PROGRESS REPORT

on

INVESTIGATION OF MEANS FOR EVALUATING THE QUALITY OF HULL PLATE STEEL BY TESTS CONDUCTED ON FURNACE OR LADLE SAMPLES

by

W. G. N. HEER, S. A. HERRES, AND C. H. LORIG
BATTELLE MEMORIAL INSTITUTE
Under Navy Contract NObs-45030

COMMITTEE ON SHIP CONSTRUCTION
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL RESEARCH COUNCIL

Advisory to

BUREAU OF SHIPS, NAVY DEPARTMENT
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Serial No. SSC-12

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Date: October 15, 1947

NATIONAL RESEARCH COUNCIL
2101 Constitution Avenue
Washington, D.C.

October 15, 1947

Chief, Bureau of Ships
Navy Department
Washington, D. C.

Dear Sir:

Attached is Report Serial No. SSC-12, entitled "Investigation of Means for Evaluating the Quality of Hull Plate Steel by Tests Conducted on Furnace or Ladle Samples". This report has been submitted by the contractor as a progress report of the work done on Research Project SR-97 under Contract NObs-45030 between the Bureau of Ships, Navy Department and Battelle Memorial Institute.

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

Very truly yours,

Frederick M. Feiker, Chairman
Division of Engineering and
Industrial Research

Enclosure

Preface

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

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Contract No. NObs-45030

to

NAVY DEPARTMENT, BUREAU OF SHIPS
WASHINGTON, D. C.

by

W. G. N. Heer, S. A. Herres, and C. H. Lorig

BATTELLE MEMORIAL INSTITUTE

May 28, 1947

ABSTRACT

A simple but reliable method for evaluating the notch sensitivity of hull steel before the steel has been rolled into plate is sought. The notch sensitivity of steel is believed to depend principally on deoxidation practice, temperature of hot rolling, rate of cooling following hot rolling, and susceptibility to strain aging.

At present, no method is known for obtaining sound test samples in the as-cast condition from low-silicon hull steel. Sound samples for test purposes may be obtained from ingot castings of steel with relatively high (about .25%) silicon additions. Sound samples were obtained from unkilled low-silicon steel by hot working the cast samples.

Several series of both the low- and high-silicon steels were made both with and without aluminum deoxidation and tested by standard V-notch Charpy impact tests and by a round Charpy impact bar, which was developed to save machining time and cost.

Notched-bar impact values of the high-silicon steels with or without aluminum deoxidation, are low and not significantly different. A marked superiority of the aluminum-killed steels is apparent when these steels are properly normalized and also when these or the low-silicon steels are hot rolled at proper temperatures. Specimens hot rolled and then subjected to strain aging show a further decrease in notched-bar impact resistance of the nonaluminum as compared with the aluminum-killed steels.

A series of notched-bend bar tests qualitatively indicated the same trends by fracture appearance and manner of breaking, but no quantitative evaluations were obtained from static bend tests.

On the suggestion of Mr. E. G. Touceda, a series of wedge-impact tests of the type used by the malleable iron industry were made. Results obtained to date with this test are not conclusive and further work is planned. Future work will also include further attempts to obtain sound as-cast samples from semi-killed steels.

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INTRODUCTION

This report deals with work carried out under the subject contract since its inception during the month of September, 1946. The object is to develop a fairly simple but reliable method for evaluating the quality of hull steel before the steel is rolled into plate. Various testing procedures are already being employed for determining one or more characteristics of a steel before it is tapped. In the steel casting industry, a spiral fluidity test is sometimes used to obtain an early indication of the mold-filling capacity of the steel. Recently, a test has been introduced for obtaining a preliminary measure of the hardenability of steel. A test piece, similar to the Jominy end quench specimen, is cast from a furnace sample into a metal mold, heated rapidly to the desired temperature, and then end quenched. Hardness measurements on this specimen are used to determine whether alloy adjustments are required before the heat is tapped.

The problem of steel quality is more complex. The present approach will be to make the assumption that the quality of finished plate is a function of its strength and notch-toughness characteristics, and that an indication of toughness is obtained by making standard notched-bar impact tests over a suitable range of testing temperatures. It is realized that the basic difficulty with hull steel, and the ultimate measure of its quality, is the service performance in a rigid, welded ship structure. However, there is considerable evidence to indicate that notch sensitivity of the unwelded plate is an important factor in determining its ultimate performance. The Board of Investigation convened by the Secretary of the Navy to inquire into "The Design and Methods of Construction of Welded Steel Merchant Vessels" concluded in its Final Report:[1]

> "(a) The fractures in welded ships were caused by notches and by steel which was notch sensitive at operating temperatures. When an adverse combination of these occurs, the ship may be unable to resist the bending moments of normal service. (Notch sensitivity may be defined as the property of a material which reflects its reluctance to absorb energy in the presence of notches and other strain inhibitors, such as low temperature and high rates of strain.)"

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1 Government Printing Office, Washington, D. C., 1947.

and

"(d) Existing specifications are not sufficiently selective to exclude steel which is notch sensitive at ship operating temperatures."

The steels to be considered in this investigation are those specified as Grade M and Grade HT, Navy Department Specification 48S5f of November 15, 1945, and the initial work will be done on steel within the chemistry specified for Grade M composition: 0.31% max. C, 0.75% max. Mn, 0.25% max. Si, 0.045% max S, and 0.055% P. Grade M steel is usually produced as a semi-killed type with very low silicon content (e.g., 0.03%), 0.20-0.25% C, and 0.40-0.50% Mn. A very small aluminum addition is sometimes made to the ladle or mold to control rate of gas evolution during solidification.

Such steel does not give sound ingots, but contains numerous blowholes which weld closed during hot rolling of the steel. In order to obtain sound steel in small ingots, a silicon content of about 0.15% minimum must be used, and no means of obtaining small as-cast samples of satisfactory soundness from low-silicon, semi-killed steels is now known.

The notch sensitivity of steel of Grade M composition is known to depend to a large extent on the following factors:

1. Degree of deoxidation with aluminum.
2. Temperature of hot rolling or normalizing.
3. Rate of cooling following hot rolling or normalizing.
4. Susceptibility to strain aging.

While only the first of these factors is determined by steelmaking practice, the variables of processing the finished plate may be regarded as bringing out the good or poor quality inherent in the steel at the time it is poured. Since hull plate steel is very definitely exposed to important variations in temperature of hot rolling, rate of cooling after hot rolling, and conditions of strain aging, it is evident that there is no assurance that an "as-cast" sample will behave like finished plate from the same furnace melt.

In the design of a test, it is not sufficient to distinguish differences between as-cast samples, unless such differences can be shown to persist in plate finished from the same steel. The fundamental causes of variations in notch sensitivity of steel of Grade M type composition are not known, although a good background which permits some predictions is gradually developing.[2,3] Thus far, no success has been had in attempts to correlate chemical composition or other physical properties with notch sensitivity.

It is established that hull plate made from steel fully killed with aluminum is less notch sensitive in the hot-rolled condition than steel not aluminum killed, and also is less subject to further decrease in notch-impact resistance when the steels are strain aged. For various reasons, it has been considered uneconomical to produce hull plate from fully killed steel. However, the use of aluminum-killed steel provides a means of obtaining samples with high notched-bar impact resistance in comparison with nonaluminum steel. These samples can be used to determine

2. J. R. Low and M. Gensamer, "Aging and the Yield Point in Steel", Metals Technology, December, 1943 (A.I.M.E. T.P., 1644).
3. S. Epstein and H. L. Miller, "Aging in Iron and Steel", Metals Handbook, American Society for Metals, Cleveland, 1939, pp. 602-611.

the utility of various testing methods to be considered.

In summary of the above discussion, to accomplish the purpose of developing a test which will show up the same quality differences as the notched-bar impact test and which will be convenient to carry out on furnace or ladle samples, it is necessary to overcome three problems:

1. Production of good- and poor-quality steel to "test the test". It is to be expected that this can be done by varying the deoxidation practice and heat treatment according to established practices.
2. Obtaining sound samples for testing. It is not known whether this can be done for low-silicon, as-cast samples. Additions of deoxidants to the sample may change its properties.
3. Accounting for variables in processing of plate which may increase the notch sensitivity of finished plate in comparison to that of the furnace or ladle test samples.

The following sections describe the progress of experimental work directed toward solution of these problems.

EXPERIMENTAL WORK

Production of Steels for Testing

The initial effort was to prepare good-and poor-quality steels, as determined by notched-bar impact tests, by altering the deoxidation practice used. The deoxidation variable was the amount of aluminum added. Table 1 gives chemical compositions of experimental steels used. The aluminum-treated and nonaluminum-treated steels which were used as comparisons are listed in pairs which were made up in two ways, matched melts and split melts. Most of the melts listed in Table 1 are split melts, made by pouring off part of the steel and then adding aluminum to the remainder of the melt. Matched melts were two melts made to obtain aluminum- and nonaluminum-treated steels of as nearly as possible identical time of melting, time of additions, power input to furnace, tapping temperature, and chemical composition except for aluminum content.

Table 2 gives a typical melting record for a split melt. A matched set of melts would be made in the same manner, except that there would be no difference in the treatment of different ingots or castings poured from the melt.

In both the split melts and matched melts, base metal of Armco iron punchings was placed in the furnace with 0.10 per cent manganese as ferromanganese and the amount of silicon indicated in Table 1 as ferrosilicon before the melt-down was started. At the end of the melt-down period, the melt was skimmed free of slag, ferromanganese, ferrophosphorus, ferrosilicon, and granular graphite were added to bring the molten metal to the desired composition before pouring.

