 E 6015 type electrode was used.

While the use of the E 6020 type electrode results in considerably less cracking, as compared with the E 6010, the explanation for this difference is not too obvious since the arc atmosphere of the E 6020 is relatively high in hydrogen; however, the volume of gas generated per inch of electrode consumed is considerably less. As previously pointed out by Voldrich,[21] additional study will be necessary in order to obtain a better understanding of the difference in behavior of these two electrodes.

TABLE 18. THE EFFECT OF THE ELECTRODE COATING UPON UNDERBEAD WELD CRACKING IN STEEL NO. 39

Type Electrode	Coating	Hydrogen Content of Coating	Underbead* Cracking, %
E 6010	Cellulosic	High	78
E 6015	Lime	Low	0
E 6020	Mineral	? (See text)	20

* Average of ten specimens.

When the welding conditions were originally selected for the crack-sensitivity test, an initial plate temperature of 0°F. was chosen in order to make conditions exceedingly drastic so that cracking would occur in the less sensitive steels. For similar reasons, a small electrode size and a high rate of travel were used.

Later in the investigation, it was deemed desirable to study the effect of the initial plate temperature upon underbead cracking(22). For this study, nine steels were selected, Heats 2b and 11, and Steels 30, 31, 32, 33, 34, 37, and 38. Crack-sensitivity tests were made on these steels using the same procedure as previously described with the exception that initial plate temperatures of 0°, 60°, 120°, and 200°F. were used with the specimen being held in a bath at these temperatures. Twenty weld specimens were made on each steel at each of the above four temperatures. A summary of the results from these tests is shown in Figure 20. The results of this study were somewhat surprising since the maximum cracking did not occur when the specimens were welded at 0°F. as was anticipated. From Figure 20, it will be noted that in most cases the steels were slightly more crack sensitive when welded at 120°F. than at 0°F. This is especially noticeable in the case of the less crack-sensitive steels, Nos. 33, 11, and 30. An initial temperature of 200°F. practically eliminated cracking in the less sensitive steels and sharply reduced the cracking in the more sensitive steels.

This influence of the initial temperature upon underbead cracking has been confirmed by similar results from other grades of steel, and, in the case of certain higher alloy steels, the effect is more noticeable, the difference in cracking between 0°F. and 120°F. or 150°F. being much more pronounced.

Phenomenon of Underbead Cracking

Since the major portion of this investigation has been centered around underbead cracking, it appears desirable to consider the phenomenon by which underbead cracks are developed.

There has been considerable misapprehension concerning the properties of the hard structure in the heat-affected zone, it being assumed that martensite is inherently brittle and that this lack of ductility is the most likely cause of cracks. Although relatively hard, the martensite or structure resulting from the drastic quenching of carbon-manganese or manganese-molybdenum steels and similar types that

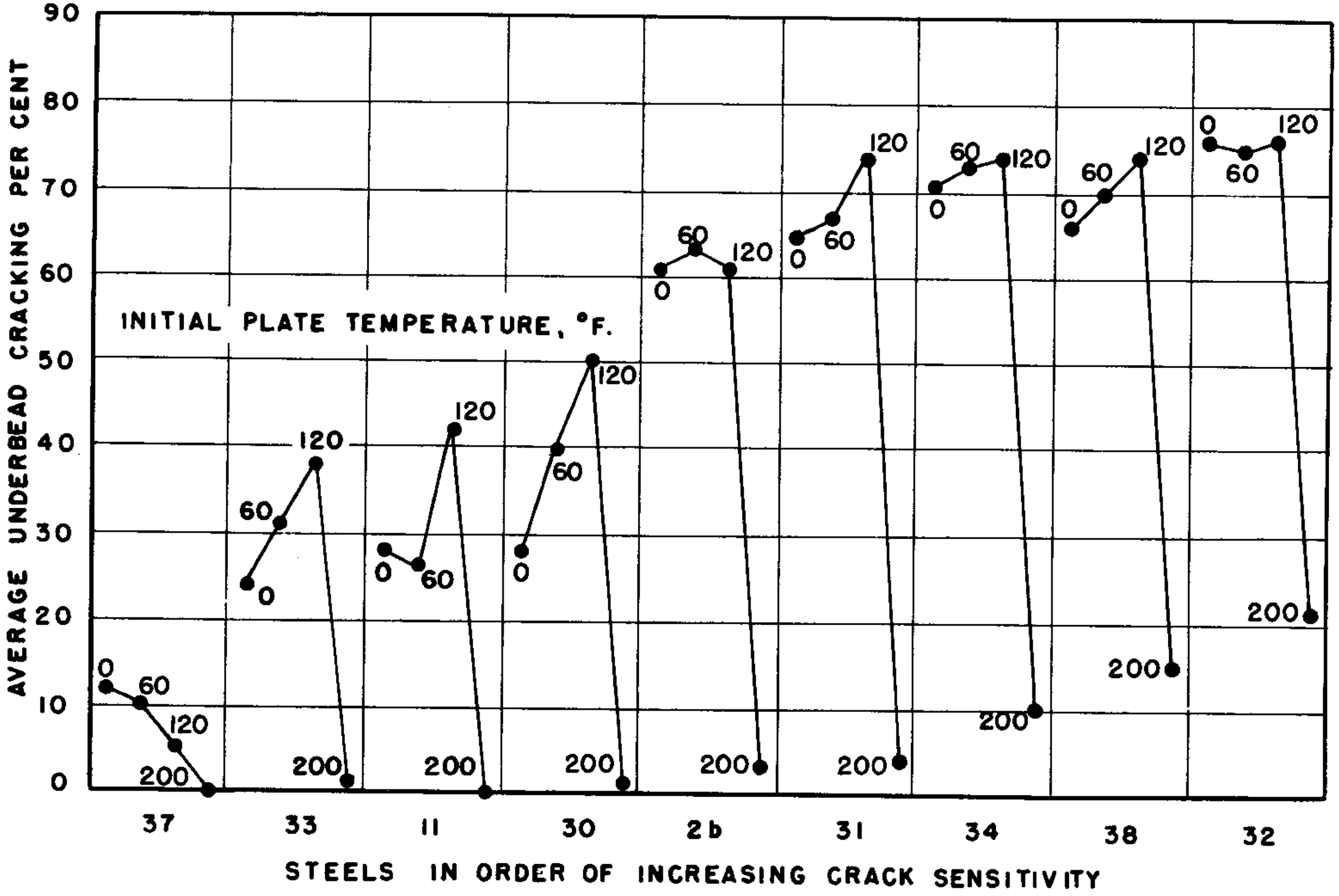

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FIGURE 20. INFLUENCE OF INITIAL PLATE TEMPERATURE ON UNDERBEAD CRACKING.

might be used for structural purposes is not normally brittle. In order to demonstrate that these quenched structures are ductile, both tensile and impact tests were made using water-quenched and untempered specimens from two commercial heats, Steels 23 and 26. The chemical analysis of these two steels is shown in Table 19.

TABLE 19. CHEMICAL ANALYSIS OF STEELS USED TO STUDY THE PROPERTIES OF FULLY HARDENED STEEL

Steel No.	Chemical Composition, Per Cent					
	C	Mn	P	S	Si	Mo
23	0.19	1.46	.020	.018	0.25	0.37
26	0.14	1.44	.013	.027	0.25	0.48

After water quenching from 1650 F., the threaded-end tensile specimens were ground under water from 0.530 inch to 0.500 inch in diameter with a 2-inch parallel section. To study the effect of even more drastic quenching, a second set of specimens was machined to 0.249 inch in diameter, water quenched from 1650°F., and tested in that condition and size.

The data from the above quenched specimens are shown in Table 20, together with the tensile data for the hot-rolled steel. These data show that,with a tensile strength of over 210,000 psi., the reduction in area of the fully quenched steel (Steel No. 23) was approximately 50 per cent when using the 0.500-inch specimen and 47 per cent for the small specimen. These values compare favorably with the reduction in area of the hot-rolled steel which was approximately 56 per cent. The elongation in 2 inches was 15 to 16 per cent in the quenched bars as compared with

22 to 24 per cent in the hot-rolled steel.

The Charpy notched-bar impact specimens were prepared by water quenching from 1650°F., after which they were notched perpendicular to the plate surface by grinding under water, the standard Izod-V notch being used. The results obtained from these specimens are shown in Table 21. The data show that these fully hardened steels are far from being brittle but have good notched-bar impact resistance at temperatures as low as -75°F., Steel No. 26 displaying 16 to 24 foot-pounds, and Steel No. 23, 11 to 25 foot-pounds, at this low temperature, as compared with 39 to 41 foot-pounds and 25 to 29 foot-pounds at $+75$°F., respectively, for the two steels.

TABLE 20. TENSILE DATA FROM HOT-ROLLED AND WATER-QUENCHED UNTEMPERED MANGANESE-MOLYBDENUM STEELS

Steel No.	Condition of Steel	Specimen Diam., In.	Elong. in 2", %	Red. of Area, %	Yield* Strength, psi	Tensile Strength, psi	BHN
23	Hot-rolled	0.505	22.5	56.5	70,500	101,200	202
26	" "	0.505	24.0	61.5	68,700	102,500	207
23	Quenched	0.500	15.0	49.0	143,500	212,200	421
23	"	0.500	15.5	52.0	146,500	212,200	-
26	Quenched	0.500	16.0	57.0	137,500	187,500	363
26	"	0.500	16.0	58.0	136,700	184,300	-
23	Quenched	0.247	8.5	46.5	-	221,300	-
23	"	"	8.5	48.5	-	219,700	-
26	Quenched	0.247	10.5	59.0	-	195,200	-
26	"	"	11.0	59.0	-	196,200	-

* Yield strength from strain at 0.2 per cent offset.

TABLE 21. NOTCH-BAR IMPACT STRENGTH OF WATER-QUENCHED MANGANESE-MOLYBDENUM STEELS

Steel No.	Testing Temp.	Impact Strength, Foot-Pounds Charpy					
		-75°F.	-40°F.	-5°F.	+40°F.	+75°F.	+210°F.
23		11	11	15	23	25	33
"		11	13	18	25	25	24
"		12	13	18	25	27	34
"		25	24	18	30	29	35
26		16	21	22	36	39	40
"		17	21	24	37	39	43
"		21	23	25	37	40	43
"		24	23	28	42	41	45

Note: The above data were obtained from Charpy specimens with a V-type Izod notch, the notch being perpendicular to the plate surface. After water quenching from 1650°F., the specimens were notched under water.

From the above tensile and impact data, it is obvious that these steels in the fully hardened state have considerable ductility and resistance to notched-bar impact. It has been shown, however, by Herres(30) that the ductility of fully hardened steels is decreased to a marked extent by the presence of hydrogen and that the tensile strength is erratically lowered. The impact properties, however, are not affected to the same extent. Fortunately, the ductility of low- and medium-carbon steels embrittled by hydrogen is rapidly recovered while standing at room temperature or by a stress-relieving treatment. The following conception of underbead cracking is similar to the discussion presented in "Metallurgical Factors of Underbead Cracking"(29), a paper concerning low-alloy high-tensile steels.

In order for underbead cracks to develop, a combination of several factors is essential; that is, the delayed transformation of retained austenite, hydrogen absorption, and stresses, the absence of any one being sufficient to eliminate the cracking.

In the previous investigation of low-alloy steels, the presence of retained austenite in the heat-affected zone was suspected from the finding that cracking occurred at about room temperature and progressed for a period of hours after welding. The presence of retained austenite was confirmed by X-ray examination and appeared to be consistent with dilatometer results. Data concerning post heat treatment supported this idea, since, regardless of the hardness of the heat-affected zone, cracking was eliminated by causing the austenite to transform completely at a sufficiently elevated temperature.

The presence of retained austenite in a low-alloy steel such as these may be explained on the basis of heterogeneous distribution of alloy content as a result of dendritic segregation during freezing as indicated by the pearlite banding following annealing. This segregation is on a microscale but results in areas both lower or much higher in alloy content than the average analysis. Some of these elements, notably manganese, diffuse so slowly that ordinary heat treatments are ineffective in remedying the condition. Carbon, of course, diffuses readily, but in the normalized or annealed condition of the steel, the carbon will tend to be segregated in the manganese-rich areas because they remain austenitic longest during cooling. In the rapid heating and cooling cycle of arc welding, carbon does not diffuse appreciably, and the high-carbon high-manganese areas tend to remain austenitic in the zone where the lower alloy areas around them form martensite.

The effect of hydrogen absorption on underbead cracking has been discussed by Herres(30) and Voldrich(31), who showed the vital role played by this gas. Herres suggests that the pressures produced when this gas precipitates at discontinuities may exceed the strength of the metal.

It has been observed that underbead cracking always occurs in the most nearly pure martensitic areas. This material has a strength in excess of 200,000 lbs. per sq. in. and the stress that cracks it must exceed that figure. It is obvious, then, that shrinkage stresses alone are quite inadequate to initiate such cracks when it is realized that the unaffected parent metal has a yield strength under 100,000 lbs. per sq. inch. It has been demonstrated that retained austenite and the delayed decomposition to martensite play a vital part in the cracking. At the same time, decomposition of the retained austenite at room temperature in the absence of hydrogen does not cause cracking, and the fairly rapid decomposition of austenite at temperatures above 500°F. also does not lead to cracks.

Fitting these observations together, the mechanism seems to be as follows. During the welding operation with the usual weld rod, quantities of hydrogen are dissolved in the weld bead. This diffuses rapidly into the parent metal, which is heated above the transformation temperature. Hydrogen is soluble in austenite at all temperatures but is practically insoluble in cold ferrite or martensite. When the heat-affected zone transforms, therefore, hydrogen is rejected from all areas except those that remain austenitic. In these areas of austenite, the hydrogen concentrates to relatively high values. When they later transform at room temperature and hydrogen is rejected, with no place to go, enormous aerostatic pressures are set up, which disrupt the adjacent structure even though it be hardest martensite. The cracks thus formed are undoubtedly quite small, and the principal function of thermal stresses probably is to cause the cracks to grow to visible size. This growth has been observed frequently and was demonstrated in the course of the present investigation. If this austenite is transformed at elevated temperatures, the hydrogen can diffuse sufficiently to prevent the maximum stress. This is a common experience with shatter cracks, which are never produced at temperatures above 400°F.

It follows, therefore, that the more hardenable steels are in general more crack sensitive because they tend more to retain austenite. Likewise with more complete solution of the carbides, the likelihood of retaining austenite is greater.

The very nature of the arc-welding process, with its steep temperature gradients, is ideal to set up local stresses of high magnitude, though the magnitude will depend on the degree of restraint imposed. While these stresses in themselves seem inadequate to cause cracking in the martensite, they are additive to the aerostatic stresses of the rejected hydrogen and might logically be the straw that breaks the camel's back. This is in line with the experience that sometimes cracks may form when welding is done under conditions of restraint but not when there is no restraint.

Conclusions from Study of HTS Steels

The results of the investigation of these two groups of HTS steels, the plates from the steel mills, and those from the shipyards, are briefly summarized as follows:

1. The relative crack sensitivity of the high-strength hull steels can be determined by means of a single-bead weld test made under closely controlled conditions.

2. While in general the steels with the higher chemical compositions have the greater sensitivity to underbead cracking, frequently the variations in crack sensitivity found in different lots of HTS could not be accounted for on the basis of chemical analysis, hardness of the heat-affected zone, hardenability, or other properties commonly determined.

3. The thermal treatment was found to have a pronounced influence upon the crack sensitivity, homogenizing decreasing, and annealing increasing the sensitivity.

4. For similar compositions, the level of crack sensitivity appears to be closely associated with the degree of microsegregation, the cracking increasing with increased segregation.

5. While the crack sensitivity of 1-inch plate can be reduced to a marked extent by homogenizing at 2350°F. for a relatively short period, provided the carbon and manganese contents are not too high, the use of such a treatment is not commercially feasible.

6. Underbead cracking can be eliminated by the use of low-hydrogen electrodes which have not yet been developed to the point that they are universally acceptable for all types of work.

7. A good correlation was found between the crack sensitivity and depth of complete transformation in the heat-affected zone when expressed as per cent of the total depth of the zone under the weld bead. The steels with relatively deep zones of complete transformation were the most crack sensitive.

8. Of the three types of HTS steels investigated, the vanadium-containing steels displayed the best combination of high yield strength and low underbead cracking.

9. Low carbon and manganese contents and high aluminum content, together with a fine microstructure, were found to be conducive to high notched-bar impact strength.

10. A good correlation was found between the transition temperature and the acid-soluble aluminum content, high aluminum lowering the transition temperature.

11. Aluminum contents up to .015 per cent were found to be detrimental to the tensile properties normal to the plate surface.