The chemical compositions given in Table 1 show the silicon additions and recoveries. In further discussion, these steels are designated high silicon and low silicon according to the amount of silicon that was added to the melt. Low-silicon steels receive

TABLE 1. CHEMICAL COMPOSITIONS OF STEELS

Melt Number	Type of Melt	Steel	Silicon Added to Charge, %	Additions Before Tap		Composition, %				
				Silicon, %	Aluminum, Lbs./Ton	C	Mn	P	S	Si
A-2399	Split	A_2	0.10	0.25	None	0.24	0.40	0.032	0.038	0.06
A-2399	"	A_3	0.10	0.25	1.5	0.23	0.40	0.032	0.038	0.13
A-2887	Matched	G	0.10	0.25	None	0.24	0.46	0.027	0.027	0.14
A-2888	"	H	0.20	0.11	2	0.21	0.40	0.029	0.027	0.05
A-2936	"	I	0.10	0.08	None	0.21	0.37	0.024	0.032	0.01
A-2938	"	J	0.10	0.12	2	0.22	0.34	0.022	0.034	0.02
A-2773	"	M	0.20	0.00	None	0.22	0.37	0.023	0.030	0.01
A-2773	"	N	0.20	0.00	3	0.23	0.39	0.023	0.030	0.08
A-3185	"	O	0.20	0.00	None	0.17	0.37	0.024	0.028	0.01
A-3185	"	P	0.20	0.00	6	0.22	0.42	0.024	0.028	0.01

TABLE 2. MELTING RECORD

Heat No. A-2399
Date - 23 September 1946
Furnace - 500-lb. Induction
Type of Lining - MgO; Type of Backing - MgO
Type of Melt - 3 Ingot Split

Material	Total, Lbs.	C, %	Mn, %	Si, %	S, %	P, %	Al, %	Time, A.M.		Heat Log Addition	Heat Log Temp., °F.	Notes
Armco Iron	493.000	0.04	0.020	0.002	0.013	0.004		9:00		Fe, FeSi, FeMn		
FeSi	0.650			0.10				10:45				
FeMn	0.625	0.008	0.10					10:55				Melted slag removed
FeSi	1.630			0.15								
FeP	0.51					0.025		11:00		FeP	2880	
FeS	0.26				0.025			11:00		FeS	2880	
FeMn	3.320	0.020	0.53	0.002							2920	
C	1.05	0.21						11:04		FeSi & C	2940	
	501.045	0.278	0.650	0.254	0.038	0.029		11:08			2960	Slag removed
								11:11	Ingot A1 Poured	None	2980	Mold temp., 250°F.
FeSi	0.43			0.10				11:11		FeSi		
								11:12	Ingot A2 Poured		2980	Mold temp., 250°F.
Al	0.123						0.075	11:14		Al		
								11:15	Ingot A3 Poured		2940	Mold temp., 250°F.

Remarks: Bleeding and slight rimming action on Ingot A3 per cent or less silicon and high-silicon steels received 0.30 to 0.35 per cent silicon.

Obtaining Sound Test Specimens

An important requisite of any test for determination of mechanical properties of a metal is a sound test specimen. A series of experiments was carried out to determine the soundness of hull plate compositions when poured into different kinds of molds. It was found that the low-silicon steel was too unsound for test purposes when poured into either baked sand or copper chill molds in the form of round bars 1 inch in diameter and 6 inches long or of keel blocks. Raising the silicon content to 0.25 per cent or an addition of 0.1 per cent aluminum (2 lbs./ton equivalent) gave sound keel block castings, but the latter, certainly, and the former, possibly, affect the notch sensitivity of the steel sample.

Sound samples may be obtained from unsound castings by hot working, which welds blowholes, in the same manner as sound plate is obtained from unkilled ingots. It is also possible that sound castings could be obtained by centrifuging at high speeds during solidification or by use of a mold especially designed to give directional solidification. Such methods (and all chill casting) are open to the objection that the metallurgical structures developed are radically different from that of hot-rolled plate and the properties may vary correspondingly unless subsequent special heat treatments are used.

Therefore, these special casting methods and the possibility of silicon additions to the sample, were temporarily neglected. Sound samples for test purposes were obtained either from high-silicon ingot castings, or from low-silicon castings which were subjected to hot working.

Standard Notched-Bar Impact Tests

V-notch Charpy impact tests over a suitable testing temperature range were used as a standard measure of notch sensitivity or quality.

Low-temperature impact values were obtained by immersing specimens in an acetone and dry-ice bath for fifteen minutes and then transferring the specimens to the impact testing machine and breaking them within a few seconds. Figure 1 shows a schematic drawing of a hardness testing machine which was originally designed for high-temperature work, but adapted to low-temperature uses by substituting an acetone and dry-ice bath in place of the small electric furnace. Low-temperature Brinell hardness readings were obtained by immersing the ends of Charpy specimens in the bath and then applying a load of 500 kg. for 30 seconds.

Table 3 gives impact and hardness results for normalized specimens from steels A-2 and A-3 over a range of testing temperatures from 75°F. to -40°F. The specimens were taken from the center of 1/2-inch and 1-inch slices sawed from 165-lb. ingots and then normalized by holding at the temperatures indicated in Table 3 for one hour, followed by cooling in still air. Table 4 gives results of Charpy V-notch impact tests on steels G and H in both the as-cast and normalized conditions.*

* Table 8 is a summary of metal treatments for notched-bar impact tests discussed in this and subsequent sections of the report.

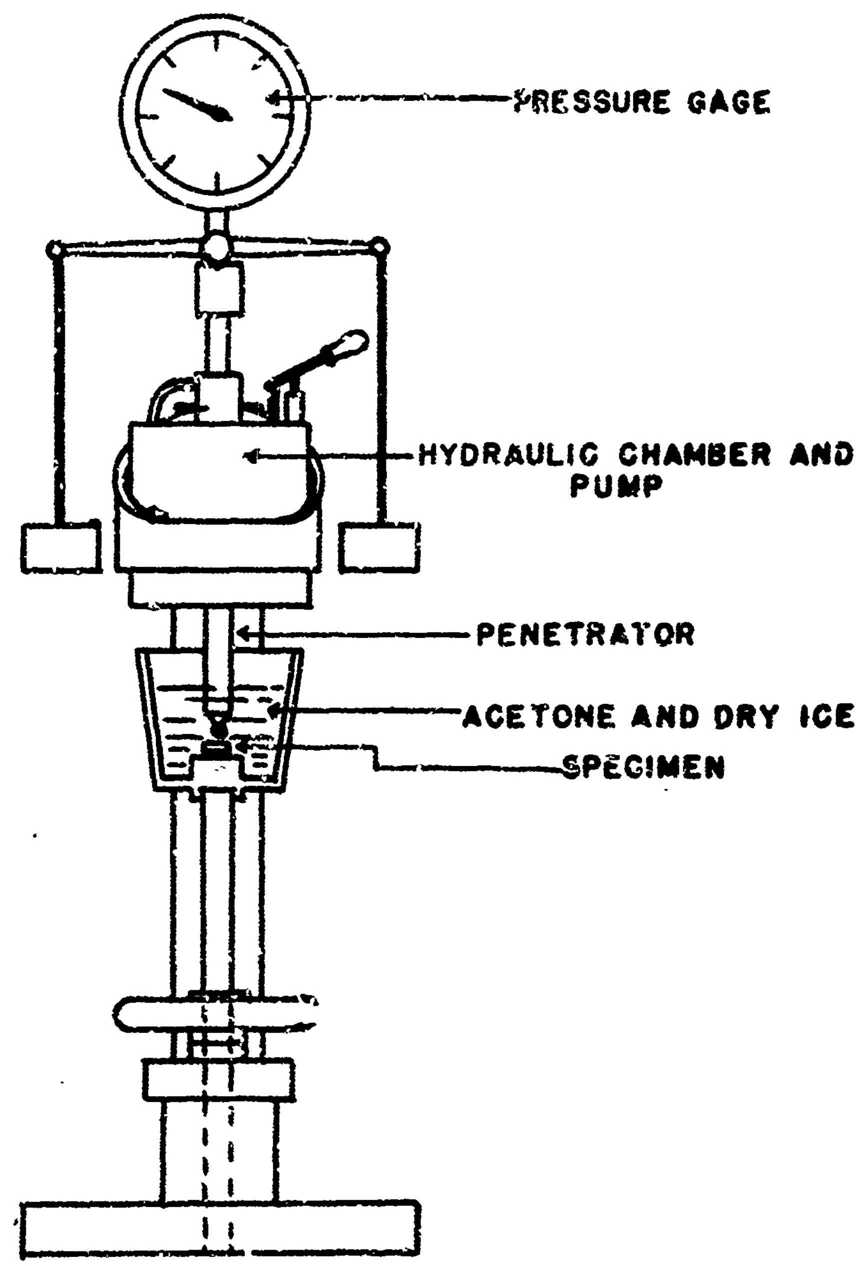

FIGURE 1. LOW TEMPERATURE HARDNESS TESTING MACHINE

TABLE 3. V-NOTCH CHARPY IMPACT AND HARDNESS TEST RESULTS FOR STEELS RECEIVING DIFFERENT DEOXIDATION TREATMENTS

Ingot No.	Normalizing Temperature, °F.	Normalizing Thickness, In.	Impact Tests, Energy Absorbed, Ft.-Lbs.			Brinell Hardness		
			75°F.	0°F.	-40°F.	75°F.	0°F.	-40°F.
A2	1500	1/2	24	7	4	109	–	–
A2	"	"	23	5	–	109	–	–
A3	"	"	17	6	4	107	–	–
A3	"	"	20	5	3	103	–	–
A2	1500	1	20	5	3	103	–	–
A2	"	"	21	6	3	111	–	–
A3	"	"	10	5	3	101	109	119
A3	"	"	10	5	4	101	–	–
A2	1650	1/2	25	7	4	113	–	–
A2	"	"	26	7	4	114	119	128
A3	"	"	32	16	4	109	–	–
A3	"	"	33	11	6	109	–	–
A2	1650	1	25	6	3	109	–	–
A2	"	"	24	4	2	109	–	–
A3	"	"	33	7	3	103	–	–
A3	"	"	32	10	3	109	–	–
A2	1800	1/2	21	5	3	109	–	–
A2	"	"	20	5	4	113	–	–
A3	"	"	38	12	5	109	–	–
A3	"	"	37	10	5	109	–	–

TABLE 3. (CONTINUED)

Ingot No.	Normalizing Temperature, °F.	Normalizing Thickness, In.	Impact Tests, Energy Absorbed, Ft.-Lbs.			Brinell Hardness		
			75°F.	0°F.	-40°F.	75°F.	0°F.	-40°F.
A2	1800	1	20	5	3	109	-	-
A2	"	"	22	5	2	113	-	-
A3*	"	"	27	10	4	103	-	-
A3	"	"	29	8	3	103	-	-
A2	1950	1/2	18	5	2	109	-	-
A2	"	"	19	4	3	114	-	-
A3	"	"	40	10	5	109	-	-
A3	"	"	39	12	5	109	-	-
A2	1950	1	18	5	3	109	-	-
A2	"	"	18	5	3	109	-	-
A3	"	"	35	12	5	103	-	-
A3	"	"	36	12	5	103	-	-

* Steel A3 received an aluminum addition equivalent to 1-1/2 lbs./ton.

TABLE 4. V-NOTCH CHARPY IMPACT-TEST RESULTS OF ALUMINUM-TREATED AND NONALUMINUM-TREATED STEELS IN THE AS-CAST AND NORMALIZED CONDITION

Steel	Heat Treatment	Testing Temperature	Impact Energy, Ft.-Lbs.		
G	As Cast	75°F.	8	9	9
H*	"	75°F.	6	10	11
G	"	0°F.	4	5	5
H	"	0°F.	3	4	5
G	"	-40°F.	3	2.5	-
H	"	-40°F.	3	3	-
G	1600°F.	75°F.	27	29	30
H	Normalize**	75°F.	47	49	50
G	"	0°F.	5	6	8
H	"	0°F.	9	10	12
G	"	-40°F.	4	3.5	-
H	"	-40°F.	3	4	-
G	1950°F.	75°F.	15	18	21
H	Normalize**	75°F.	25	30	39
G	"	0°F.	4	5	5
H	"	0°F.	5	5	6
G	"	-40°F.	3	3.5	-
H	"	-40°F.	3	8	-

* Steel H received an aluminum addition equivalent to 2 lbs./ton.
** 6 x 6 x 1-inch sections held at temperature for 1 hour and cooled in still air.

The steels tested in the as-cast condition show very poor impact resistance even in room-temperature tests. The fact that there is no significant difference in notch sensitivity between the steel treated with aluminum and that not treated with aluminum discourages the possibility of utilizing an as-cast sample for determining the quality of hull plate.

In the normalized condition, for normalizing temperatures of 1600°F. or higher, the aluminum-treated steels show markedly better notched-bar impact resistance than the nonaluminum steels, for testing temperatures of +75°F. and 0°F. At -40°F., the impact resistance of both steels has fallen off to a low value. The steel normalized in 1/2-inch-thick sections showed slightly higher impact resistance than that normalized in 1-inch-thick sections.

A thorough micro-examination was made of the specimens from A-2 and A-3 steels. No significant differences in the structures, from the surface to the center of either the 1/2- or 1-inch sections, were apparent in any one steel. Differences in structure between 1/2- and 1-inch sections from the same steels were slight as might have been anticipated from the hardness and notched-bar impact values.

Marked differences in structures were apparent between the A-2 and A-3 ingots. The silicon-treated steel (A-2) exhibited a tendency to develop a much coarser ferrite grain size and irregular carbide distribution at normalizing temperatures above 1650°F. Austenitic grain coarsening, with which these changes are associated, was inhibited at temperatures up to 1800°F. in the aluminum-treated steel (A-3).

Specimens normalized at 1500°F. were evidently not heated above the critical temperature, and, therefore, incompletely austenitized. The aluminum-treated steel was less completely austenitized and appeared to have a less uniform structure than the steel without aluminum.

No method for readily distinguishing steels with good or poor notch sensitivity was apparent from the microscopic investigation.

<u>Development of Round Notched-Bar Impact Specimen</u>

The V-notch Charpy impact test is convenient for use in determining the notched-bar impact resistance of steels over a range of testing temperatures. In this respect, it is superior to the round Izod test with a circumferential notch, which is used in some laboratories. Because the machining operations on standard Charpy specimens require more time and, consequently, greater cost in preparation, it was decided to try to use a round specimen with a circumferential notch for a beam-type impact specimen which would be cheaper to prepare.

Normalized and as-cast samples of high-silicon steels, G and H, which showed poor and good impact resistance in standard V-notch Charpy tests, were turned down to 1/2-inch-round bars in a lathe. A tungsten carbide tool ground to cut a 45° V-angle notch with a 0.01-inch notch radius was then used to cut 0.05 inch deep at two-inch intervals along the lengths of the 1/2-inch-round bars. The bars were then sawed into individual test specimens 2 inches long each with the notch in the middle of the length. The specimens were broken in a standard impact testing machine. Figure 2 is a photograph of round and standard Charpy specimens before and after breaking.

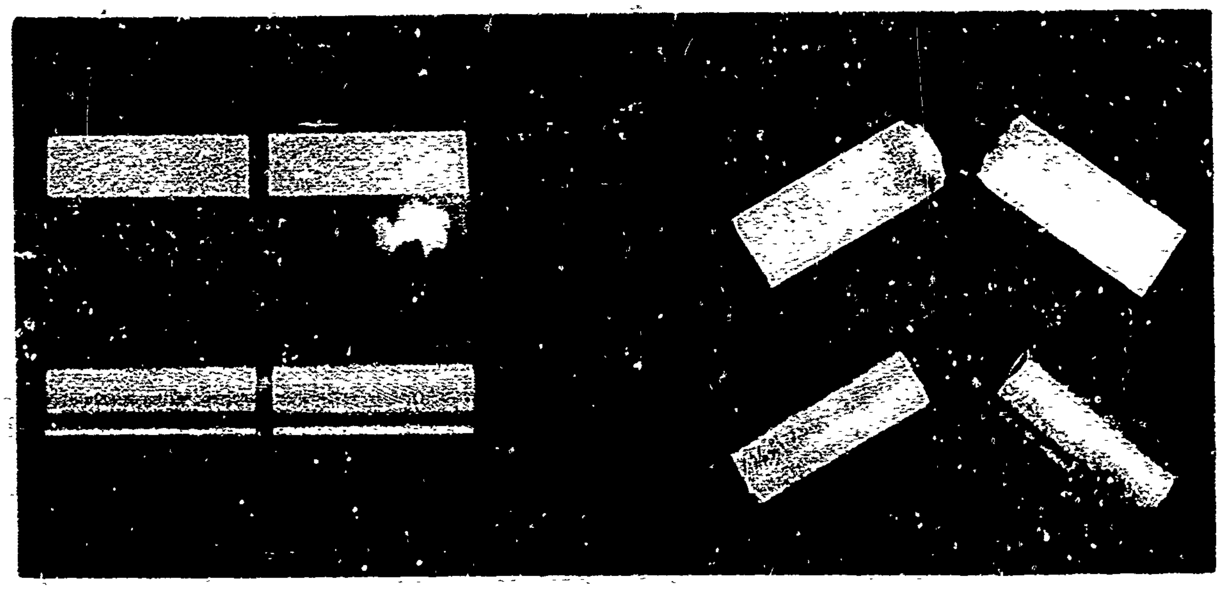

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Figure 2. Photograph of V-Notch Charpy and round Charpy specimens before and after breaking.

One difficulty with the round test pieces was that 1/2-inch-diameter bars were a little large and sometimes jammed between the hammer and the anvil of the testing machine. This was corrected by grinding off the corners at the ends of the test pieces.

Table 5 shows notched-bar impact test results for steels G and H with standard V-notch Charpy specimens and round Charpy specimens with 0.01-inch-radius notch. The values for the round specimens are higher at all testing temperatures than those for standard specimens. The decrease in impact resistance with decreased testing temperature is less severe for the round than for the standard specimens.

Round Charpy specimens with 0.005-inch-radius notches 0.05 inch deep were then machined from normalized samples of steels G and H. The values obtained are shown in Table 5 and Figure 3. The more severe notch has given lower values which are more comparable with those obtained for standard specimens than the 0.01-inch radius, and 0.005-inch radius was therefore used in preparing all subsequent round Charpy bars. Although the minimum values obtained at -40°F. are not so low for the round as for the standard specimens, the round specimen readily distinguishes between the good- and poor-quality steels. The round specimen is less expensive and time consuming to prepare, and, therefore, was used in making the tests described in the following sections of this report.

TABLE 5. COMPARISON OF NOTCHED-BAR IMPACT VALUES FOR THE STANDARD V-NOTCH CHARPY SPECIMEN AND THE ROUND CHARPY SPECIMEN

Steel	Heat Treatment	Testing Temperature	Charpy V-Notch, Ft.-Lbs.			Round Charpy 0.01-In.-Radius Notch, Ft.-Lbs.			Round Charpy 0.005-In.-Radius Notch, Ft.-Lbs.			
G	As Cast	75°F.	8	9	9	12	13	15				
H*	"	75°F.	6	10	11	10	12	12				
G	"	0°F.	4	5	5	6	6	9				
H	"	0°F.	3	4	5	5	7	7				
G	"	-40°F.	3	2.5		8	8					
H	"	-40°F.	3	3		5	5					
G	1600°F. Normalized	75°F.	27	29	30	50	51	53	28	29	30	31
H		75°F.	47	49	50	57	64	67	39	43	47	47
G	"	0°F.	5	6	8	27	28	30	10	12	13	13
H	"	0°F.	9	10	12	40	44	46	15	18	20	20
G	"	-40°F.	4	3.5		17.5	19		9	9	12	14
H	"	-40°F.	3	4		19	23		10	10	10	11
G	1950°F. Normalized	75°F.	15	18	21	36	44	44				
H		75°F.	25	30	39	44	54	57				
G	"	0°F.	4	5	5	20	23	29				
H	"	0°F.	5	5	6	28	32					
G	"	-40°F.	3	3.5		7.5	10					
H	"	-40°F.	3	8		12	13					

* Steel H received an aluminum addition equivalent to 2 lbs./ton.