The Development of High-Strength Low-Alloy Steels for Welded Construction

The first part of this report has been confined to a study of the mechanical properties, metallurgical characteristics, and the underbead cracking tendencies of HTS steels that have been used in welded naval construction. Briefly, the range of chemistry covered was from 0.14 to 0.23 per cent carbon and 0.80 to 1.55 per cent manganese, together with small additions of titanium or vanadium, or both. This range represents about the extreme limits found in commercial steels of this grade.

The purpose of this phase of the investigation is to determine the influence of chemical composition covering a much wider range than found in the commercial HTS steels, with the ultimate object being to find the composition which will give the highest yield strength and acceptable notched-bar properties, and still have a sufficiently low level of crack sensitivity to be satisfactory for welded ship construction.

The first step in this study was to determine the influence of each of the individual elements, which was later used as a guide for establishing the complete analysis of the steel.

Influence of the Individual Alloys

In order to determine the relative influence of the common alloying elements upon underbead cracking and the yield strength, a study was made of a series of laboratory heats in which the following elements were varied through the range indicated:(23)

Group	1	Heats	Carbon	0.17 to 0.32 per cent
"	2	"	Manganese	0.93 to 1.51 per cent
"	3	"	Silicon	0.27 to 0.92 per cent
"	4	"	Molybdenum	0 to 0.43 per cent
"	5	"	Vanadium	0 to 0.29 per cent
"	6	"	Chromium	0 to 1.00 per cent
"	7	"	Titanium	0 to 0.38 per cent
"	8	"	Standard Composition	-

The standard composition chosen for comparison purposes was 0.21 per cent carbon, 1.35 per cent manganese, 0.28 per cent silicon, and .015 per cent titanium with an addition of 0.4 pound of aluminum per ton. This composition was selected because previous experience indicated that laboratory heats of the above analysis cracked well within the limits of the crack-sensitivity test conditions used for the commercial steels. The indications are that laboratory heats cast into small ingots are somewhat less crack sensitive than steel of a similar analysis from commercial ingots.

The chemical analyses of the 32 laboratory heats are listed in Table 22. These steels were processed by forging the 6-5/8-inch square

TABLE 22. CHEMICAL ANALYSES OF LABORATORY HEATS USED TO STUDY THE INFLUENCE OF VARIOUS ALLOYS

Heat No.	Analyses, Per Cent								
	C	Mn	P	S	Si	Ti	Mo	V	Cr
(Group 1)									
X-1	0.17	1.36	.023	.024	0.31	.014	-	-	-
X-2	0.20	1.30	.021	.023	0.25	.001	-	-	-
X-3	0.25	1.36	.022	.023	0.29	.014	-	-	-
X-4	0.28	1.42	.022	.020	0.22	.014	-	-	-
X-5	0.32	1.26	.022	.020	0.22	.013	-	-	-
(Group 2)									
X-6	0.21	0.93	.021	.022	0.27	.010	-	-	-
X-7	0.19	1.22	.023	.018	0.28	.011	-	-	-
X-8	0.22	1.37	.023	.018	0.29	.012	-	-	-
X-9	0.21	1.51	.023	.018	0.29	.011	-	-	-
(Group 3)									
X-10	0.21	1.30	.025	.018	0.41	.012	-	-	-
X-11	0.21	1.37	.024	.019	0.55	.012	-	-	-
X-12	0.19	1.39	.023	.018	0.79	.011	-	-	-
X-13	0.20	1.31	.024	.019	0.92	.010	-	-	-
(Group 4)									
X-14	0.22	1.45	.023	.019	0.30	.025	0.10	-	-
X-15	0.21	1.49	.020	.020	0.35	.012	0.12	-	-
X-16	0.23	1.29	.023	.022	0.28	.012	0.24	-	-
X-17	0.23	1.32	.020	.020	0.30	.012	0.32	-	-
X-18	0.24	1.37	.023	.020	0.29	.014	0.43	-	-
(Group 5)									
X-19	0.21	1.27	.020	.019	0.32	.013	-	0.04	-
X-20	0.20	1.30	.021	.020	0.30	.016	-	0.08	-
X-21	0.20	1.29	.020	.019	0.30	.014	-	0.19	-
X-22	0.21	1.28	.020	.020	0.29	.018	-	0.29	-
(Group 6)									
X-59	0.20	1.37	.025	.026	0.32	.014	-	-	0.28
X-60	0.20	1.33	.024	.030	0.33	.012	-	-	0.52
X-61	0.21	1.36	.024	.026	0.34	.012	-	-	0.78
X-62	0.22	1.30	.024	.025	0.31	.015	-	-	1.00

TABLE 22. (Cont.)

	Analyses, Per Cent								
Heat No.	C	Mn	P	S	Si	Ti	Mo	V	Cr
(Group 7)									
X-41	0.23	1.36	.021	.027	0.24	Nil	-	-	-
X-42	0.22	1.33	.021	.028	0.24	.037	-	-	-
X-43	0.22	1.36	.023	.025	0.20	Nil	-	-	-
X-44	0.22	1.36	.021	.024	0.20	.038	-	-	-
(Group 8)									
X-45	0.21	1.35	.021	.030	0.27	.015	-	-	-
X-46	0.22	1.35	.023	.032	0.28	.015	-	-	-

Note: All of the above heats were deoxidized with an addition of 0.4 pound of aluminum per ton.

ingots at 2200°F. to 2300°F. into 2 by 5-inch slabs. Following reheating to 2200°F., the slabs were hot rolled to 1-inch plate in six passes with the finishing temperature being approximately 1750°F. The plates were stood on edge and allowed to air cool as in normalizing. All tests were made on the plate in the hot-rolled condition unless otherwise stated.

Influence of Chemical Analysis Upon Underbead Cracking and the Yield Strength

The results of the underbead crack-sensitivity tests together with the yield strengths for the seven groups of steels are shown graphically in Figures 21 to 27, inclusive(24). The single-bead cracking tests were made as previously described, with each of the data points in the above figures being the average of ten tests. The yield strength was determined from longitudinal 0.505-inch specimens using the load at 0.2 per cent offset as indicated on the stress-strain curve.

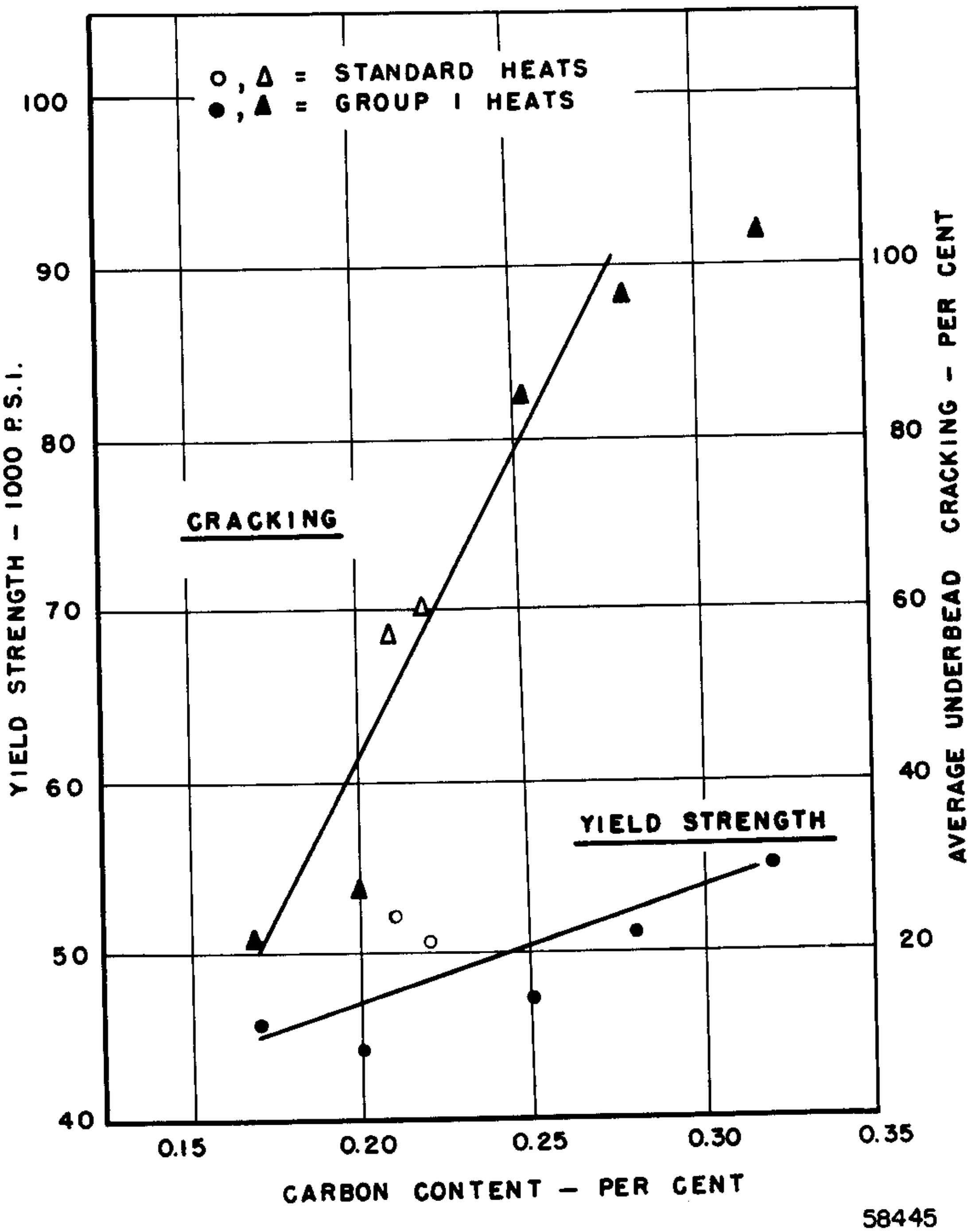

FIGURE 21. THE INFLUENCE OF CARBON CONTENT ON YIELD STRENGTH AND UNDERBEAD CRACKING.

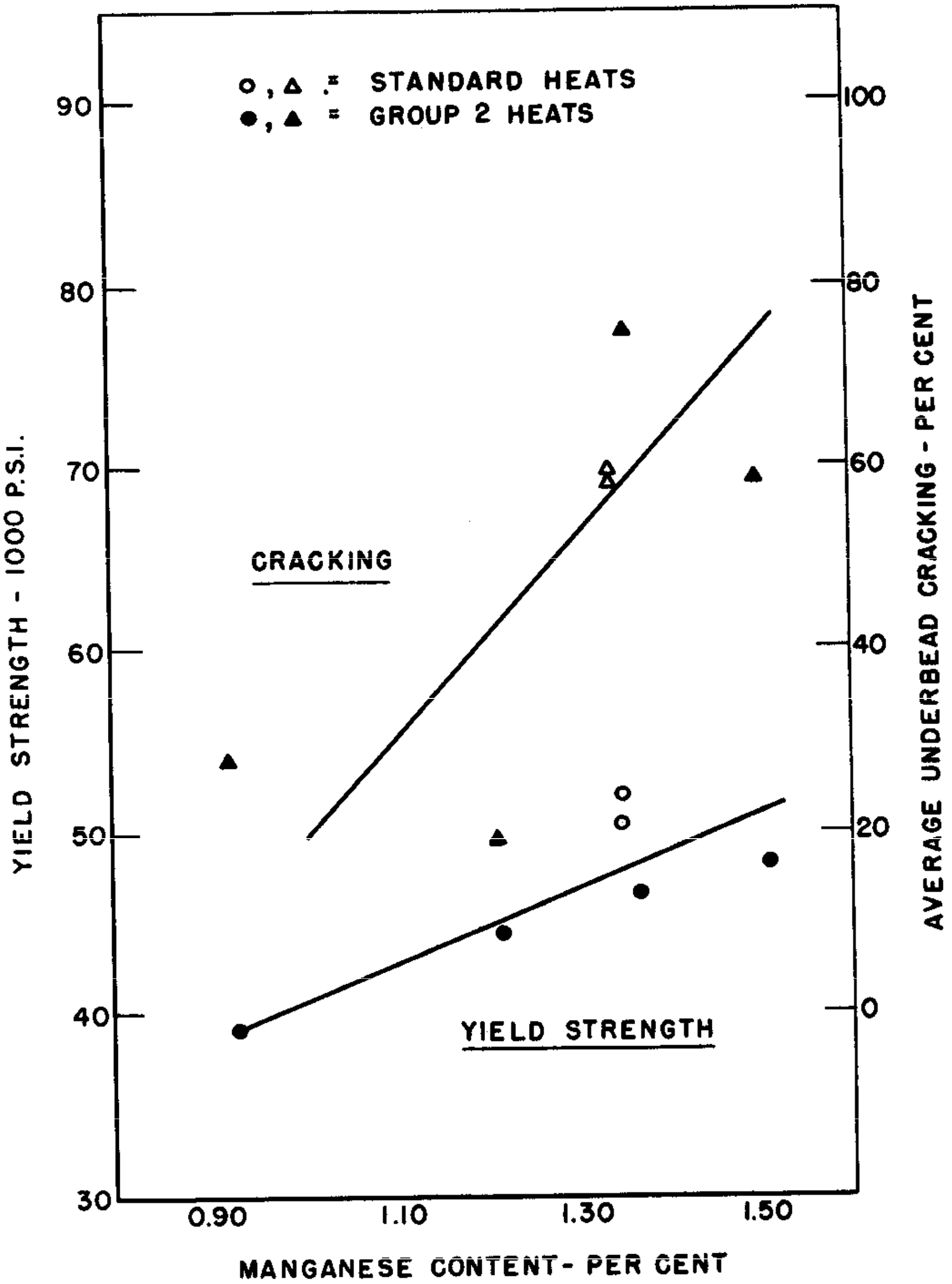

FIGURE 22. THE INFLUENCE OF MANGANESE CONTENT ON YIELD STRENGTH AND UNDERBEAD CRACKING.