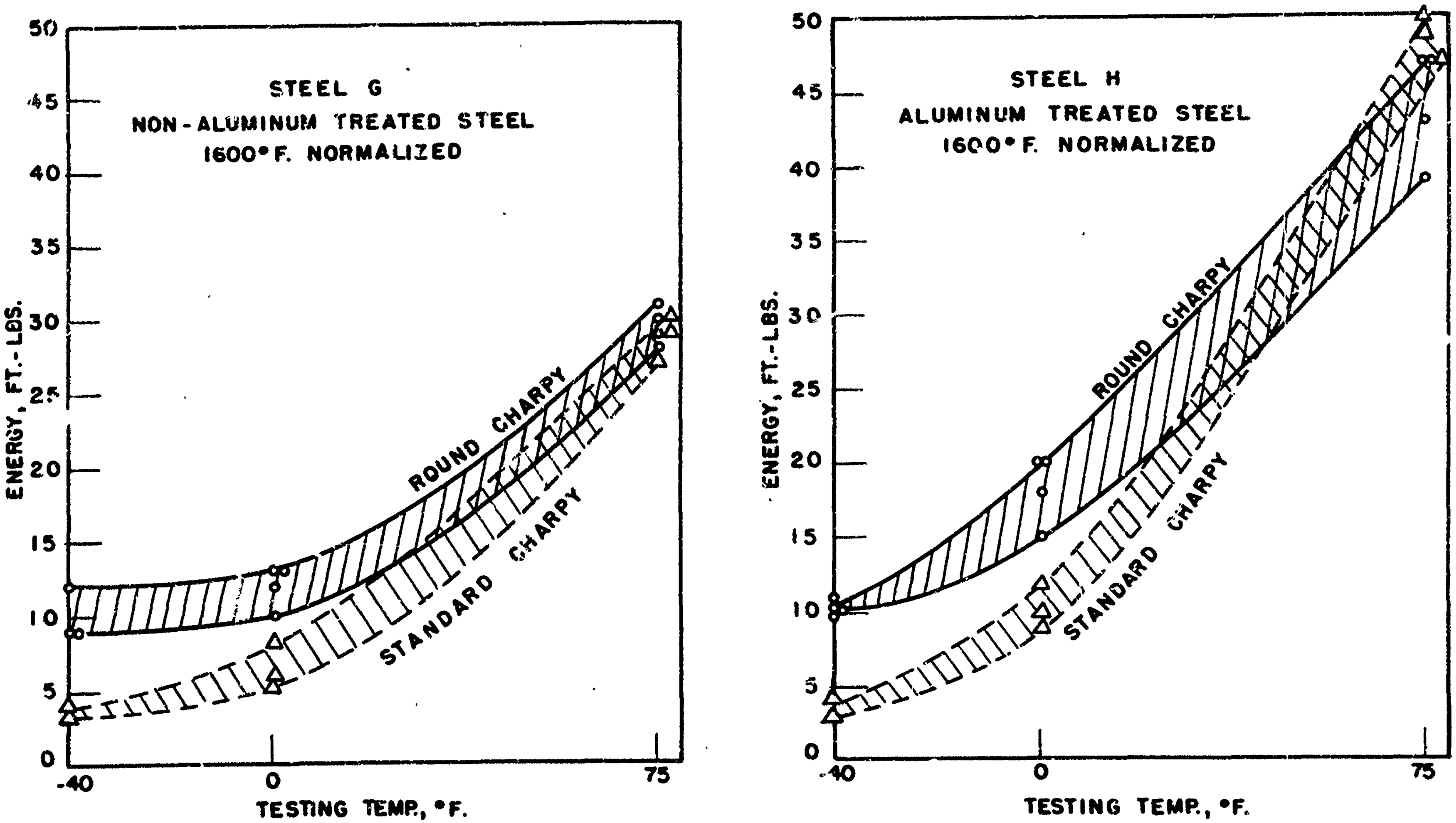

FIGURE 3 . COMPARISON OF NOTCH TOUGHNESS VALUES OF ROUND VERSUS STANDARD CHARPY TEST SPECIMENS ON IDENTICAL STEELS

Effect of Different Hot-Rolling Temperatures on Notched-Bar Impact Resistance of Aluminum-Treated and Nonaluminum-Treated Steels

Four steels, two high-silicon and two low-silicon, aluminum- and nonaluminum-treated, were hot rolled and finished at various temperatures above the critical range. Round Charpy specimens were machined from the finished bars and tested at 75°F., 0°F., and -40°F. to determine the influence of different hot-rolling finishing temperatures upon the notch sensitivity. The two high-silicon steels used in these experiments were steels G and H, previously used to standardize the round Charpy bar against the standard test. Two matched melts, J and I, were made up for low-silicon, aluminum-treated, and nonaluminum-treated steels used in the experiments. Steels I and J were poured into baked core sand molds which made small test castings 1 inch in diameter and 6 inches long. Since steels G and H were originally cast into 100-lb. ingots, small sections 1 inch square and 6 inches long were sawed from the ingots.

Samples from the high- and low-silicon steels were heated to a rolling temperature of 1950°F. in a large electric furnace and given three passes through the rolls which gradually reduced their cross sections from 1-inch rounds or 1-inch squares to square bars slightly larger than 47/64 inch. These bars were returned to the furnace, reheated to 1950°F., and rolled in three passes through the rolls from 47/64-inch squares to 39/64-inch squares. The 39/64-inch bars from the four steels were separated into four groups, and each group which contained bars from each of the four steels was reheated to one of the following four temperatures: 1500, 1600, 1800, and 1950°F. and then given the last pass through the rolls which reduced the cross section from 39/64-inch square to 9/16-inch square. This operation gave 16 groups of steels consisting of 9/16-inch-square bars from the aluminum- and nonaluminum-treated, high- and low-silicon steels which had been given their last hot-rolling finishing pass at the four hot-rolling temperatures listed above. The bars were then machined into round Charpy specimens. The resulting specimens were tested at 75, 0, and -40°F.

Results of these tests are listed in Table 6 and plotted in Figures 4 and 5. The high-silicon steels G and H (Figure 4) show a marked superiority of aluminum treated over nonaluminum steels at finish rolling temperatures of 1600 and 1800°F. The advantage is less marked at 1500°F. and not evident at 1950°F. Rolling temperature is, therefore, an important variable which must be taken into account in development of a steel-quality test.

The low-silicon steels I and J (Figure 5) show less difference than was expected between the aluminum-treated and nonaluminum-treated steels. A possible explanation was that with the low-silicon content, an aluminum addition equivalent to 2 lbs./ton was insufficient for full deoxidation.* An additional pair of steels, O and P, was, therefore, made to determine the effect of an aluminum addition equivalent to 6 lbs./ton on the notched-bar impact resistance of the low-silicon steel after hot rolling. Figure 6 shows that, with the larger aluminum addition, a marked superiority in impact resistance is shown for the aluminum-treated steel finish hot rolled at 1600 or 1800°F.

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* The amount of aluminum required for deoxidation is influenced by the raw materials and melting practice, and would be expected to be somewhat higher for the induction-furnace practice used in preparing these steels than for normal basic open-hearth practice.

TABLE 6. EFFECT OF DIFFERENT HOT-ROLLING FINISHING TEMPERATURES ON NOTCH-TOUGHNESS PROPERTIES OF ALUMINUM- AND NONALUMINUM-TREATED, HIGH- AND LOW-SILICON STEELS

Hot-Rolling Finishing Temperature	Testing Temperature	Steel G High Silicon, Impact Energy, Ft.-Lbs.				Steel H High Silicon + Aluminum, 2 Lbs./Ton Impact Energy, Ft.-Lbs.			
1500°F.	75°F.	46.5	52	66		90	91		
"	0°F.	16.5	22	23.5		27	28		
"	-40°F.	18	16.5			22	19		
1600°F.	75°F.	43	45			110+	110+	110+	
"	0°F.	17.5	17			41	45		
"	-40°F.	10.5	15			27	23		
1800°F.	75°F.	47	36	29		110+	110+	110+	
"	0°F.	9	12	13	16	23	24	30.5	
"	-40°F.	7.5	10			11	13		
1950°F.	75°F.	46	44			33	44	55	
"	0°F.	13	15.5	17		9.5	8.5		
"	-40°F.	11	13			6.5	9.0		
		Steel I Low Silicon, Impact Energy, Ft.-Lbs.				Steel J Low Silicon + Aluminum, 2 Lbs./Ton Impact Energy, Ft.-Lbs.			
1500°F.	75°F.	30	51			55	60	73	
"	0°F.	12	17.5	19		18	18	19.5	
"	-40°F.	9	12			8.5	11.5		
1600°F.	75°F.	17	25			36	43	70	83
"	0°F.	11.5	15.5			20	21.5		
"	-40°F.	8.5	8.5			16.5	19.5		

TABLE 6. (CONTINUED)

Hot-Rolling Finishing Temperature	Testing Temperature	Steel I Low Silicon, Impact Energy, Ft.-Lbs.				Steel J Low Silicon + Aluminum, 2 Lbs./Ton Impact Energy, Ft.-Lbs.		
1800°F.	75°F.	35	33			20	23	
"	0°F.	13	14	14.5		10	15	
"	-40°F.	6	7			8	11	
1950°F.	75°F.	15	19	23		16	17	
"	0°F.	9	9.5	10	14	8	9.5	12.5
"	-40°F.	8.5	7			11	12.0	
		Steel O Low Silicon, Impact Energy, Ft.-Lbs.				Steel P Low Silicon + Aluminum, 6 Lbs./Ton Impact Energy, Ft.-Lbs.		
1600°F.	75°F.	40	39*	56*	79	90	83	97
"	0°F.	15.5	21.5	15*		50	45	47
"	-40°F.	7	9			21	26	22
1800°F.	75°F.	78*	35*	40*		108	108	75*
"	0°F.	7	8.5	10		37	34	35
"	-40°F.	10	7	6		19	19	22

* Test specimen contained flaw.