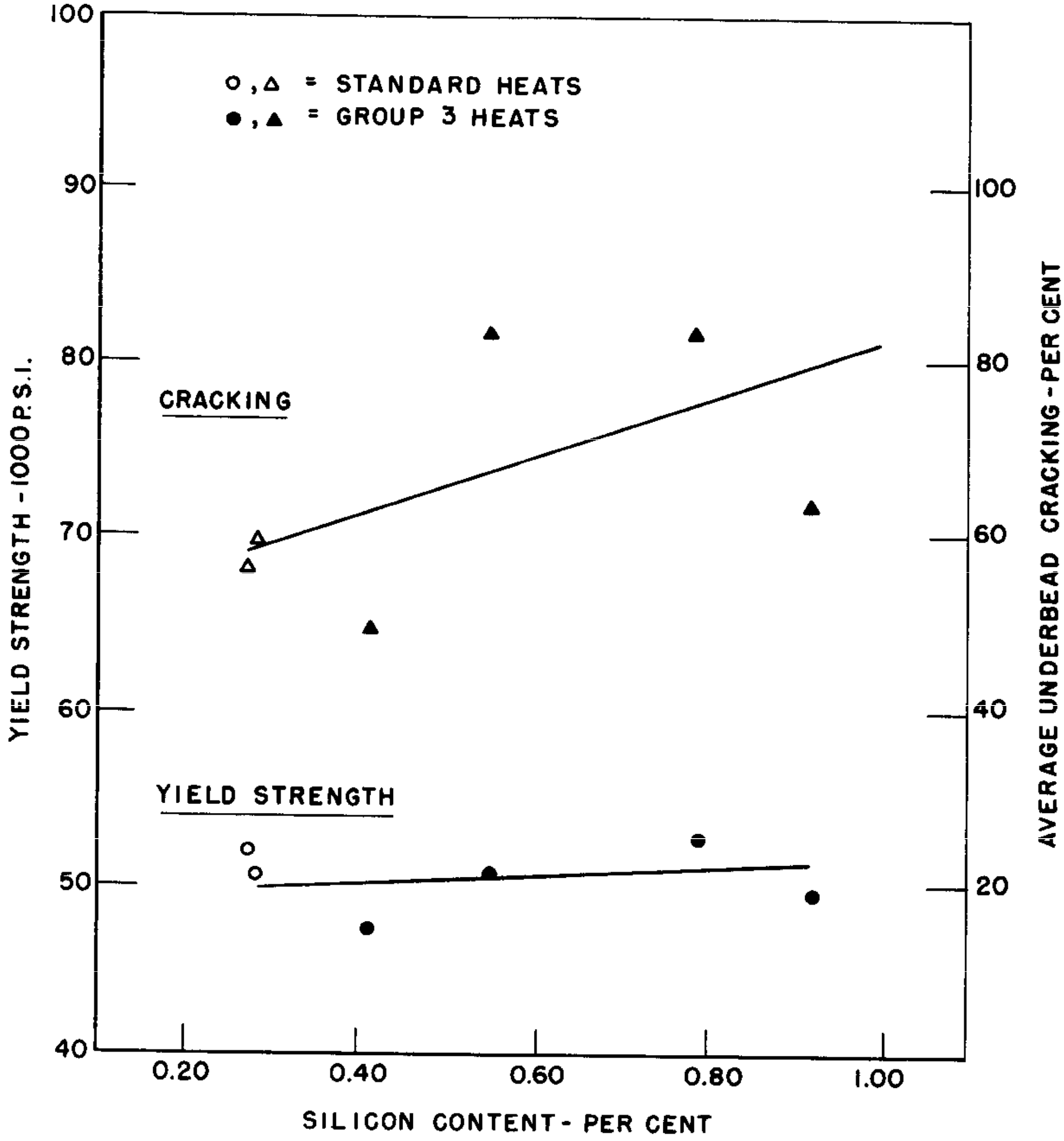

FIGURE 23. THE INFLUENCE OF SILICON CONTENT ON YIELD STRENGTH AND UNDERBEAD CRACKING

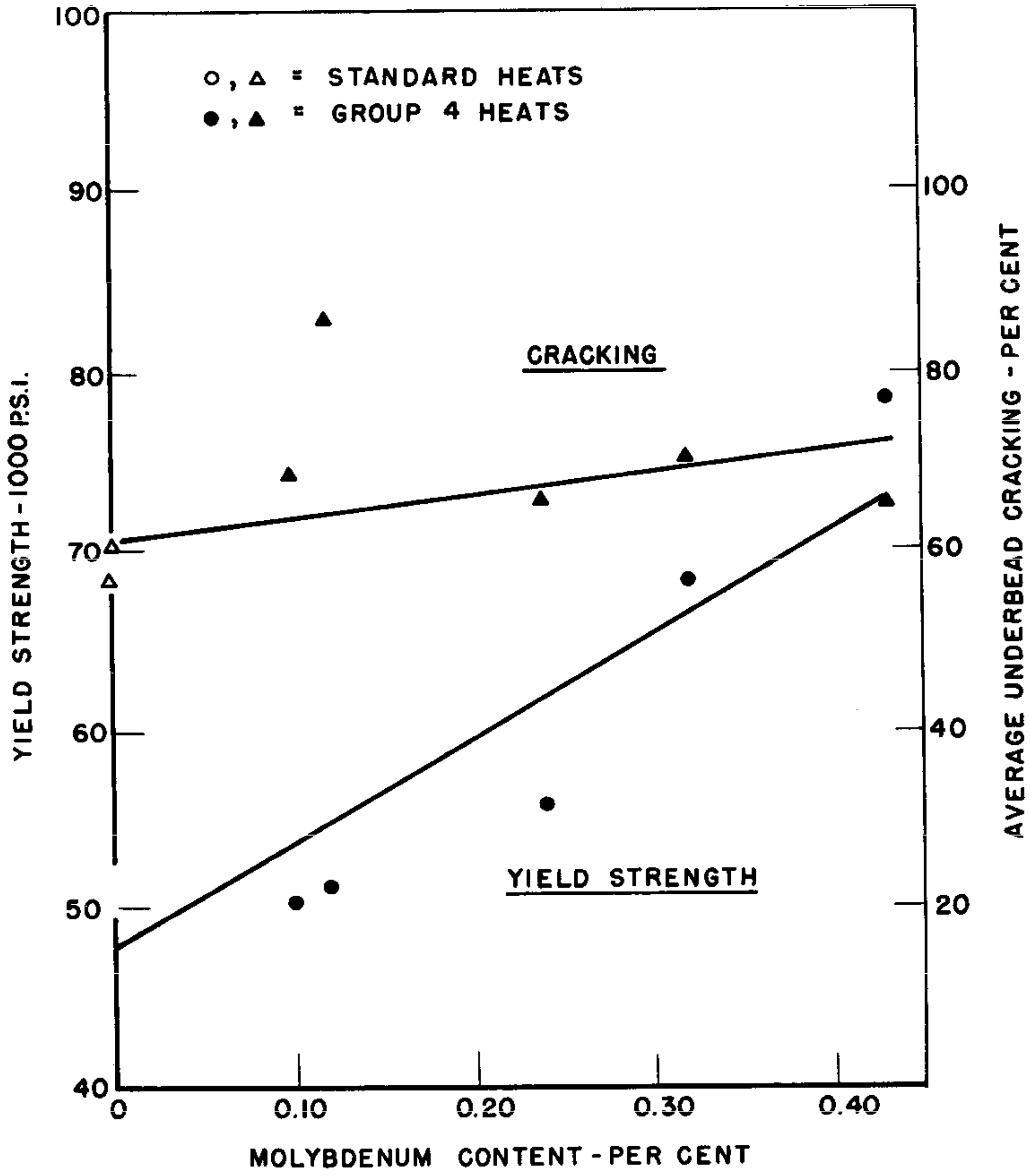

FIGURE 24. THE INFLUENCE OF MOLYBDENUM CONTENT ON YIELD STRENGTH AND UNDERBEAD CRACKING

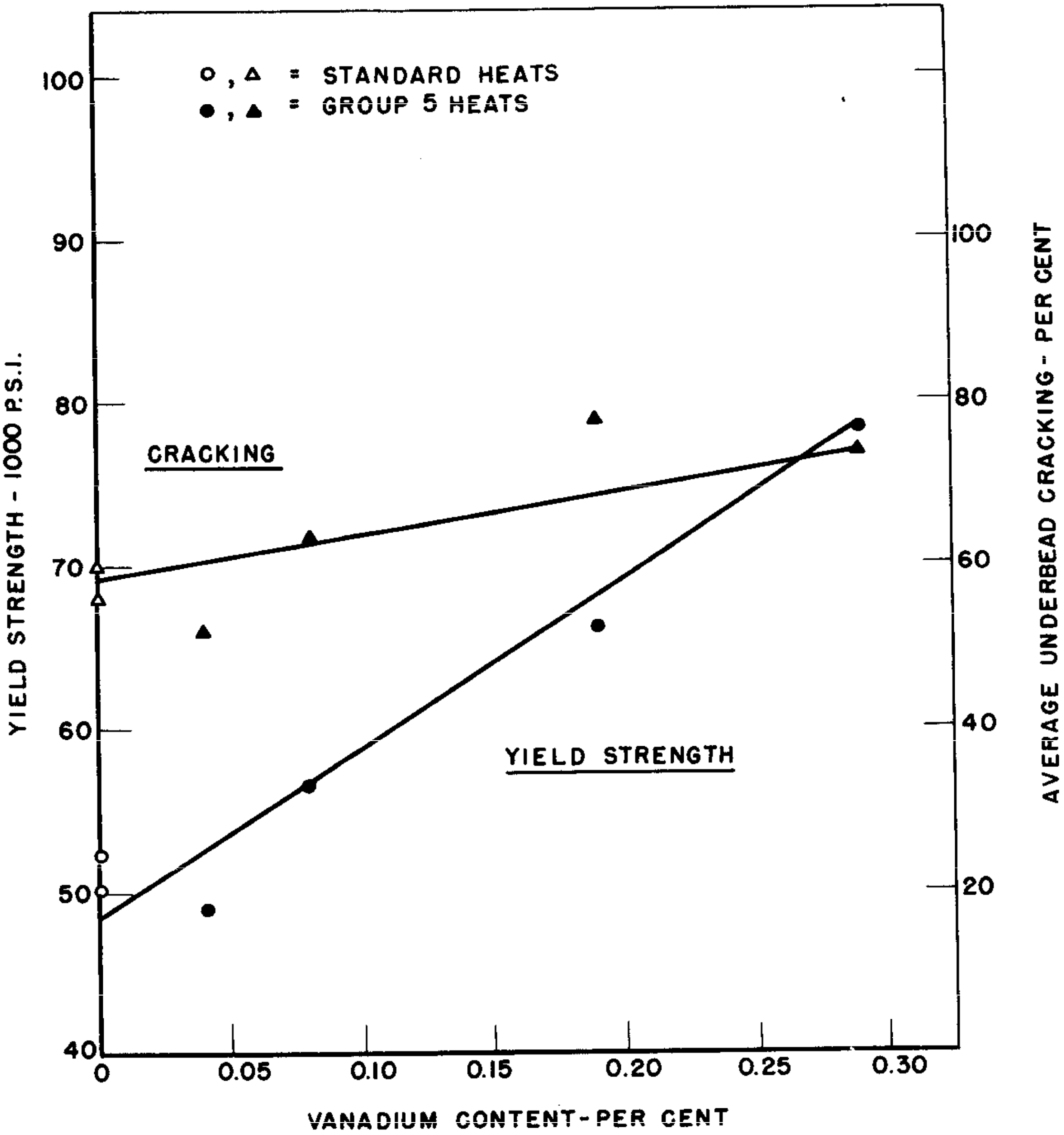

FIGURE 25. THE INFLUENCE OF VANADIUM CONTENT ON YIELD STRENGTH AND UNDERBEAD CRACKING

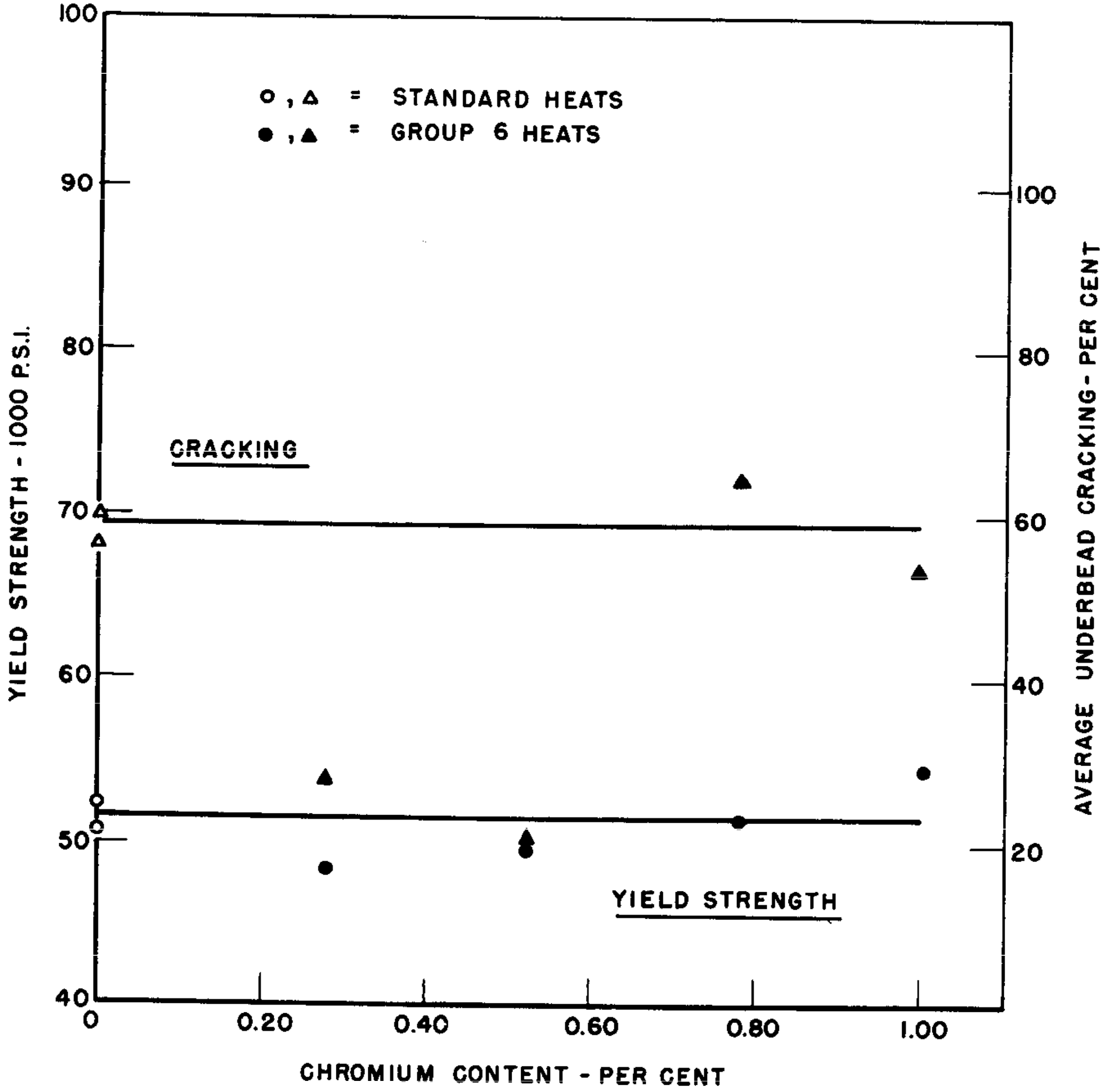

FIGURE 26. THE INFLUENCE OF CHROMIUM CONTENT ON YIELD STRENGTH AND UNDERBEAD CRACKING

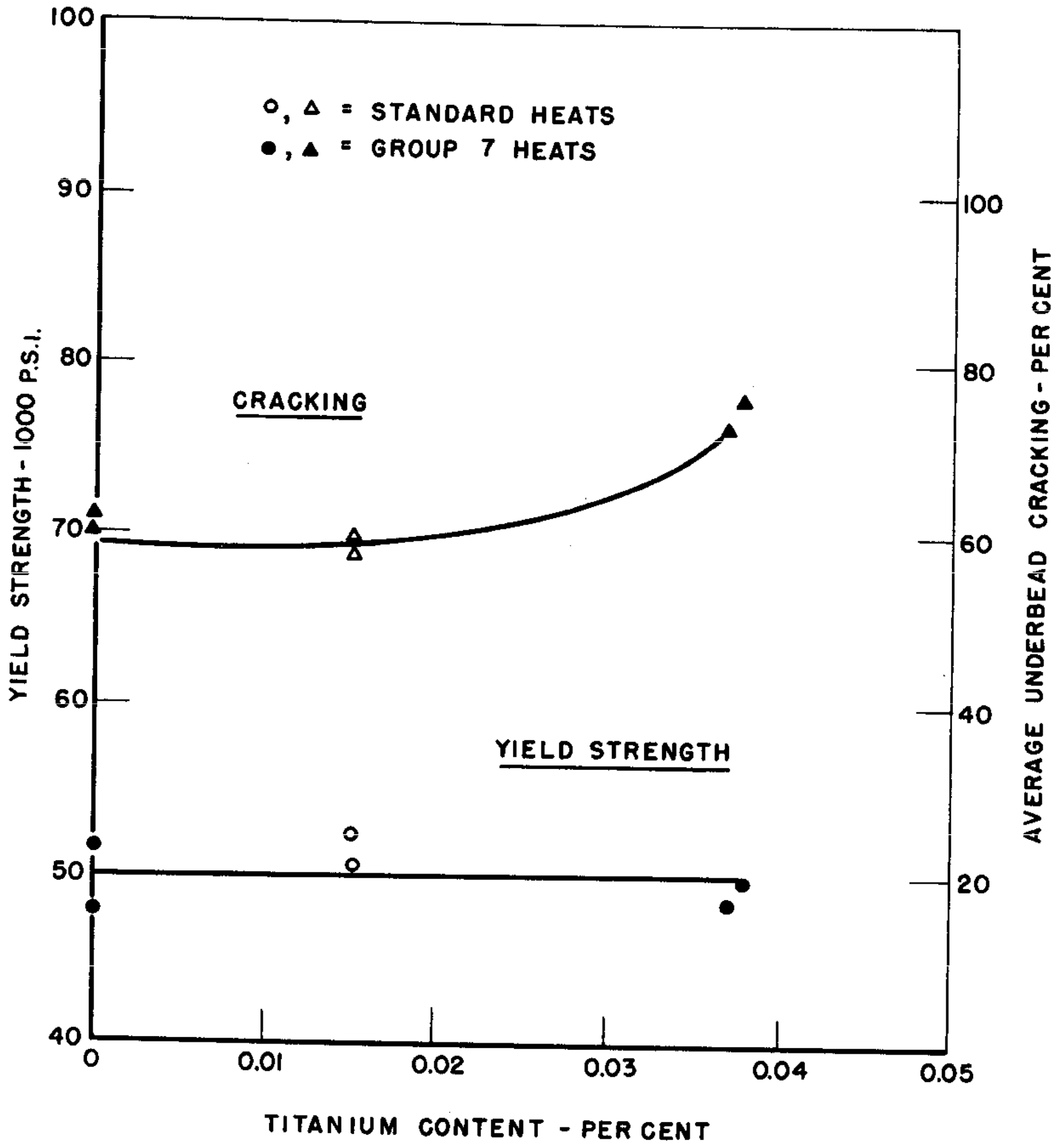

FIGURE 27. THE INFLUENCE OF TITANIUM CONTENT ON YIELD STRENGTH AND UNDERBEAD CRACKING

A comparison of the above figures shows that carbon and manganese, especially carbon, have a pronounced influence upon underbead cracking, the cracking increasing rapidly as the carbon or manganese content is raised. An increase in the silicon content from about 0.20 per cent to about 0.90 per cent, however, resulted in only a small increase in the cracking, but there was no significant gain in yield strength.

The addition of vanadium and molybdenum, up to approximately 0.30 and 0.40 per cent, respectively, resulted in no significant increase in underbead cracking, but was accompanied by an increase in yield strength of approximately 25,000 psi. It will be noted that the gain in yield strength resulting from increasing the carbon from 0.17 per cent to 0.32 per cent was only about 10,000 psi., while the cracking increased from approximately 20 to 100 per cent.

Little advantage appeared in these tests from adding chromium since the yield strength was not increased appreciably, even though additions up to 1 per cent were not detrimental to the underbead crack sensitivity. The addition of titanium produced no appreciable effect upon either the yield strength or crack sensitivity, as is indicated in Figure 27.

The Effect of Aluminum Deoxidation

While investigating the influence of deoxidation practices upon the notched-bar impact properties, it was noted that the aluminum content appeared to affect the underbead weld cracking of the steel. In order to determine if the aluminum content resulting from deoxidation was an important factor with respect to weld cracking, a series of six heats were made with aluminum additions of 0, 1/4, 1/2, 1, 2, and 5 pounds per ton. The chemical analyses of these heats, together with the standard composition, are shown in Table 23. These heats were cast in 8 by 8-inch molds and rolled directly to 1-inch plate on a small commercial mill. All tests were made on the plate in the hot-rolled condition.

The results of the underbead cracking tests are shown in Figure 28, and other pertinent data including the yield strength are shown in Table 24. From Figure 28, it appears that the aluminum content may have a marked influence upon the weld crack sensitivity of the steel though, from other evidence, it appears that this effect depends on other factors as well. A small or medium amount of aluminum appears to be the most detrimental, indicating that the aluminum should either be omitted or added in a large amount to minimize weld cracking.

TABLE 23. CHEMICAL ANALYSES OF STEELS USED TO STUDY THE INFLUENCE OF ALUMINUM CONTENT

Heat No.	Analyses, Per Cent							Aluminum Added, Pounds per Ton
	C	Mn	P	S	Si	Ti	Al*	
X-23	0.20	1.25	.021	.022	0.27	.007	Nil	0
X-24	0.23	1.36	.019	.021	0.29	.006	< .005	0.25
X-25	0.22	1.24	.020	.020	0.27	.013	< .005	0.5
X-26	0.22	1.31	.021	.021	0.27	.016	.029	1
X-27	0.20	1.29	.018	.020	0.31	.015	.064	2
X-28	0.22	1.26	.019	0.20	0.27	.015	0.180	5
X-45	0.21	1.35	.021	.030	0.27	.015	.003	0.4
X-46	0.22	1.35	.023	.032	0.28	.015	.003	0.4

* Acid-soluble aluminum content.

Heats X-45 and X-46 are the standard composition steels.

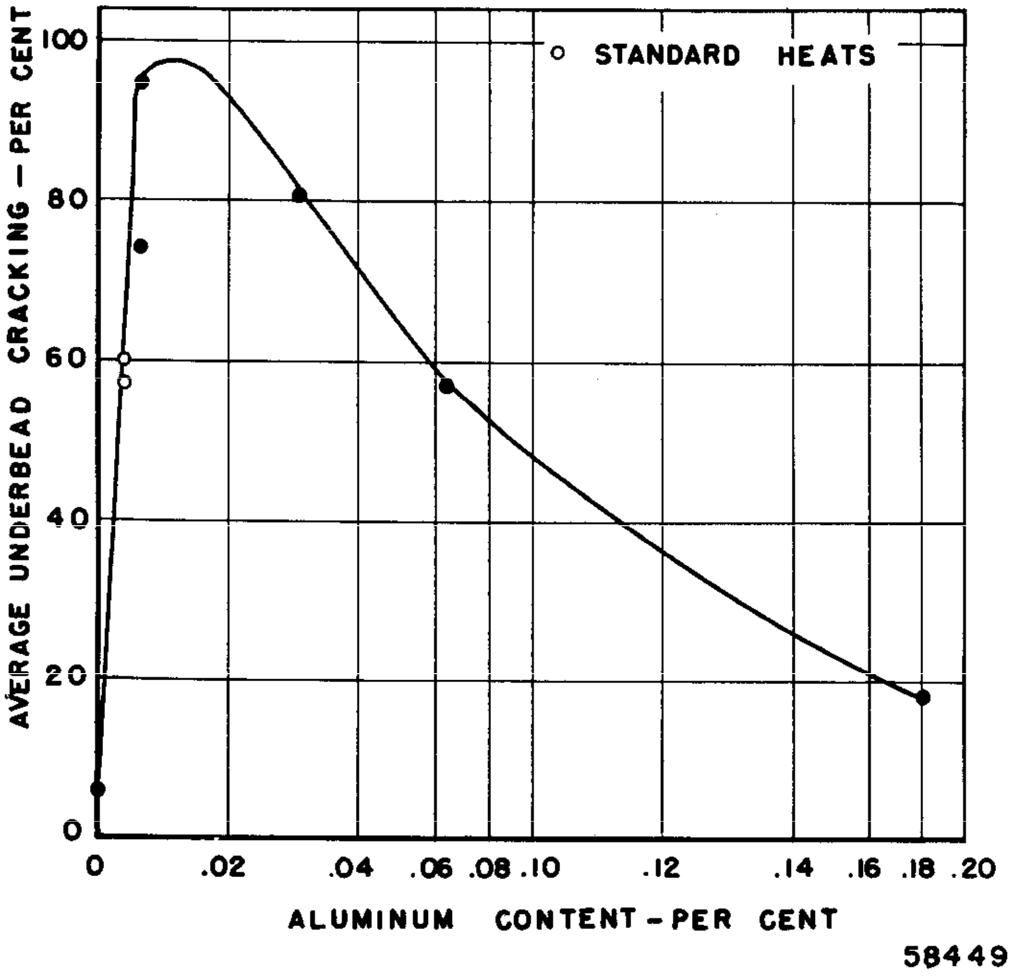

FIGURE 28. THE EFFECT OF ALUMINUM CONTENT UPON UNDERBEAD WELD CRACK SENSITIVITY

TABLE 24. DATA FROM HEATS MADE FOR STUDYING THE INFLUENCE OF ALUMINUM ADDITIONS

Heat No.	Analyses, Per Cent		Aluminum Added, Pounds per Ton	Yield Strength, psi.	Underbead Weld Cracking, %
	C	Mn			
X-23	0.20	1.25	0	47,500	6
X-24	0.23	1.36	0.25	50,880	95
X-25	0.22	1.24	0.5	47,750	74
X-26	0.22	1.31	1	49,630	81
X-27	0.20	1.29	2	48,250	57
X-28	0.22	1.26	5	48,380	17
X-45	0.21	1.35	0.4	52,100	57
X-46	0.22	1.35	0.4	50,750	60

Since the reason for the apparent influence of aluminum was not obvious and the data rather limited, a second group of heats were made to see if the above results could be verified. Three 450-pound induction furnace heats were made, and each heat was poured into two ingots, the first ingot being cast without the use of aluminum, while the second ingot was poured from the remainder of the heat after being deoxidized with an addition of 0.5 pound of aluminum per ton of steel. The 6-5/8-inch ingots were then processed into 1-inch plates by forging and rolling in the same manner as the first group of 32 heats.

From Table 25, it will be noted that the chemical analyses of these six ingots are quite similar with the exception of the manganese content, which varies from 1.13 per cent to 1.40 per cent and, therefore, must be taken into consideration.

The data from the crack-sensitivity tests in Figure 29 confirm the previous results since they definitely show that the crack sensitivity was increased to a marked extent by the addition of 1/2 pound of aluminum per ton as compared to a similar steel with no aluminum. The

TABLE 25. CHEMICAL ANALYSIS OF SPLIT HEATS MADE TO STUDY THE EFFECT OF ALUMINUM

Heat No.	Ingot No.	C	Mn	P	S	Si	Ti	Al*	Aluminum added, lbs. per Ton
X-29	1	0.21	1.16	.023	.024	0.20	.008	Nil	0
X-29-A	2	0.21	1.13	.019	.025	0.17	.008	.005	0.5
X-31	1	0.22	1.28	.023	.027	0.26	.008	Nil	0
X-31-A	2	0.21	1.25	.023	.026	0.24	.006	.005	0.5
X-33	1	0.21	1.40	.022	.025	0.26	.009	Nil	0
X-33-A	2	0.21	1.40	.022	.024	0.24	.007	.005	0.5

* Acid-soluble aluminum content.

influence of manganese content is also well illustrated in the above figure.

Influence of Chemical Analysis Upon the Notched-Bar Impact Strength

The effects of the various elements included in this study upon the notched-bar impact strength (Charpy V-Notch cut parallel with plate surface) when tested at 75°F. are shown in Figures 30 to 36, inclusive(25). These figures illustrate how the notched-bar impact strength of the hot-rolled plate decreases as the carbon, silicon, molybdenum, vanadium, and chromium contents are increased.

In the case of manganese and titanium, the scatter band is rather wide, and the data do not appear to follow a definite pattern, so it is difficult to draw any conclusion from the data other than that these elements do not appear to be especially detrimental in the range investigated.

In reviewing the notched-bar properties of these steels, it appears that the notched-bar impact strength of the standard heats, Heats X-45 and X-46, is higher than might be expected, being especially noticeable in Figures 31, 33, and 35. The reason for this apparent discrepancy is not obvious since it can not be explained on the basis of chemical analysis and the other properties are in the expected range with the exception that the yield strength appears slightly high. It might be pointed out that the standard heats were made at a different time than the remainder of the heats in this study and some slight difference in processing might account for the high impact strength.

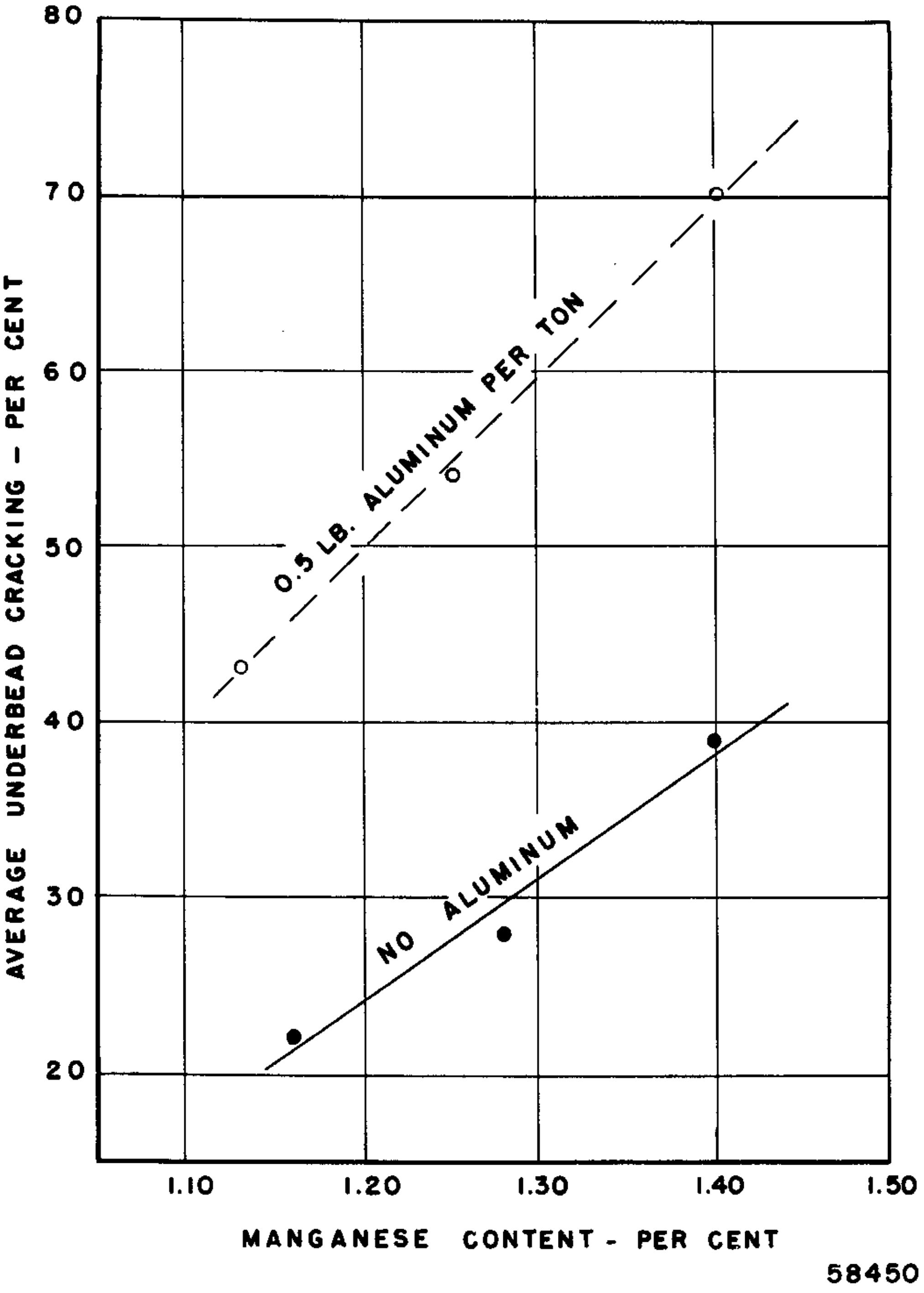

FIGURE 29. THE EFFECT OF ALUMINUM AND MANGANESE CONTENTS UPON UNDERBEAD CRACKING.

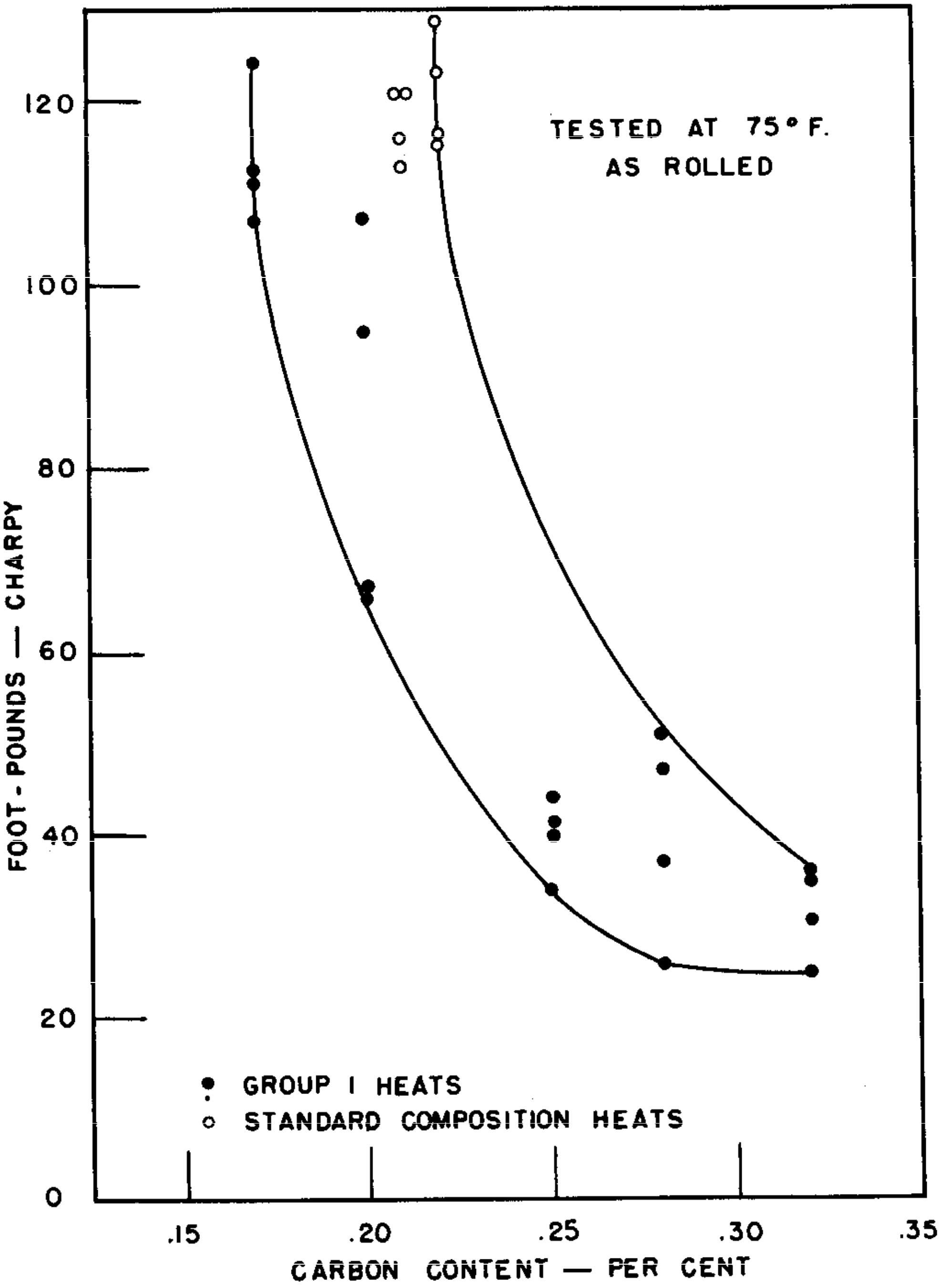

FIG. 30. THE EFFECT OF CARBON CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5438
58707