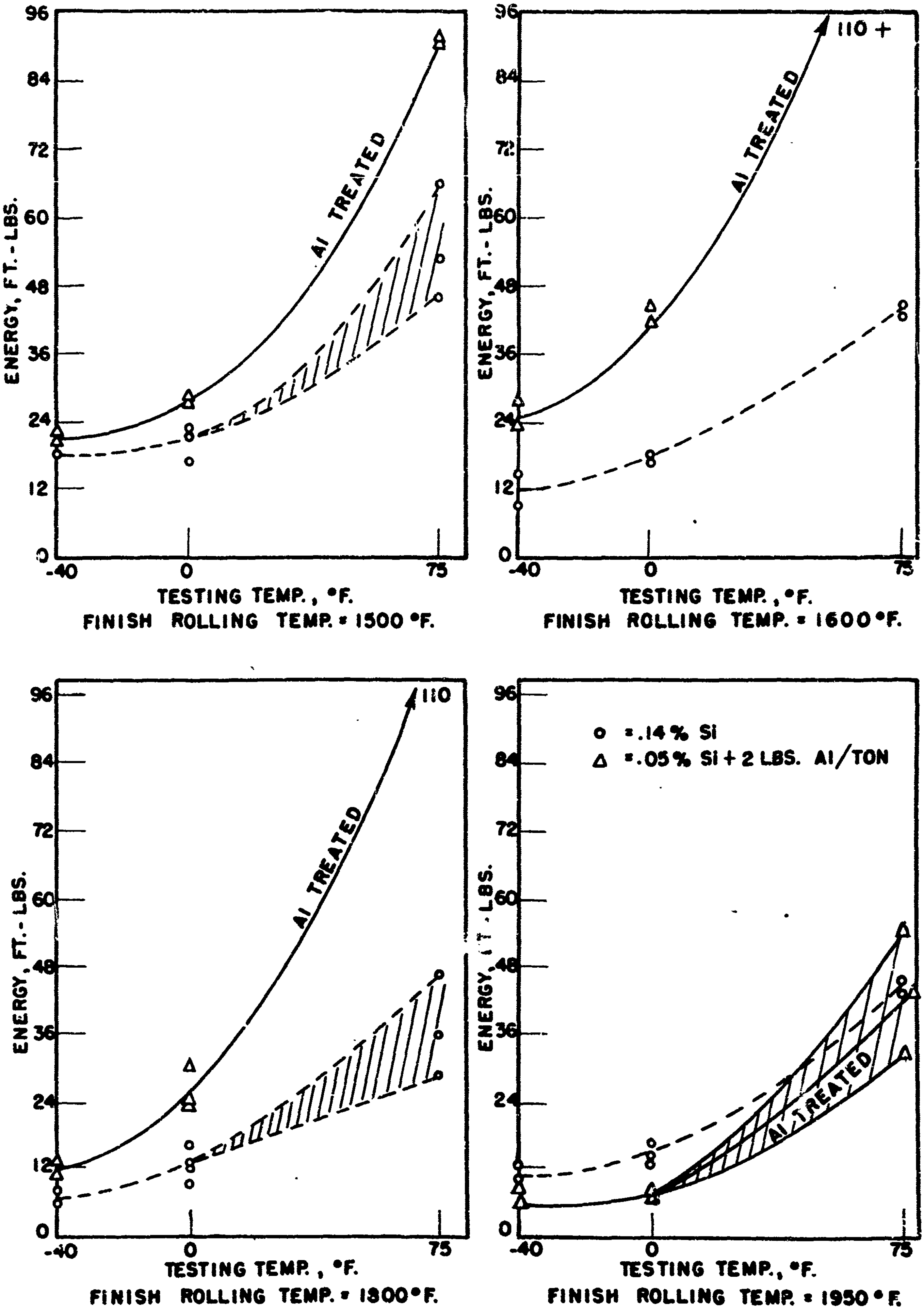


FIGURE 4. NOTCH TOUGHNESS CURVES ON HIGH-SILICON HULL PLATE STEEL HOT-ROLLED AT DIFFERENT TEMPERATURES

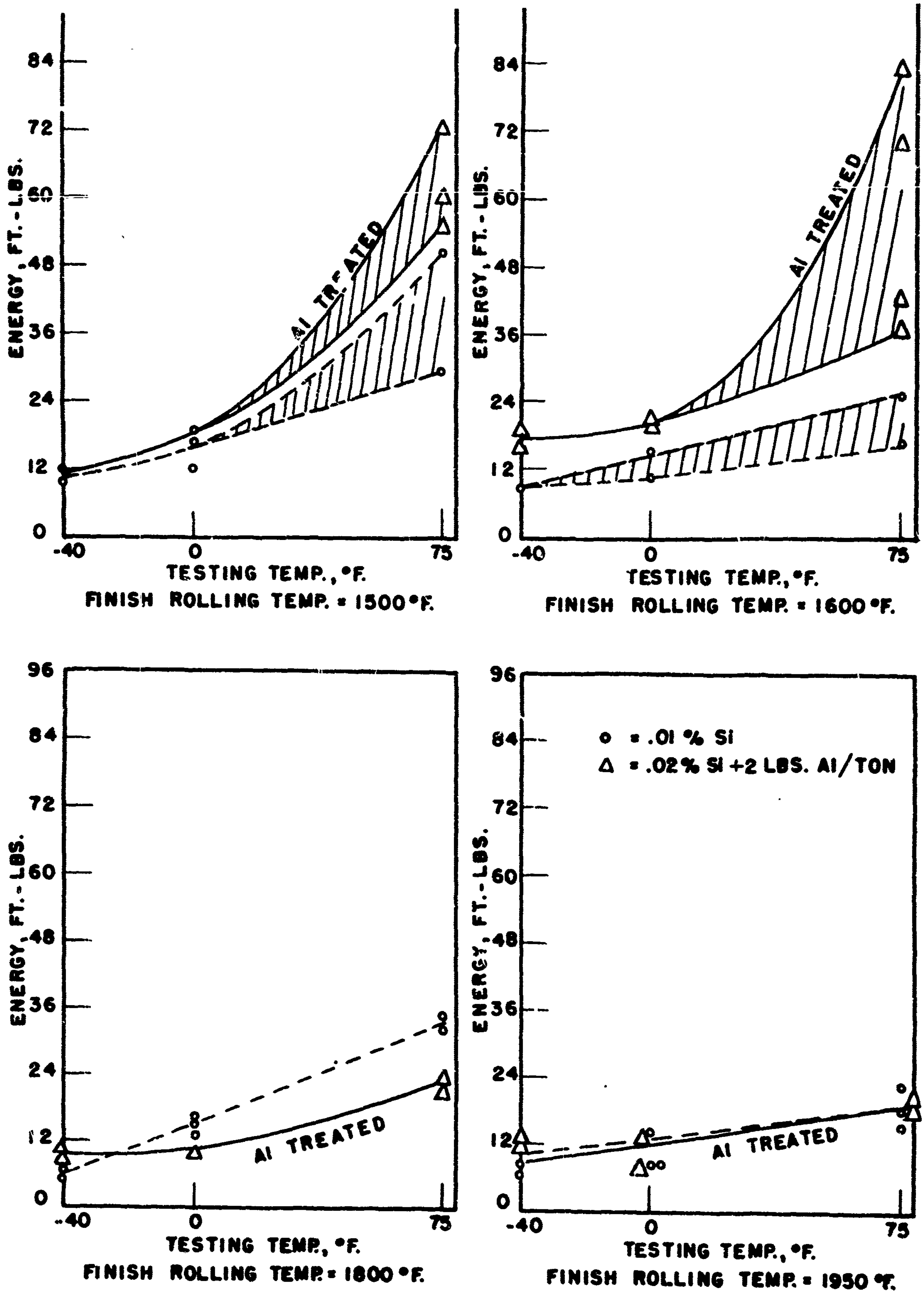


FIGURE 5. NOTCH TOUGHNESS CURVES LOW-SILICON HULL PLATE STEEL HOT-ROLLED AT DIFFERENT TEMPERATURES

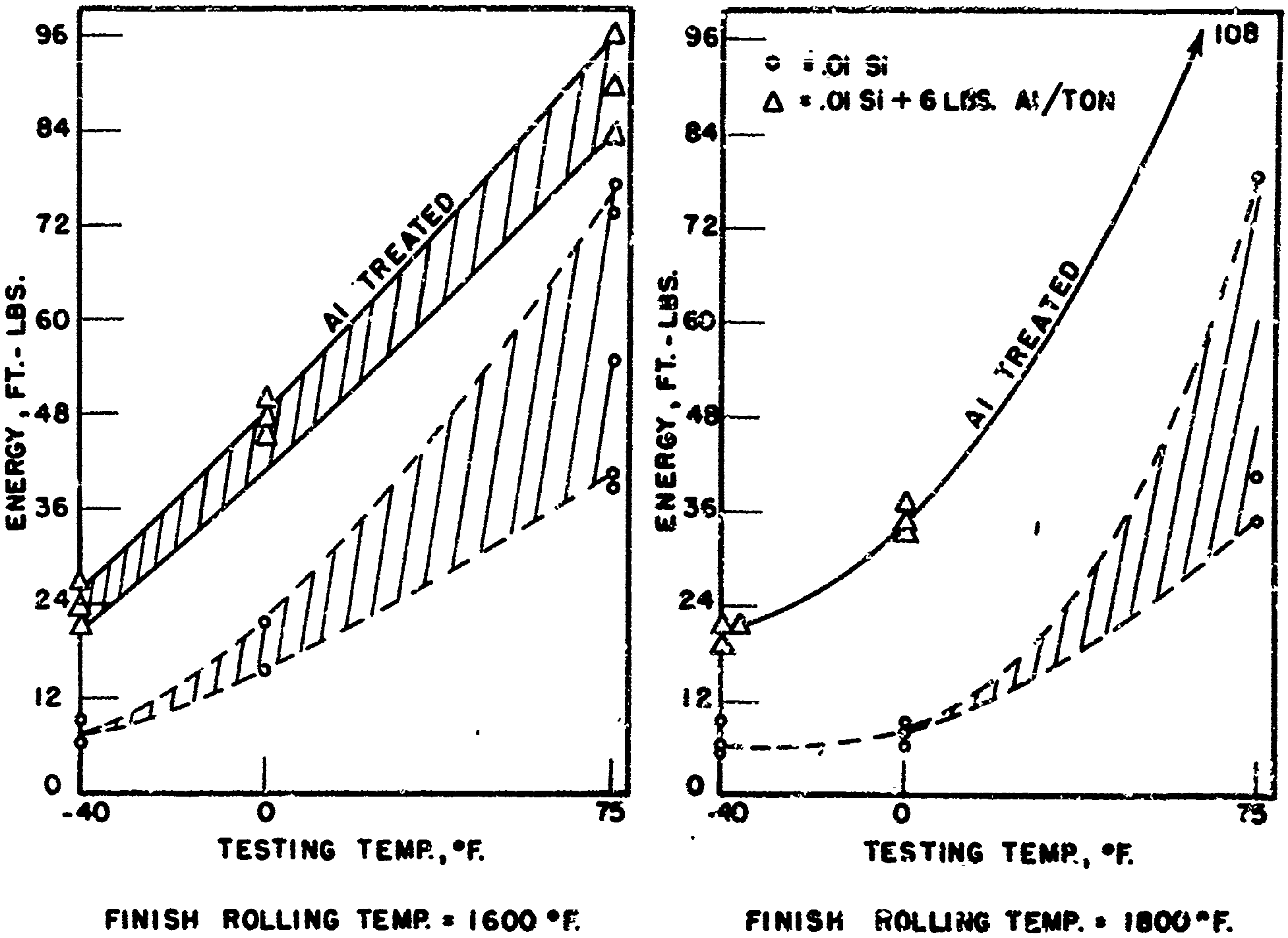


FIGURE 6. NOTCH TOUGHNESS CURVES ON LOW-SILICON HULL PLATE STEEL HOT-ROLLED AT DIFFERENT TEMPERATURES

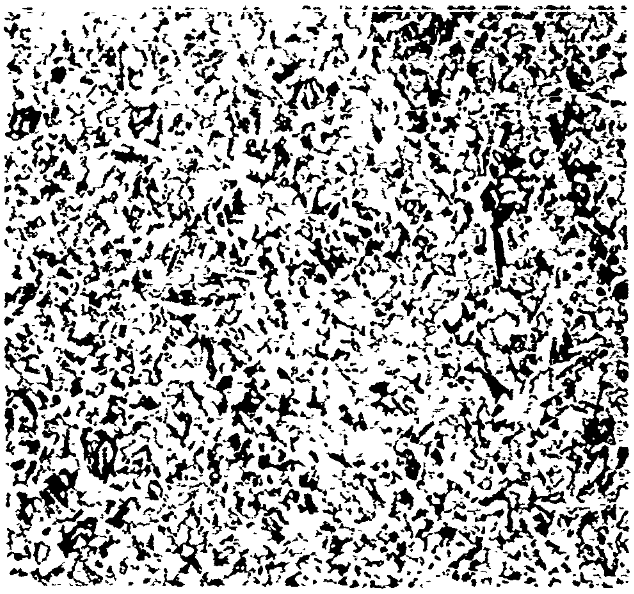
Microscopic examination of these hot-rolled steels was carried out. As illustrated by the photomicrographs of Figures 7 and 8, the aluminum-treated steels hot rolled and finished at 1600 and 1800°F. have a finer ferrite grain size and a more regular carbide distribution than the steel without an aluminum addition. For 1950°F. hot rolling, all steels are coarse grained with irregular carbide distribution, and for 1500°F. hot rolling, the grain size is fine but not uniform, while the carbide distribution is irregular and there is a tendency toward banding (alternate concentrations of carbide and ferrite in layers parallel to the rolling direction).