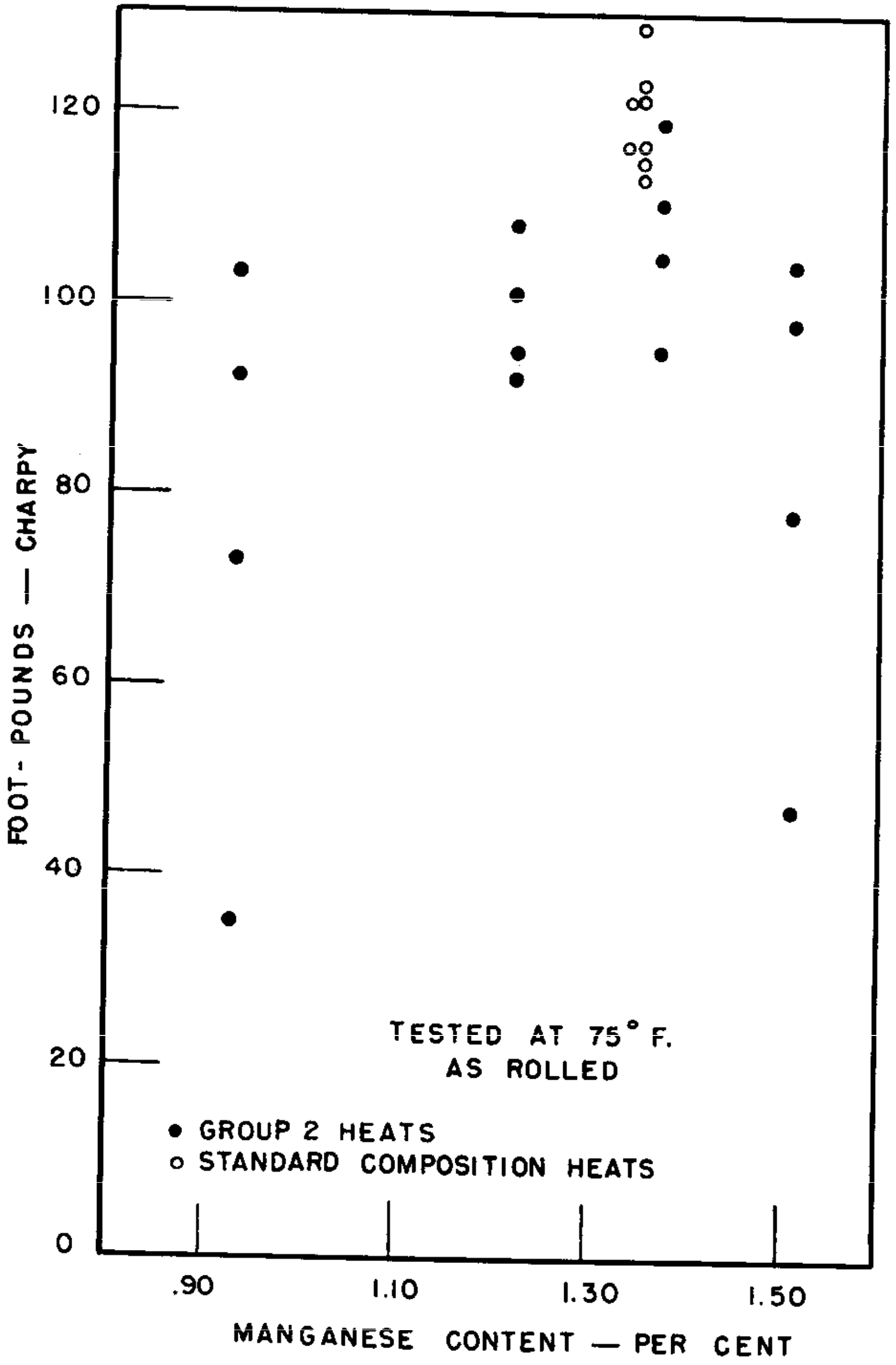

FIGURE 31. THE EFFECT OF MANGANESE CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5439
58708

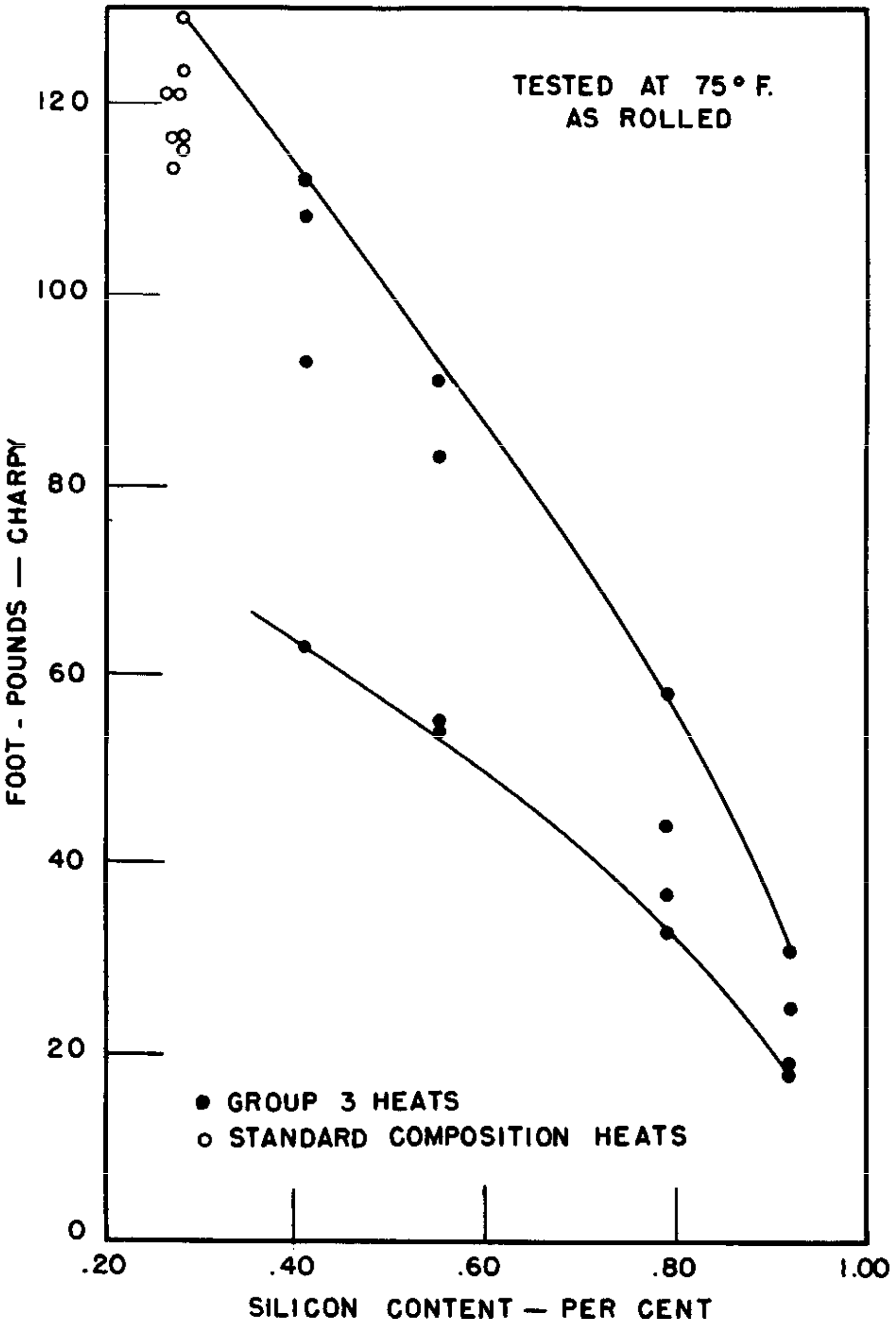

FIGURE 32. THE EFFECT OF SILICON CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5440
58709

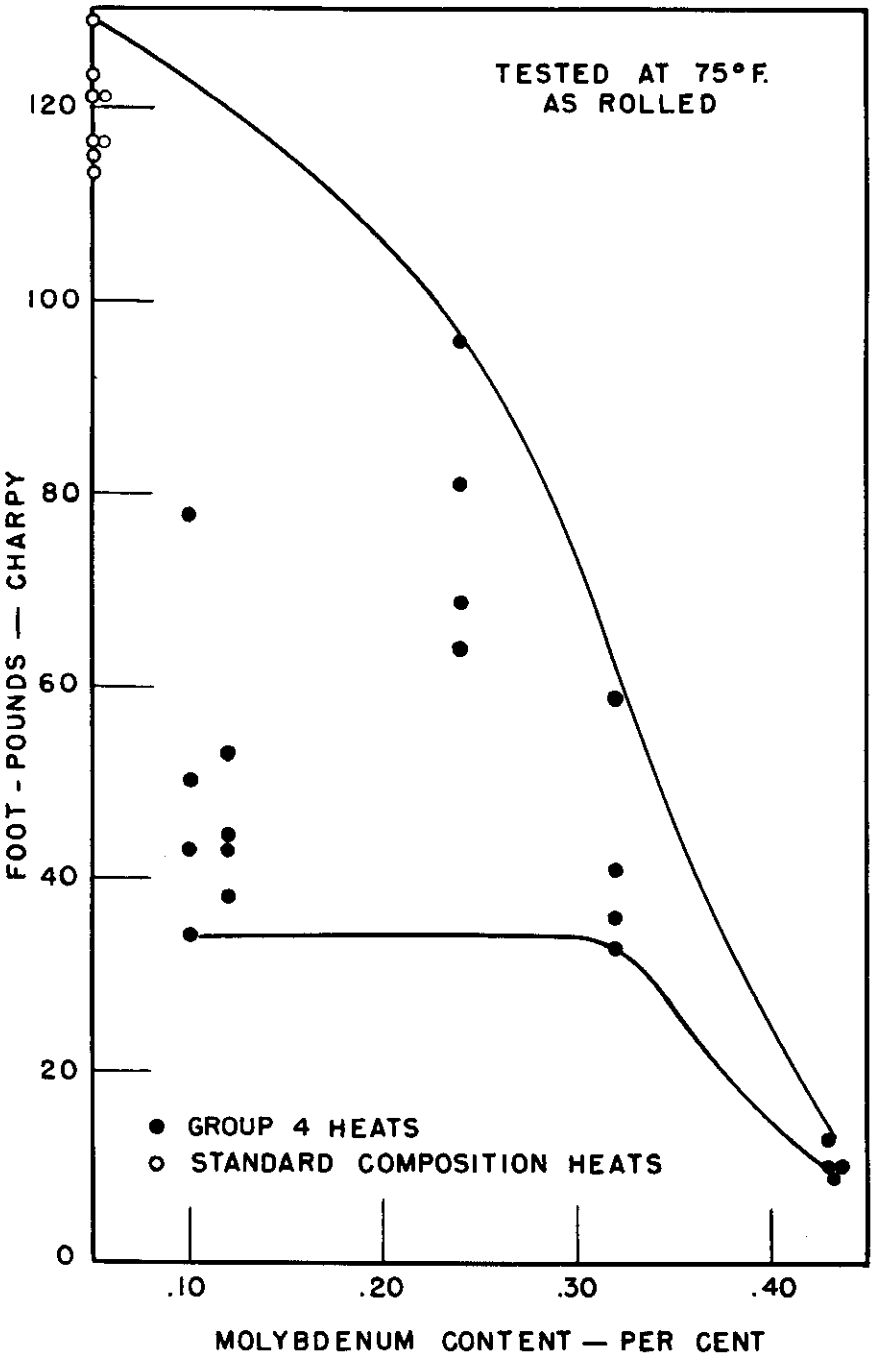

FIGURE 33. THE EFFECT OF MOLYBDENUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5441
58710

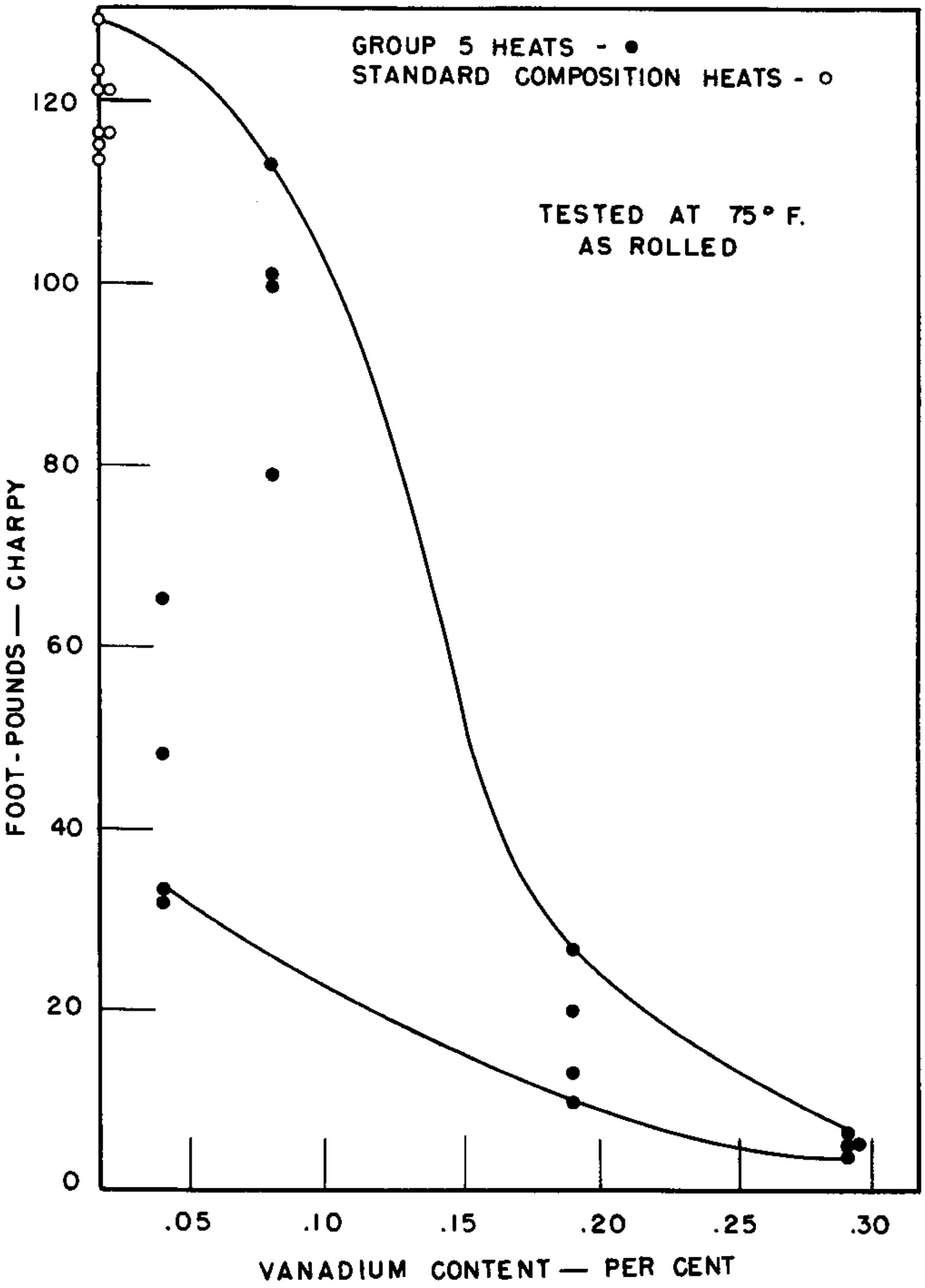

FIGURE 34. THE EFFECT OF VANADIUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5442
58711

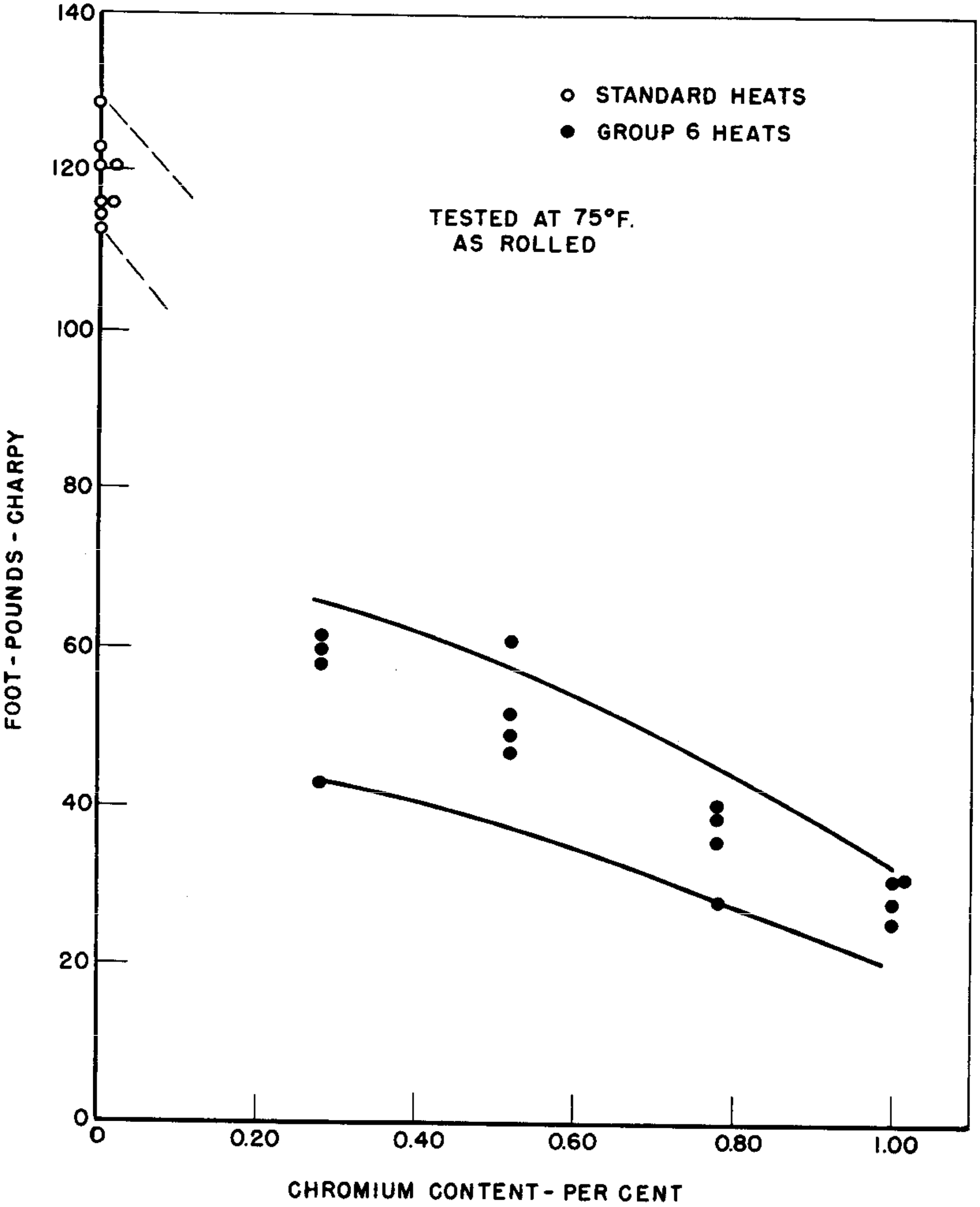

FIGURE 35. THE EFFECT OF CHROMIUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

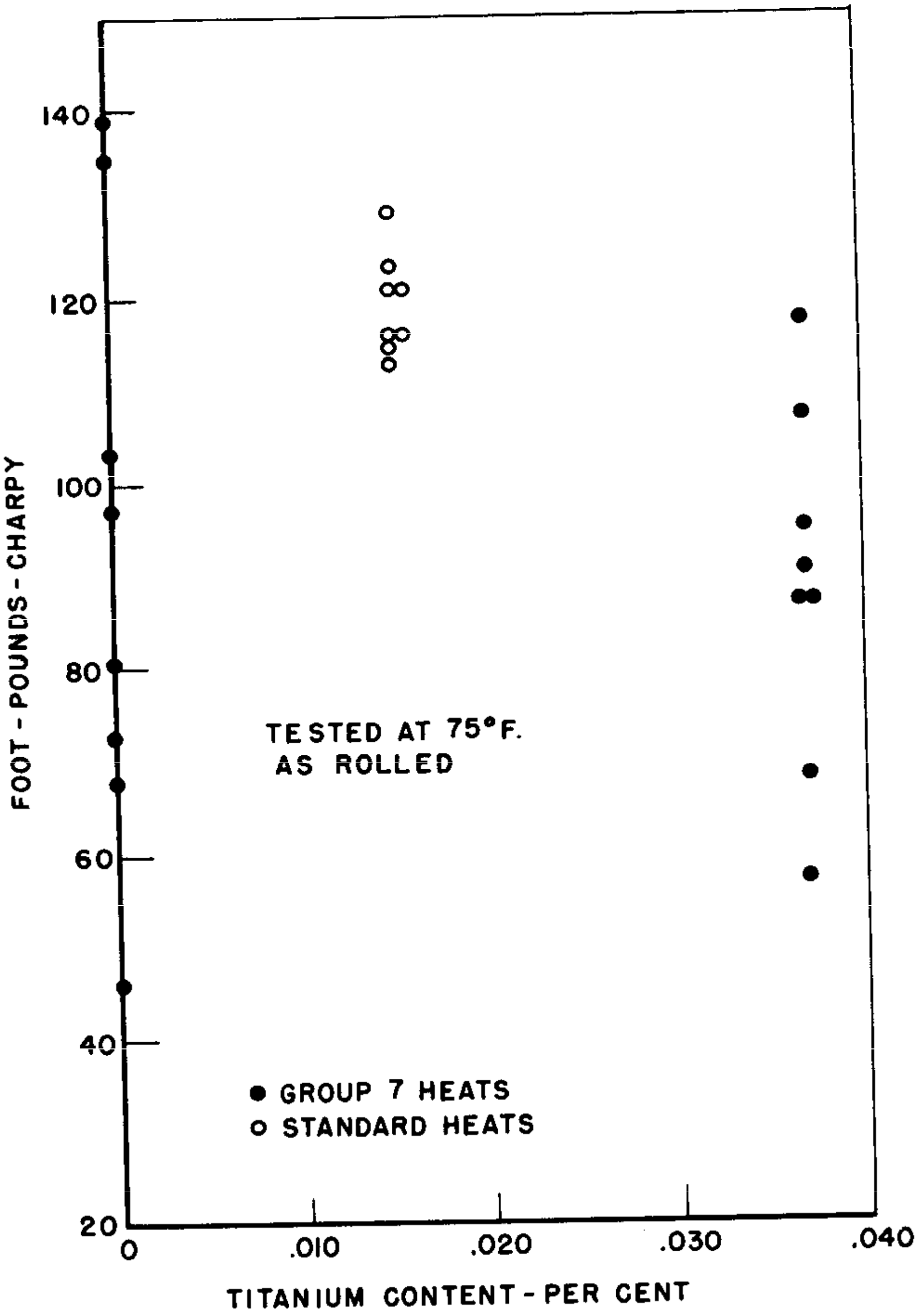

FIGURE 36. THE EFFECT OF TITANIUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

When tested at room temperature, the aluminum content had little influence upon the notched-bar strength. The expected effect, however, was found when tested at lower temperatures, the intermediate aluminum contents producing the highest notched-bar strength at -40°F. as shown in Figure 37.

Optimum Chemical Analysis

From this study of the influence of carbon, manganese, silicon, chromium, molybdenum, vanadium, titanium and aluminum contents upon the behavior of a low-alloy high-tensile strength hot-rolled steel, it is obvious that both the carbon and manganese contents, especially the carbon, must be carefully limited in order to minimize the underbead cracking. With the carbon and manganese contents lowered to obtain the desired weldability, the required yield strength must be obtained by the addition of such alloys as molybdenum or vanadium which do not increase the underbead cracking.

Low-Carbon-Manganese-Vanadium Steels with no Aluminum

Since the addition of small or medium amounts of aluminum was found to increase the susceptibility to underbead cracking, the aluminum may be omitted(26). In order to ensure sound ingots, the silicon content should then be not less than about 0.25 per cent.

In order to determine the physical properties and the accompanying level of underbead cracking that could be obtained by the above approach, a series of four laboratory induction furnace heats were made aiming at the following chemical analysis with vanadium contents of 0, 0.20, 0.30, and 0.40 per cent:

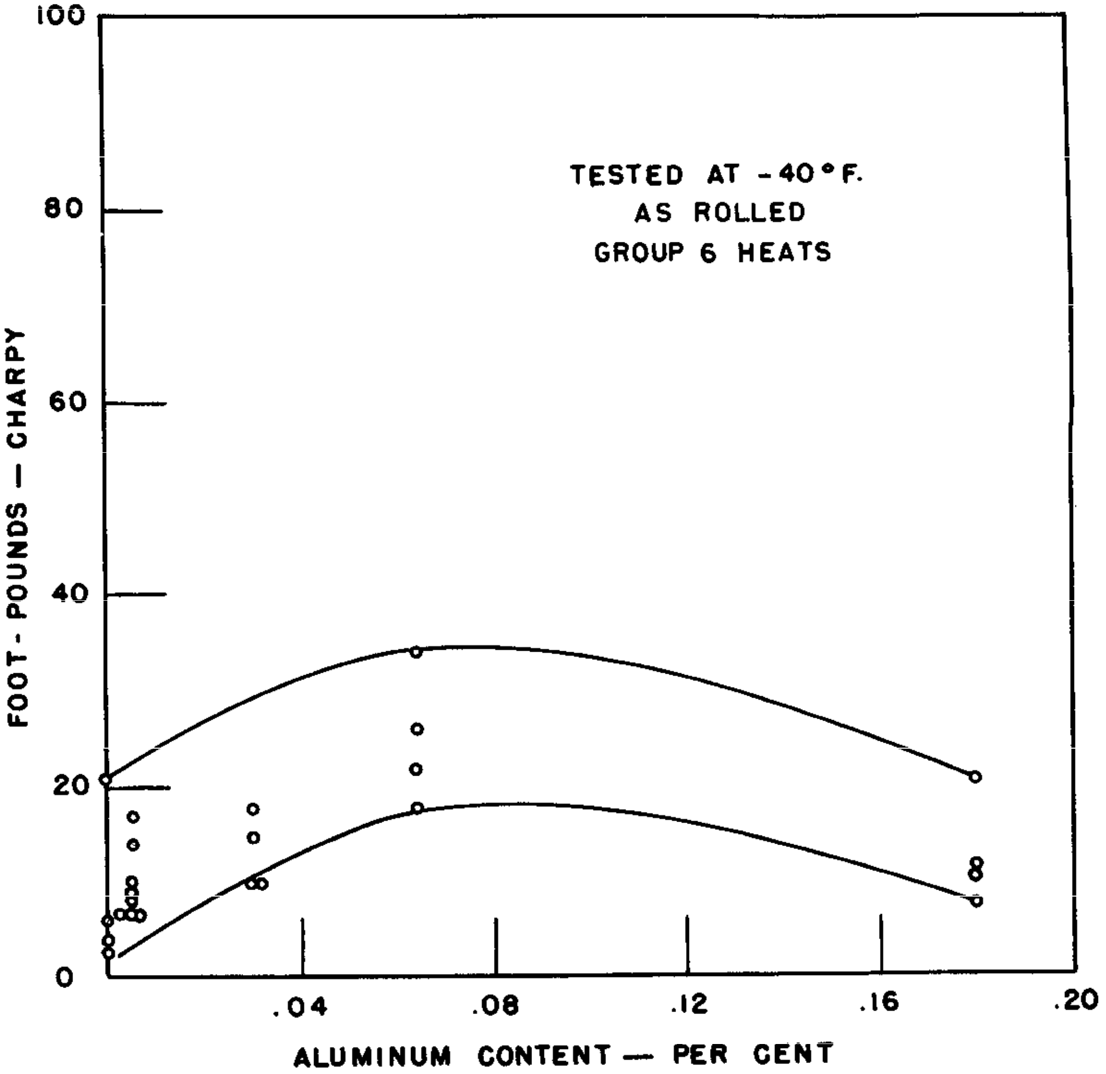

FIG. 37. THE EFFECT OF ALUMINUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT -40 ° F.

0-5443
58712

C	Mn	Si	Ti	Al	V
0.16 max.	1.20 max.	0.30	.015	None	See text

The chemical analysis of these four heats is shown in Table 26. It will be noted that the manganese content of three of the heats is 10 to 14 points higher than desired but that otherwise the analyses are in the desired range. The titanium recovery was erratic as would be expected when no aluminum is used. After processing the heats to 1-inch plate in the same manner as the other laboratory heats, they were tested in the hot-rolled condition.

TABLE 26. CHEMICAL ANALYSES OF LOW-CARBON VANADIUM STEELS WITH NO ALUMINUM

Heat No.	Analyses, Per Cent C	Mn	P	S	Si	Ti	V	Aluminum Added
972	0.17	1.22	.018	.018	0.29	.005	Nil	None
X-38	0.16	1.30	.017	.043	0.29	.005	0.22	None
X-39	0.15	1.34	.013	.041	0.30	.025	0.29	None
X-40	0.16	1.32	.012	.040	0.33	.025	0.39	None

The results of the underbead cracking tests and the yield strengths of these steels are shown in Figure 38. These data show that the susceptibility to underbead cracking can be reduced to an extremely low level by limiting the carbon content and omitting the aluminum while obtaining the desired yield strength by the addition of vanadium. By adding 0.39 per cent vanadium to a 0.16 per cent carbon steel with 1.30 per cent manganese, and omitting the aluminum, a yield strength of 72,000 psi. was obtained from the 1-inch hot-rolled plate which cracked

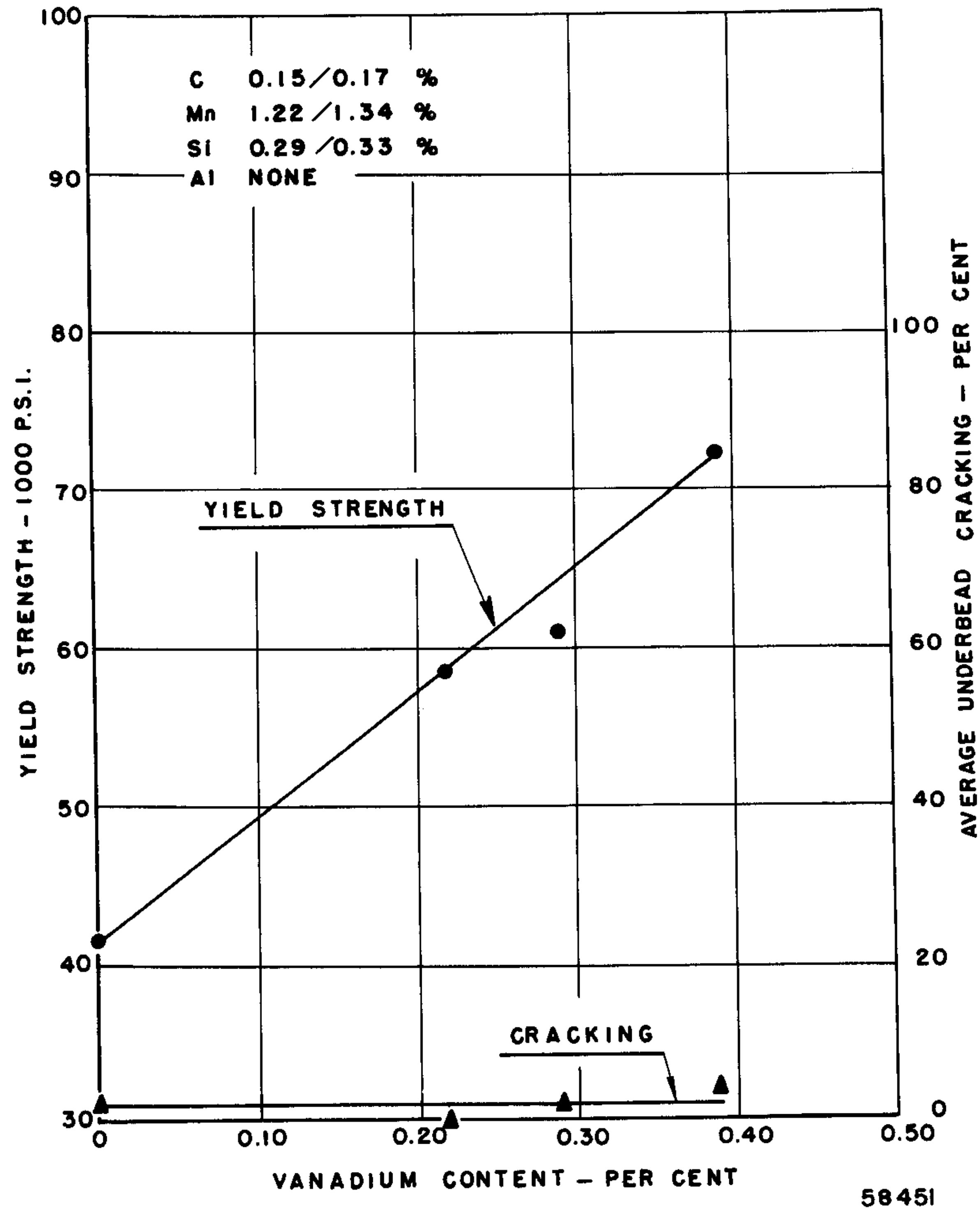

FIGURE 38. THE INFLUENCE OF VANADIUM CONTENT ON THE YIELD STRENGTH AND UNDERBEAD CRACKING OF LOW-CARBON STEEL.

only 4 per cent, indicating an extremely low tendency towards underbead cracking.