In general, the microstructures parallel those discussed earlier for normalized steels. Although qualitative differences are apparent, it would not be possible to make an accurate estimate of notch sensitivity of the various steels on the basis of the micro-examination alone.

Effect of Strain Aging on Notched-Bar Impact Resistance of Aluminum-Treated and Nonaluminum-Treated Steels

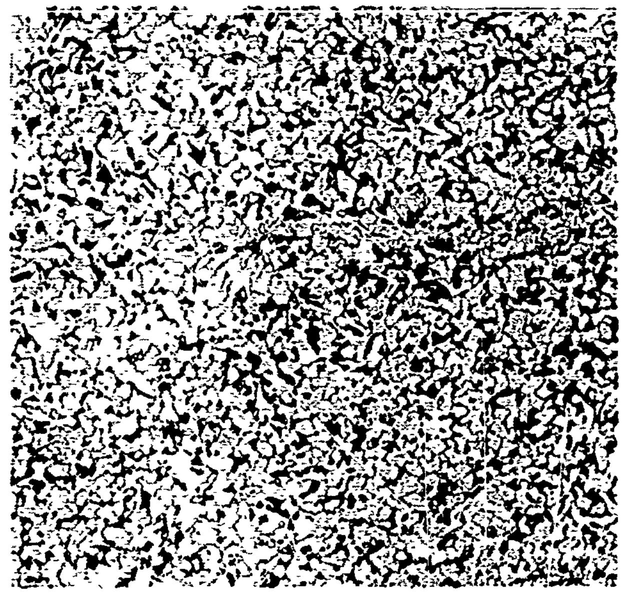
Two low-silicon steels, with and without aluminum (M and N), were cast into 1-inch rounds 6 inches long, and two high-silicon ingots, with and without aluminum (G and H), were sectioned to give 1-inch-square bars 6 inches long. These bars were hot rolled and finished at 1800°F.

The hot-rolled 9/16-inch bars were machined into 0.500-inch and 0.527-inch rounds. The 0.500-inch rounds were notched, then sawed into two-inch lengths to be used directly for round Charpy specimens. The 0.527-inch rounds were slightly tapered for a short distance on one end and cold reduced 10 per cent in cross-sectional area by drawing through a 0.500-inch die. The cold-drawn bars were then sawed into two-inch



X100 49906

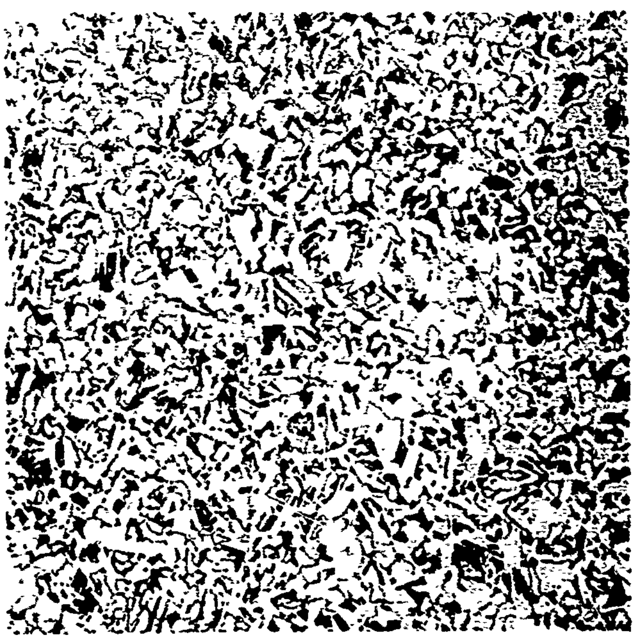
a. No aluminum



X100 49908

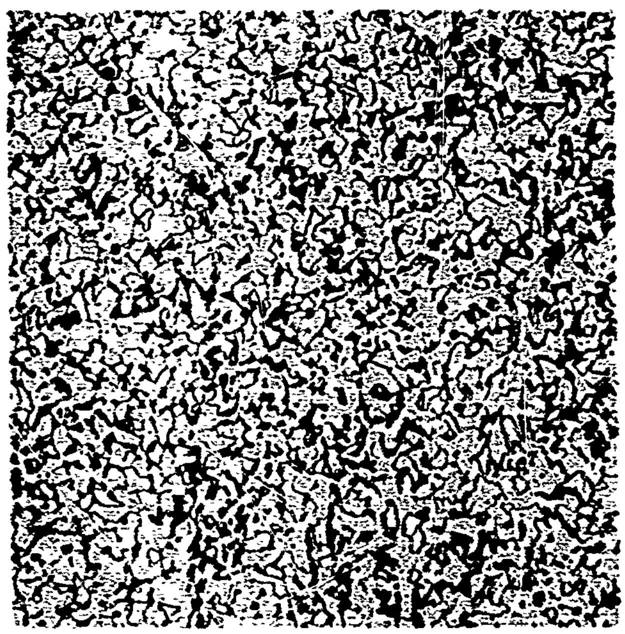
b. Aluminum Added.

Hot-rolled and finished at 1600°F.



X100 49907

c. No aluminum

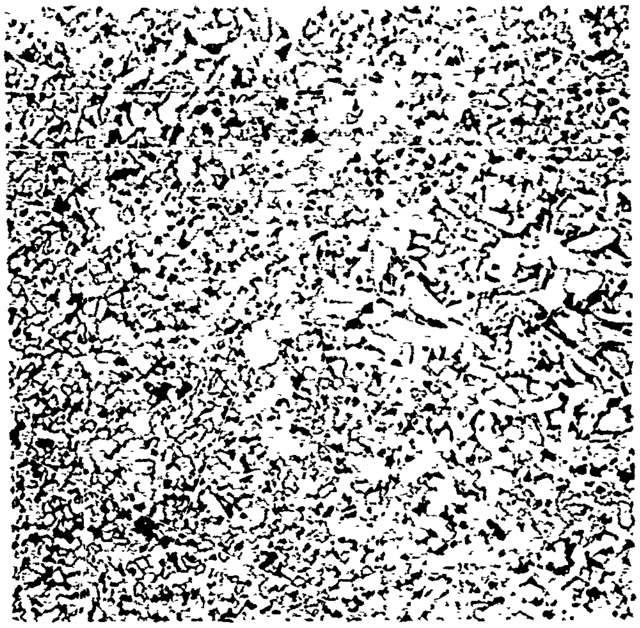


X100 49909

d. Aluminum added.

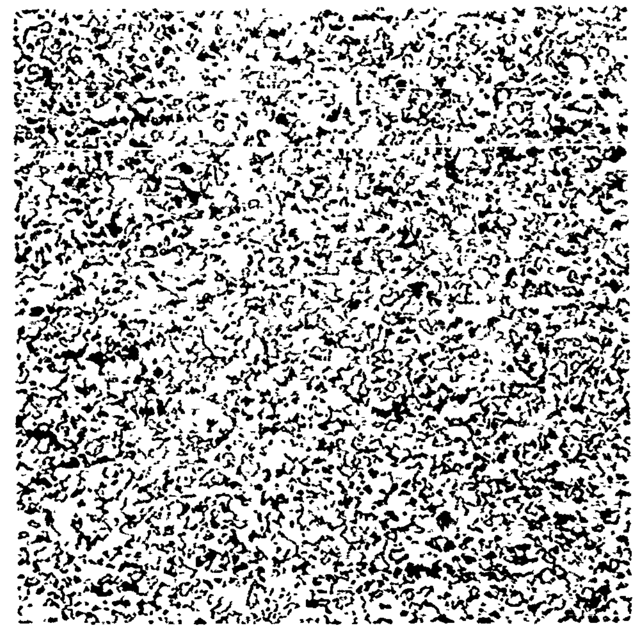
Hot-rolled and finished at 1800°F.

Figure 7. Microstructures of a high-silicon steel hot rolled at various temperatures. Aluminum addition equivalent to 2 pounds per ton.



X100 49913

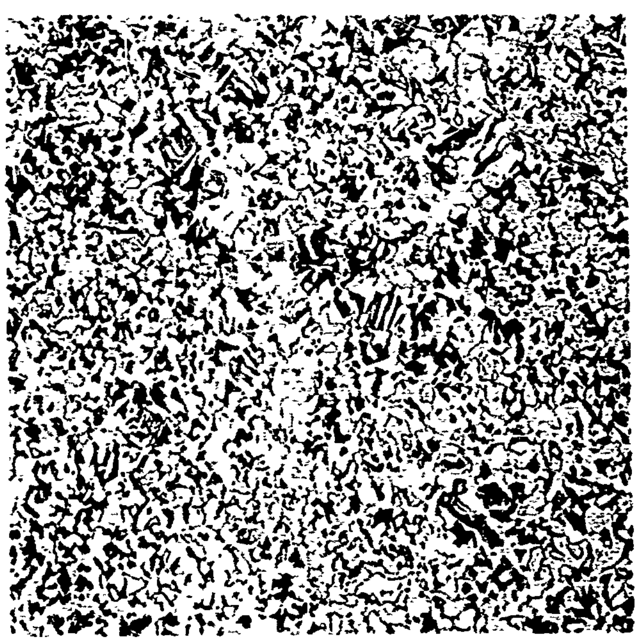
a. No aluminum



X100 49915

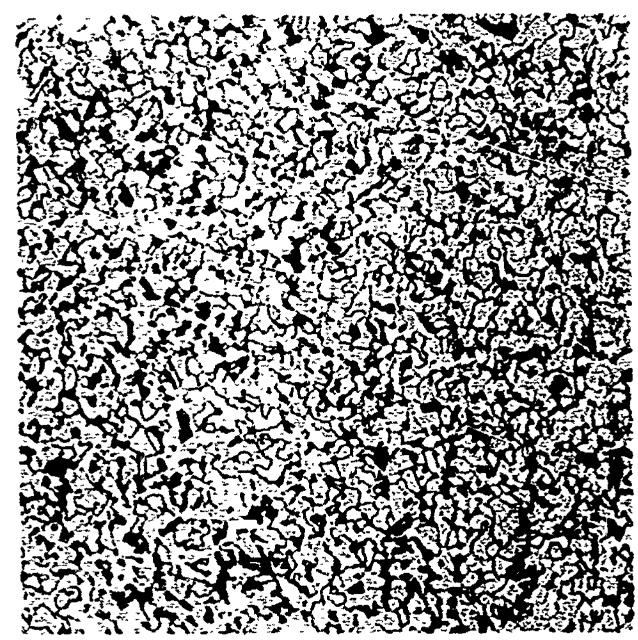
b. Aluminum added.