The notched-bar impact strength of the two low-carbon (0.16 per cent max.) heats containing 0.22 and 0.39 per cent vanadium tested at temperatures ranging from -75°F. to 210°F. using specimens notched parallel with the plate surface is shown in Figure 39. Although aided by the relatively low carbon content, the Charpy strength of these vanadium steels is quite low when tested in the hot-rolled condition. It is obvious, however, that omitting the aluminum in order to lower the underbead cracking is not conducive to good notched-bar impact strength.

High-Aluminum Vanadium-Molybdenum Steels

In order to determine if any advantage might be gained, especially in the notched-bar impact strength, by using a large addition of aluminum and a combination of vanadium and molybdenum as alloys to increase the strength, a series of four heats were made with a vanadium content of approximately 0.12 per cent and the molybdenum ranging from 0.12 to 0.72 per cent(27). Each heat was deoxidized with an addition of 4 pounds of aluminum per ton of steel. The chemical analyses of these steels are listed in Table 27.

TABLE 27. CHEMICAL ANALYSES OF LOW-CARBON VANADIUM-MOLYBDENUM HEATS MADE WITH FOUR POUNDS OF ALUMINUM PER TON

Heat No.	Analyses, Per Cent							
	C	Mn	P	S	Si	V	Mo	Al
X-48	0.15	1.28	.016	.027	0.31	0.12	0.12	0.19
X-50	0.14	1.30	.020	.027	0.28	0.12	0.32	0.19
X-52	0.15	1.31	.020	.029	0.32	0.13	0.49	0.19
X-54	0.13	1.28	.018	.031	0.29	0.13	0.72	0.19

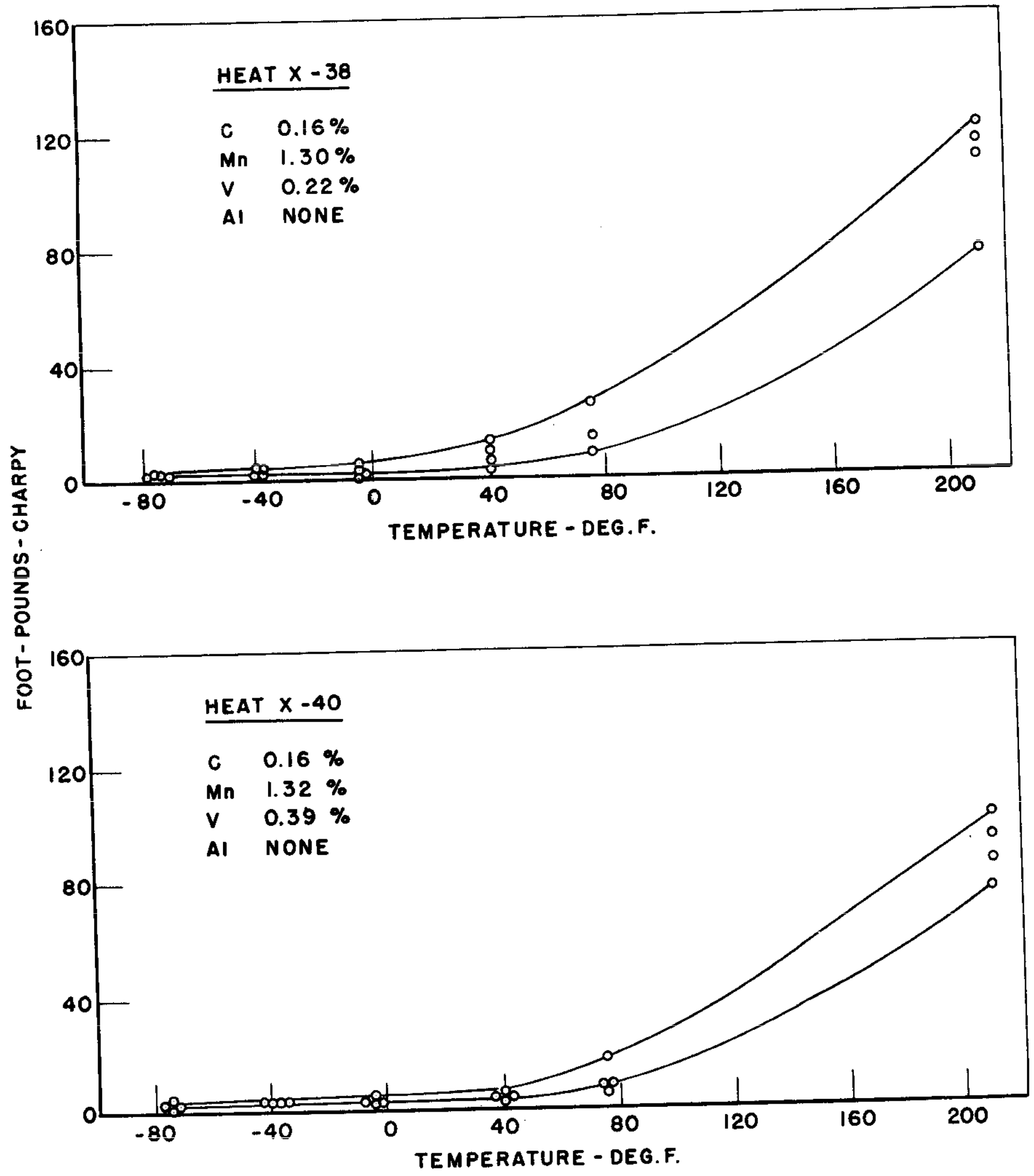

FIGURE 39. NOTCHED-BAR IMPACT STRENGTH OF HOT-ROLLED LOW-CARBON MANGANESE-VANADIUM STEEL WITH ALUMINUM OMITTED

These heats were forged and rolled into 1-inch plate in the manner previously described. A brief summary of the test results from the hot-rolled plate is shown in Table 28 and Figure 40. These data again show that high yield strength hot-rolled steels can be produced, which display a very low tendency towards underbead cracking but have relatively low notched-bar impact strength. In this case, the use of a large aluminum addition and the combination of vanadium and molybdenum did not improve the impact strength to any appreciable extent.

TABLE 28. SUMMARY OF DATA FROM HOT-ROLLED LOW-CARBON VANADIUM-MOLYBDENUM HEATS MADE WITH FOUR POUNDS OF ALUMINUM PER TON

Heat No.	Analyses, Per Cent			Yield Strength, psi.	Red. of Area, %	Underbead Weld Cracking,%	Charpy Impact V-Notch, Ft-lbs.	
	C	Mn	Mo				Tested -40°F.	Tested 75°F.
X-48	0.15	1.28	0.12	53,880	64.2	1	6-16	32-50
X-50	0.14	1.30	0.32	67,130	63.8	0	5-7	33-35
X-52	0.15	1.31	0.49	72,500	60.7	1	3-8	14-19
X-54	0.13	1.28	0.72	75,000	64.1	0	3-4	9-11

Note: 1. All the above tests were made on 1-inch plate.

From these results it appears that the combination of high yield (70,000 psi. minimum) and notched-bar impact strengths, together with low sensitivity to underbead cracking, cannot be obtained from hot-rolled, one-inch plate with these combinations of alloying elements. It is necessary, therefore, to resort to some other scheme to obtain this combination of properties.

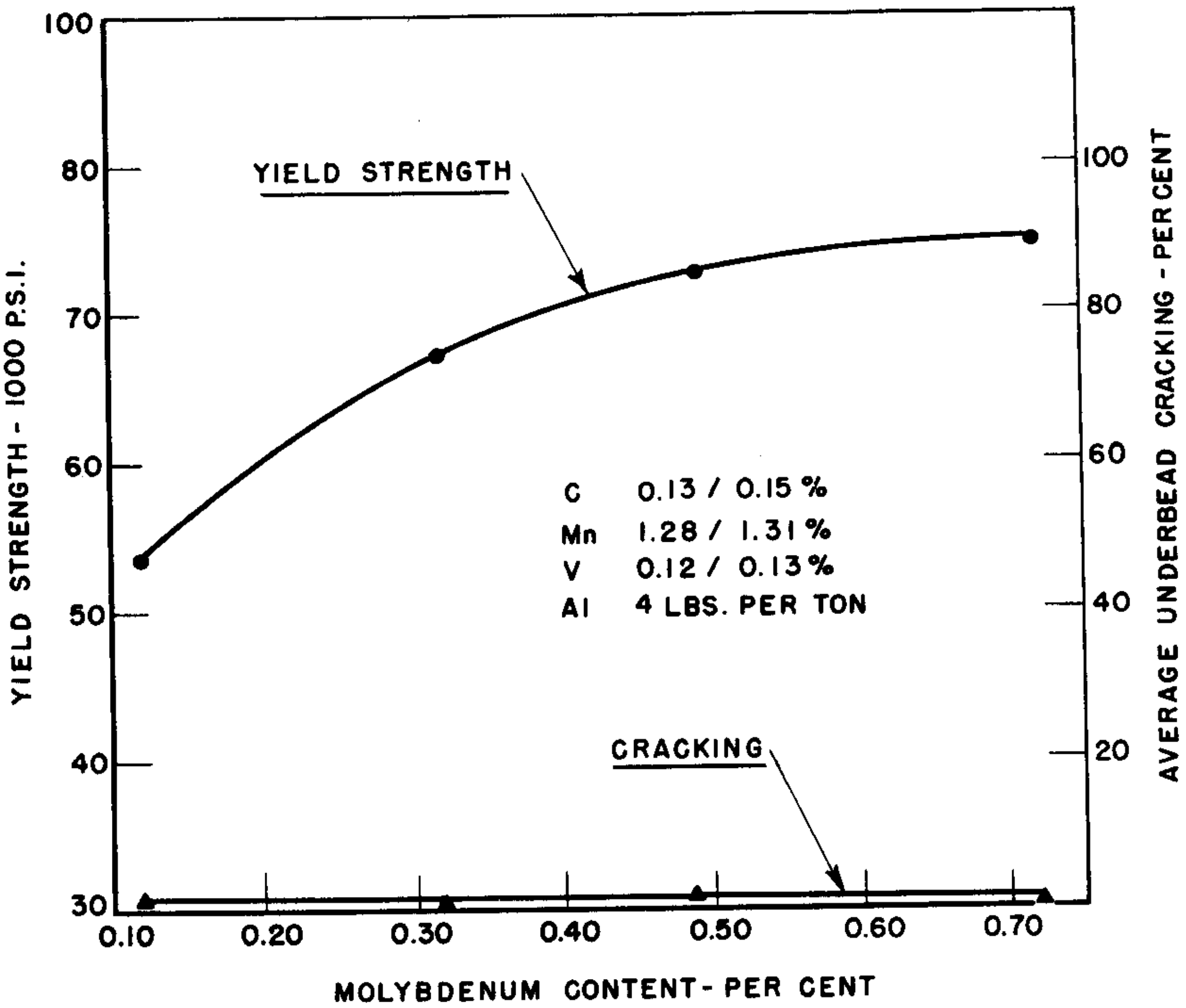

FIGURE 40. THE INFLUENCE OF MOLYBDENUM CONTENT IN VANADIUM-BEARING LOW-CARBON STEEL WITH HIGH ALUMINUM CONTENT

Heat-Treated Plate

Since previous work indicated that the crack sensitivity of hot-rolled plate was not altered appreciably by quenching and tempering, the use of such a heat treatment appeared to be a practical method for improving the notched-bar impact strength and still retaining the other desired properties.

Carbon-Manganese Steel

In order to obtain more information, especially about the welding characteristics of quenched and tempered steel, 1-inch plate from a commercial heat with 0.18 per cent carbon and 1.25 per cent manganese (Steel No. 30) was water quenched from 1650°F. after being at temperature for one hour, followed by tempering at 1000°F. for one hour(28). The chemical analysis, tensile strength, and notched-bar impact properties of Steel No. 30 are shown in Table 29. The tensile tests show that the above heat treatment developed a yield strength of 90,000 psi. and a notched-bar impact strength of 18 to 30 foot-pounds Charpy (V-notch specimen) at -32°F. as compared with only 7 to 21 foot-pounds for the hot-rolled steel tested under similar conditions. The underbead cracking tests showed that the quenched and tempered steel cracked 38 per cent as compared with 28 per cent for the hot-rolled plate. This difference is insignificant in view of the gain in tensile strength.

From the above results, it is obvious that the underbead cracking could be reduced and the notched-bar impact strength further improved by lowering both the carbon and manganese contents and still retaining a high strength, 75,000 psi. to 85,000 psi. yield strength. To determine the

TABLE 29. CHEMICAL ANALYSIS AND PHYSICAL PROPERTIES OF HOT-ROLLED AND QUENCHED AND TEMPERED ONE-INCH PLATE FROM STEEL NO. 30

Steel No.	Chemical Composition, Per Cent							
	C	Mn	P	S	Si	Ti	V	Al
30	0.18	1.25	.023	.026	0.28	.007	.004	.016

Steel No.	Condition of Plate	Tensile Properties			
		Elong. in 2", %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
30	Hot-rolled	34.6	64.9	50,350	76,150
30	Quenched & tempered	23.4	62.8	90,880	108,200

Steel No.	Condition of Plate	Notched-Bar Impact Strength, ft-lbs.* Testing Temperature, Degrees F.				
		-84	-32	-4	33	76
30	Hot-rolled	6	11	25	31	79
"	" "	6	21	26	52	57
"	" "	6	7	26	52	76
"	" "	5	18	24	76	58
30	Quenched & Tempered	7	22	64	82	71
"	" " "	8	25	70	76	67
"	" " "	12	18	40	67	67
"	" " "	12	30	38	64	75

*(Charpy specimens with Izod V-type notch.)

Note: Chemical analysis and tensile properties of hot-rolled plate from Tables 2 and 4, respectively.

results of lowering the carbon and manganese, a commercial plate steel was tested having a carbon content of 0.15 per cent and 0.79 per cent manganese, the steel being supplied by the producer in the form of 3/4-inch quenched and tempered plate(20). The chemical analysis, heat treatment, and tensile properties are shown in Table 30. It will be noted that the yield strength is in excess of 80,000 psi.

TABLE 30. CHEMICAL ANALYSIS, TENSILE PROPERTIES, AND HEAT TREATMENT OF QUENCHED AND TEMPERED 3/4-INCH COMMERCIAL PLATE

Steel No.	Chemical Analysis, Per Cent C	Mn	P	S	Si	Mo	Cr	Zr	Al*
24	0.15	0.79	.024	.032	0.73	0.16	0.61	0.14	.033

* (Acid-soluble aluminum content)

	Tensile Properties of Heat-Treated Plate*			
Steel No.	Elong. in 2", %	Red. of Area, %	Yield Strength, psi.	Tensile Strength, psi.
24	21.3	64.0	83,300	101,000

*(The plate was water quenched from 1650°F. and tempered for one hour at 1200°F.)

The twenty weld-bead cracking tests made on specimens from this heat showed no evidence of underbead cracking. This might be expected as a result of the low carbon and manganese contents, while the high silicon or the small amounts of molybdenum, chromium, and zirconium would not be considered as detrimental.