Hot-rolled and finished at 1600°F.



X100 49914

c. No aluminum.



X100 49916

d. Aluminum added.

Hot-rolled and finished at 1800°F.

Figure 8. Microstructures of a low-silicon steel hot rolled at various temperatures. Aluminum addition equivalent to 6 pounds per ton.

lengths, notched at their centers, and used for round Charpy specimens. The latter strained test specimens were placed in a beaker of boiling water and aged for 40 minutes at 212°F. The strain-aged and nonstrain-aged specimens were broken at 75°F., 0°F., and -40°F. The notch-toughness values thus obtained before and after are recorded in Table 7 and plotted in Figure 9. It may be seen that there has been a marked decrease in the notched-bar impact resistance of both low- and high-silicon steels with no aluminum addition, but that the same steels with aluminum addition show no significant decrease after the strain-aging treatment.

In processing, fabrication, and service, hull plate steel is subjected to varying degrees of strain aging. The decrease in notch toughness induced by strain aging may have a very important influence on service performance. The above tests indicate that various steels may be more or less susceptible to strain aging and that this variable must be taken into account in development of a steel quality test.

Notched-Bar Bend Tests

The notched-bar bend test has considerable merit in that it closely represents the condition of structural failure in hull steels. As shown by Sachs, and others[4], when metals are tested in tension or bending, the presence of a notch increases the load at fracture if the metal breaks in a completely brittle manner.

4. G. Sachs, L. J. Ebert, and W. F. Brown, "Comparison of Various Structural Alloy Steels by Means of the Static Notch-Bar Tensile Test". Metals Technology, Vol. 13, No. 8, December, 1946. (A.I.M.E. T.P., 2110.)

TABLE 7. NOTCH-TOUGHNESS PROPERTIES OF LOW- AND HIGH-SILICON STEELS BEFORE AND AFTER STRAIN AGING

Steel	Treatment	Type	Before Strain Aging, Impact Energy, Ft.-Lbs.			After Strain Aging, Impact Energy, Ft.-Lbs.		
			75°F.	0°F.	-40°F.	75°F.	0°F.	-40°F.
G	Hot Fin. Rolled 1800°F.	High Si	47	9	7.5	21.5	10.5	9
"	" " "	"	36	12.5	10	21.5	10	8.5
"	" " "	"	29	13	-	21.5	10	7.5
"	" " "	"	-	16	-	20.5	10	7
"	" " "	"	-	-	-	18	9	6
"	" " "	"	-	-	-	14	8.5	5
H	" " "	" + Al**	110+	23	11	100+	36	11.5
"	" " "	" + Al	110+	24	13	96	27.5	9
"	" " "	" + Al	100	30.5	-	89	23	8.5
"	" " "	" + Al	-	-	-	78.5	14	8
"	" " "	" + Al	-	-	-	74	15.5	7.5
"	" " "	" + Al	-	-	-	68.5	-	-
M	" " "	Low Si	26	8.5	6	14	8	4.5
"	" " "	"	15*	11	-	12	5.5	2.5
"	" " "	"	-	-	-	8.5	5	2.5
"	" " "	"	-	-	-	6.5	-	2.5
N	" " "	" + Al**	45	24	-	55	25	12
"	" " "	" + Al	51.5	12	9	45.5	24.5	11.5
"	" " "	" + Al	-	-	-	41	16	11
"	" " "	" + Al	-	-	-	-	-	9

* Specimen contained a flaw.
** Aluminum addition equivalent to 3 lbs./ton.

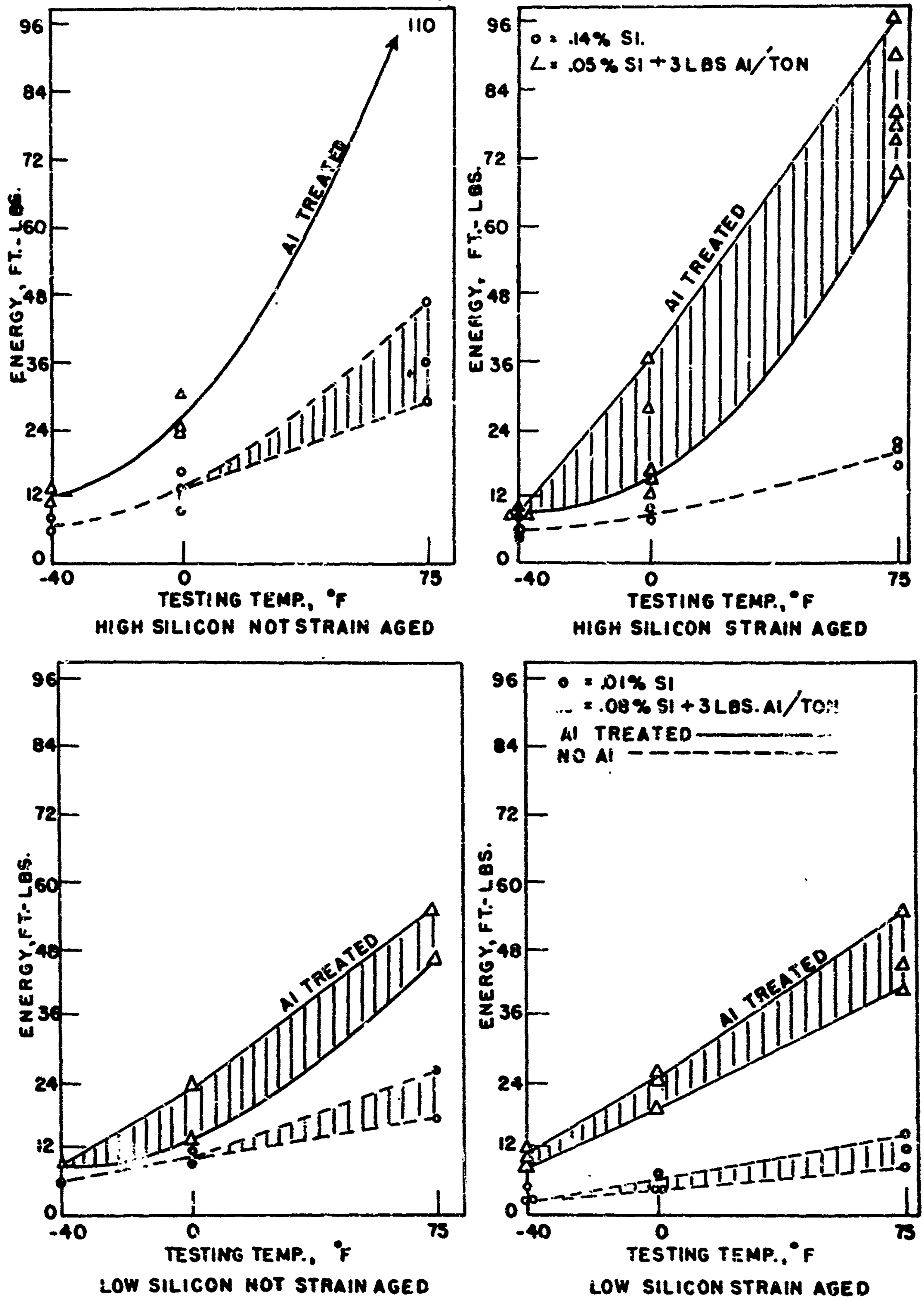


FIGURE 9, EFFECT OF STRAIN AGING UPON THE NOTCH TOUGHNESS OF HULL PLATE STEELS

Whether or not a steel is brittle depends on the severity of the stress concentration system introduced by the notch, the temperature of testing, and the rate of loading. A steel which fails in a ductile manner, by shear deformation, under a given set of testing conditions may fail in a brittle manner, by cleavage fracture, if the temperature of testing is lowered or the severity of the stress concentration increased (either by decreasing the radius of the notch or increasing the cross-sectional area of the bar).

A series of bend bars was made from samples of steels A-2 and A-3 which had been normalized at 1950°F. and had room-temperature Charpy impact values of 18-19 ft.-lbs. and 35-40 ft.-lbs., respectively. The bars were machined with a V-notch of 45° angle and 0.01-inch radius. Testing was carried out in testing machine which limited the size of the bars to be broken to 2-inch depth of section. The notched bars were mounted on 4-inch centers in the machine and slowly loaded to failure. The depth of notch, the cross-sectional area, and the temperature of testing were variables.

Initial tests were made on 1-inch-square bars, 6 inches in length, with V notches 0.079 inch deep (Figures 10a and 10b). A similar set with depth of bar increased to 2 inches was broken next (Figures 10c and 10d). A third pair of bars with a notch depth of 1/2 inch was then broken (Figures 10e and 10f). The latter notch depth was calculated to give the maximum stress concentration for this size bar (Figure 11).

The differences in breaking loads among the above pairs of steels are not sufficient to separate the two steels.* A pair of bars with a

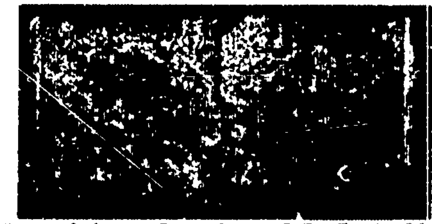
* The slightly higher breaking loads for the steel without aluminum than for the steel with aluminum are only equivalent to the difference in Brinell hardness of the same two steels, Table 3.

Bend Bar Fractures

No Aluminum

a. Breaking load - 16,500 lbs.

Aluminum Treated



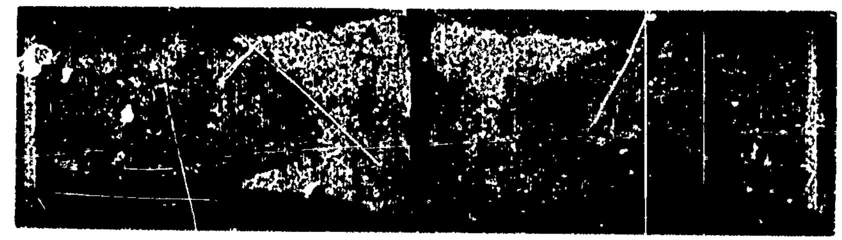
b. Breaking load - 15,700 lbs.