The results of notched-bar impact tests broken at temperatures ranging from -75°F. to 212°F. are shown in Figure 41. These results were obtained from longitudinal Charpy specimens with an Izod V-notch cut perpendicular to the plate surface. At -75°F., the notched-bar impact strength was between 15 and 21 foot-pounds, and when tested at -40°F. was between 21 and 25 foot-pounds. These results can be considered satisfactory notch-bar properties. The indications are, however, that better impact strength might be obtained from this steel since some ferrite was found in the microstructure. Tests showed that the ferrite was the result of incomplete austenitizing previous to quenching.

Joint Efficiency of Welded Heat-Treated Plate

While high strength can be obtained from the quenched and tempered plate, the question arises concerning the influence of the heat-affected zone upon the strength of the plate following welding. To answer this question, tests were made to determine the tensile efficiency of welded butt joints in quenched and tempered plate. For this purpose, two commercial steels were used, Steel No. 24, which was previously described in Table 30, and Steel No. 40, a manganese-molybdenum steel. In this case, both steels were water quenched from 1600°F. and tempered at 1200°F.

The welds were made with 3/16-inch high-strength lime-coated electrodes (approximately an E 9015). Each side of the double-V joint was welded in four passes as illustrated in Figure 42, the temperature of the plate being allowed to drop to 200°F. between each pass. Tensile bars 1-1/2 inches wide were prepared as indicated in Figure 42.

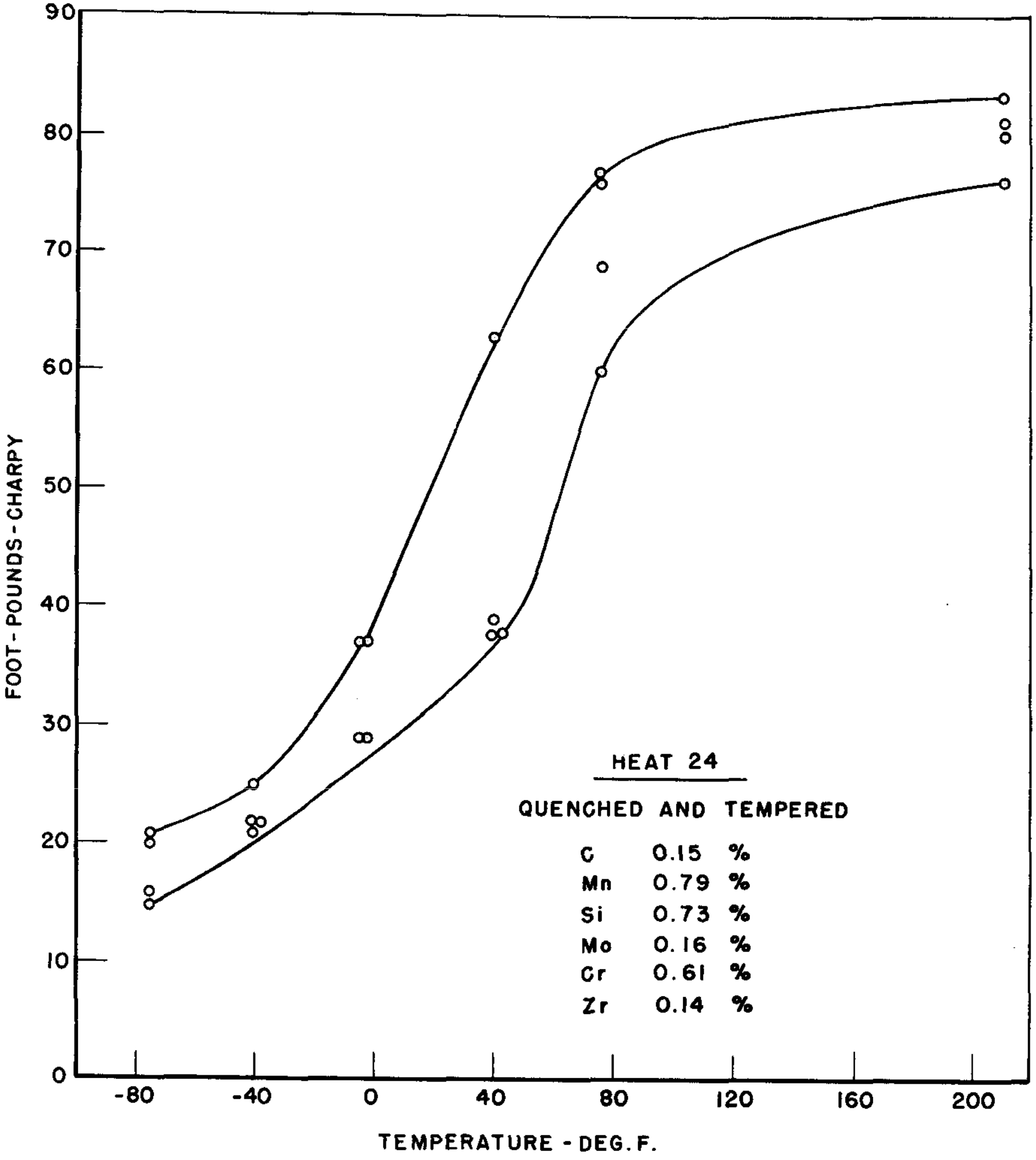

FIGURE 41. THE EFFECT OF TEMPERATURE UPON THE NOTCHED-BAR IMPACT STRENGTH OF QUENCHED AND TEMPERED PLATE

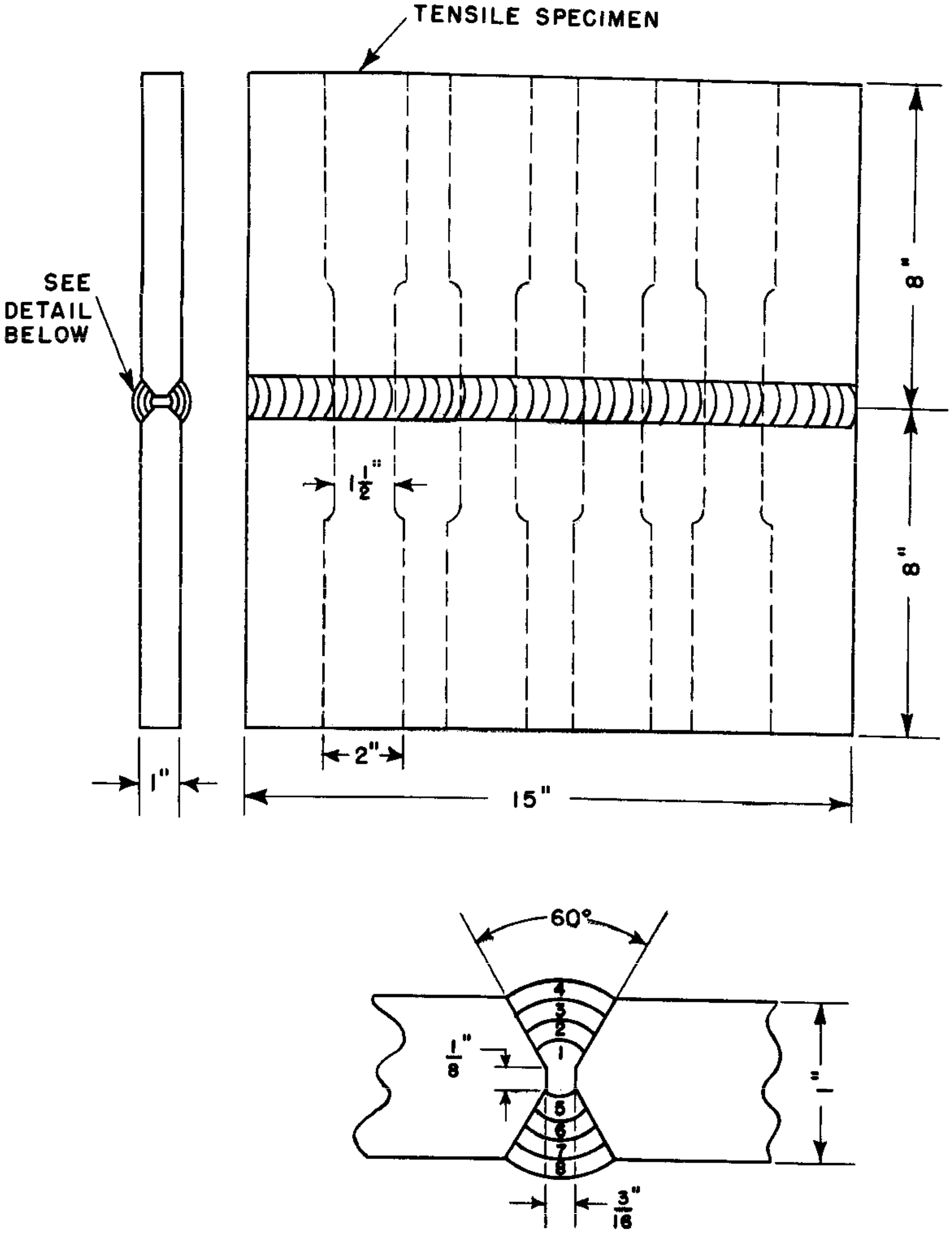

FIGURE 42. METHOD OF PREPARING TENSILE SPECIMENS FOR DETERMINING THE JOINT EFFICIENCY OF QUENCHED AND TEMPERED BUTT-WELDED PLATE

The data obtained from these tests are shown in Table 31.

TABLE 31. DATA FROM JOINT EFFICIENCY TESTS

Steel No.	Chemical Composition, Per Cent						Description of Specimen	Yield Strength, psi.
	C	Mn	Si	Mo	Cr	Zr		
24	0.15	0.79	0.73	0.16	0.62	0.14	3/4" plate - not welded	79,600
24							3/4" plate - welded reinforcement intact	78,500
24							3/4" plate - weld beads machined flush	78,400
40	0.14	1.24	0.24	0.43			1" plate - not welded	86,600
40							1" plate - welded reinforcement intact	82,800
40							1" plate - weld beads machined flush	84,100

Note: The fracture in all the specimens from Steel 24 occurred 2 to 3 inches from the weld; in Steel 40 the fractures were all approximately 1-1/2 inches outside the weld.

The data in Table 31 indicate that the strength of the weld and heat-affected zone is equivalent to that of the base plate.

Conclusions Concerning the Selection of Low-Alloy High-Tensile-Strength Steels for Welded Construction

A study of the influence of carbon, manganese, silicon, molybdenum, vanadium, chromium, titanium, and aluminum showed that increases in carbon and manganese content, especially carbon, were accompanied by a marked increase in under-bead cracking. The addition of silicon or chromium up to approximately 1.0 per cent had little effect upon under-bead cracking but was of little value since the yield strength of the hot-rolled steel was not increased appreciably. The addition of titanium up to approximately .04 per cent behaved in a similar manner.

The use of vanadium and molybdenum was found to increase the yield strength to a marked extent with no significant increase in underbead cracking.

The use of small or medium amounts of aluminum for deoxidation in the steelmaking practice was found to be quite detrimental with respect to underbead cracking, the cracking being reduced substantially by either omitting the aluminum or by using large additions, such as 4 pounds per ton.

By limiting the carbon and manganese contents to 0.13/0.15 and 1.30 per cent, respectively, and adding approximately 0.12 vanadium and 0.50 per cent molybdenum to obtain the desired strength, it was found that a yield strength in excess of 70,000 psi. could be obtained from 1-inch hot-rolled plate with an extremely low tendency towards underbead cracking. The notched-bar impact strength of this steel, however, was relatively low regardless of the aluminum content.

It was found that both high yield strength and notch-bar toughness, accompanied by low underbead cracking, could be obtained from quenched and tempered plate made from steel with limited carbon and manganese contents. The joint efficiency of this heat-treated plate when butt welded with a high-strength electrode was practically 100 per cent.

Subjects for Additional Investigation

In the course of this investigation, a number of observations have been made which appear to be pertinent with respect to a better understanding of the response of steel to the metal-arc welding cycle but will require more study in order to determine their full significance. Since these subjects should be appropriate items for future investigation, those which appear to be most promising will be discussed briefly.

Influence of Cooling Rate and Electrode Size

Since it has been well established that preheat temperatures of about 400°F. or higher, such as frequently used for the welding of the more hardenable steels, will normally eliminate underbead cracking, it was generally assumed that the cracking became progressively worse as the initial temperature was decreased. The evidence obtained in the course of this investigation now indicates that this is not always the case since increasing the initial temperature of the crack sensitivity specimens from 0°F. to 120°F. resulted in slightly more cracking in most of the HTS steels(32). It was also noted that increasing the electrode size from 1/8- to 3/16-inch increased the cracking in these tests(20). It is not known, however, in this latter case, whether this increase in cracking was the result of the slower cooling rate or higher stresses caused by the larger area heated. This effect of the initial or preheat temperature has been found to be even more pronounced in some of the higher strength steels. These results are significant, because they indicate that the most drastic cooling rates are not necessarily the most detrimental but that there are certain intermediate rates which may produce the maximum cracking and which appear to vary with the type of steel.

In the case of some high-carbon steels, it is well known that the most drastic quenching does not retain the most austenite, but that an intermediate rate, such as the oil quenching of tool steel, retains more austenite than water quenching. There may be a similar situation in the case of welding, the slower cooling rate resulting from the higher initial temperature may cause the retention of more austenite which transforms at or near room temperature.

There is an obvious need for more information concerning the austenite transformation in the various types of low- and medium-carbon steels, particularly the behavior of the last 4 or 5 per cent of austenite, which apparently decomposes at constant temperature during the first 24 to 48 hours after welding. This information would do much towards explaining the mechanism of underbead cracking and thereby aid in providing means for overcoming this difficulty.

Response of Steel to Rapid Heating

A study of the microstructure under the weld bead on the crack-sensitivity tests revealed a good correlation between the depth of the zone of complete transformation, when expressed as per cent of the total depth of the affected zone, and the crack sensitivity of the steel(33). At first, this appears to be an indication of hardenability, but this did not prove to be the case, as hardenability determined by the conventional manner did not correlate well with underbead cracking. This relationship of the heat-affected structure and cracking appears to indicate a pronounced difference in the response of various lots of HTS steels to the rapid thermal cycle developed during welding, which cannot be explained from the information now available.

It was also shown in this investigation that the aluminum content of the steel has a strong influence upon underbead cracking, small or medium amounts being quite detrimental(34). While the reasons for this are not known, it may be that aluminum is one of the factors which influence the rate of thermal response of the steel. Thermal response during heating is the rate at which complete austenitization takes place and, more particularly, the rate of dissolution of carbides.

In studying the rate of response, it is suggested that the effect of the type, size, and distribution of the carbides should be investigated together with the influence of alloy banding or segregation. The influence of these factors can be studied by means of the rapid dilatometer technique in which the specimens are rapidly heated followed immediately by a controlled cooling cycle which will indicate the manner in which the steel responded during heating.

An understanding of the factors affecting the rate of response of steel to the thermal cycle developed during welding could lead to a broadening of the field of readily weldable steels.

Cracks in the Weld Deposited Metal

While developing the crack-sensitivity test, vertical cracks were frequently found in the weld-deposited metal when the single bead weld specimens were sectioned longitudinally(35). As far as could be determined, these cracks did not extend to the surface of the weld bead, but occasionally they did cross the fusion zone and join the underbead cracks.

At first it was thought that the chief cause of these vertical cracks might be the very rapid cooling resulting from using an initial specimen temperature of 0°F. It was later found, however, that these cracks occurred in about the same number when the initial specimen temperature was raised to 60°F.

Metallographic examination of these vertical cracks showed that they were interdendritic in the columnar structure of the weld metal indicating that they may be shrinkage or hot cracks. Since in most weldability studies the beads are sectioned transversely, it appears that the presence of these vertical cracks which lie in a plane perpendicular to the axis of the weld bead, would not be exposed.

Since the scope of this investigation was limited to a study of the base metal, the cause of the vertical weld-metal cracks was not investigated. It is suggested that this type of cracking should be studied because its presence in test specimens may induce failure and cause erroneous evaluation of the ductility of the heat-affected parent metal, or of the weld metal itself. Likewise, the presence of such cracks in welded structures could lead to disastrous failures.

Notched-Bar Impact Properties of Plate

In studying the notched-bar impact properties of the plate steels in this investigation, a marked difference was noted in the longitudinal and transverse characteristics which became more pronounced as the aluminum content was increased to .020 per cent. In no case did the transverse tests indicate a transition zone when tested in the range of -80°F. to 210°F., although the longitudinal specimens from a part of these steels showed a definite transition zone when apparently similar heats did not(36). The reasons for these differences in behavior are not known. There is also evidence to indicate that homogenizing some heats increased the notched-bar impact strength to an appreciable extent, while in the case of other heats there were no benificial effects. From the above it is evident that more fundamental work is needed in this field.

CES:HMB:ALW/abn

September 23, 1948

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