Notch depth 0.08 inch
Bar depth - 1 inch
Bar width - 1 inch

No Aluminum

c. Breaking load - 64,000 lbs.

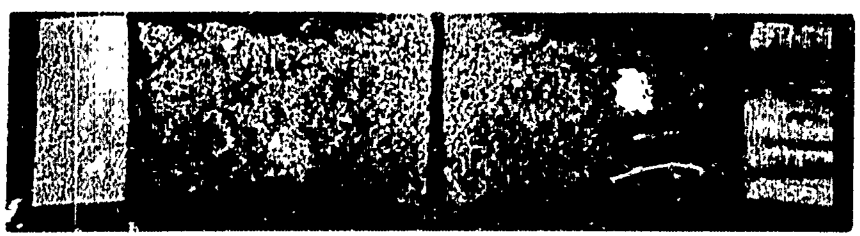
Aluminum Treated



d. Breaking load-60,000 lbs.

Notch depth - 0.08 inch
Bar depth - 2 inches
Bar width - 1 inch

No Aluminum



e. Breaking load - 42,700 lbs.

Aluminum Treated

f. Breaking load - 38,500 lbs.

Notch depth 1/2 inch
Bar depth - 2 inches
Bar width - 1 inch

Figure 10. Fracture photographs and breaking loads of bars tested at room temperature.

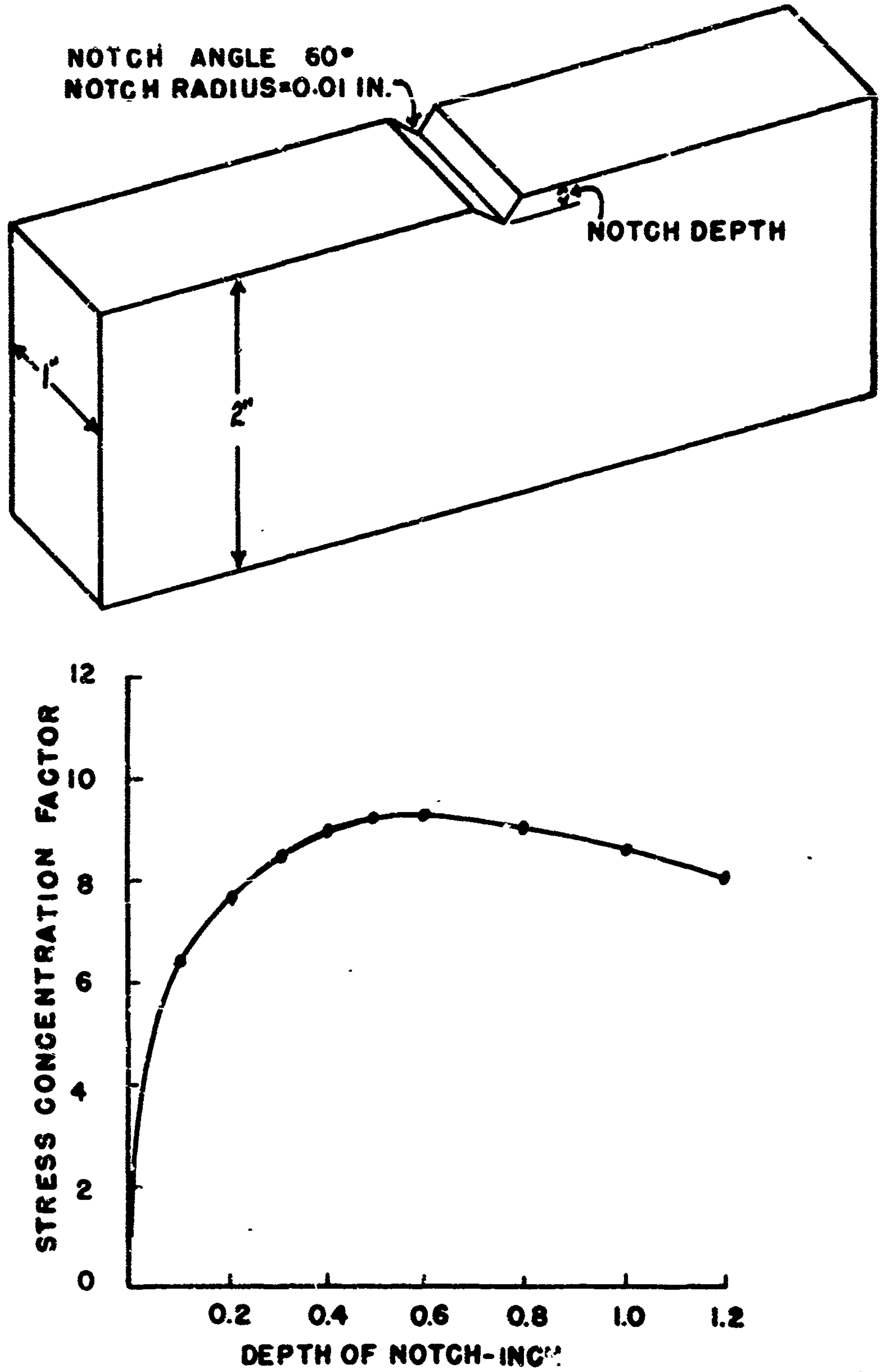


Figure 11. Variation in stress concentration as a function of notch depth for bar of indicated dimensions. (Calculation by L. R. Jackson, Applied Physics Division, Battelle Memorial Institute.)

1-inch-square cross section and a 0.08-inch-deep notch was broken at -40°F., using the arrangement sketched in Figure 12. Fracture photographs and breaking loads are shown in Figure 13. At low testing temperature, the breaking load of steels should increase (as does the Brinell hardness in Table 3), and this was observed for the aluminum-treated steel (compare Figures 10b and 13b), but the steel without aluminum (compare Figures 10a and 13a) shows a falling off in breaking load with decreasing temperature. This falling off may be attributed to its lack of notch toughness.

The two steels could be qualitatively separated by their fracture appearance or manner of breaking. The nonaluminum steel snapped apart when the breaking load of the notched-bend bars was reached in room-temperature tests, while the aluminum-killed steels broke with a ductile fracture under a gradually decreasing load. It would be possible to measure the rate of crack propagation or the energy of breaking calculated from stress-deformation curves of room-temperature, notched-bar bend tests. However, this approach does not appear to offer any particular advantage over the notched-bar impact test.

The falling off in bend load of the notch-sensitive (nonaluminum) steel does provide a demonstration of the danger of using such steels for critical structures.

Wedge-Impact Tests

The Walker wedge test, which has been used in the malleable iron industry as a measure of impact resistance of malleable iron after annealing, was investigated on the suggestion of Mr. E. G. Touceda,

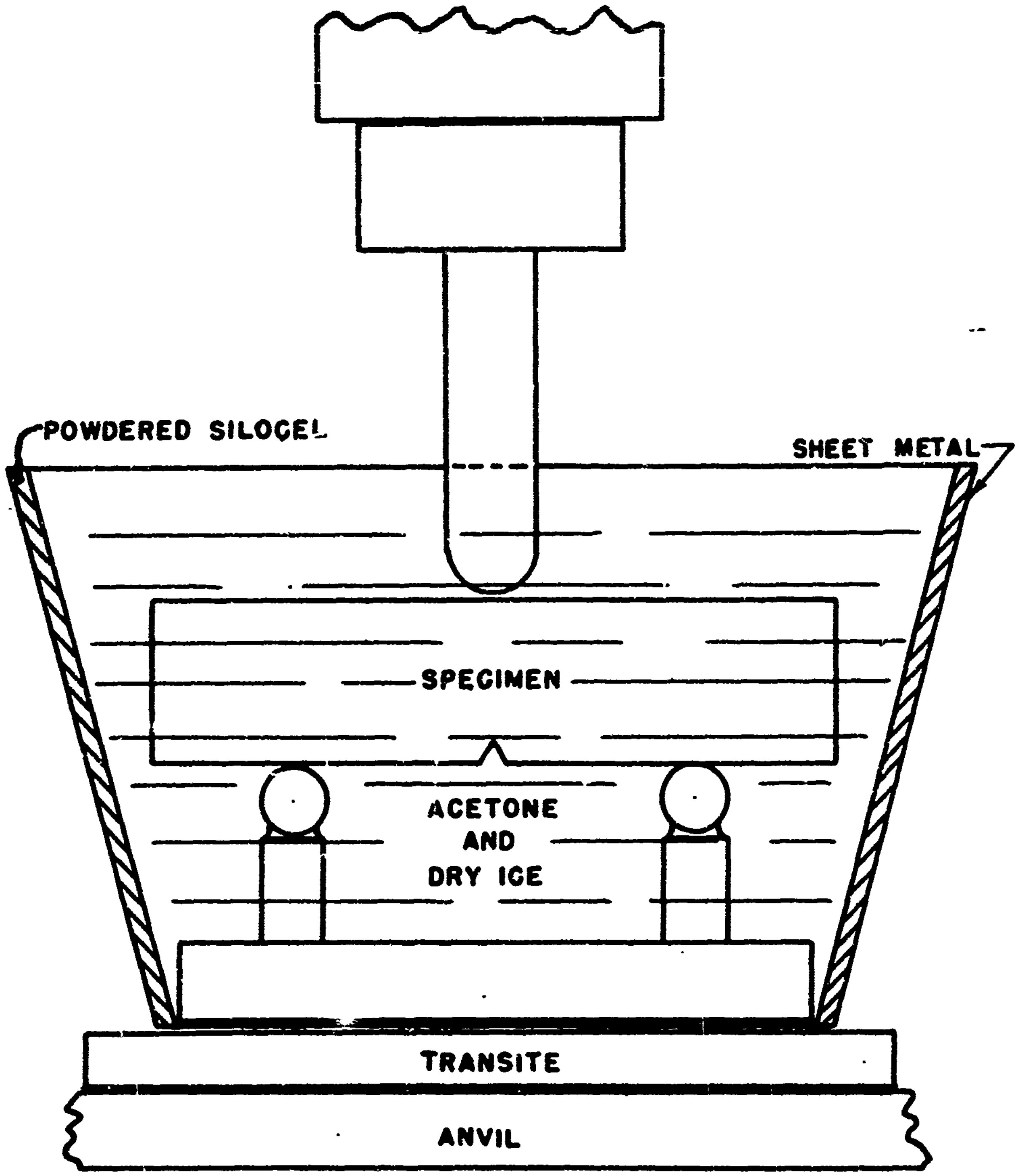
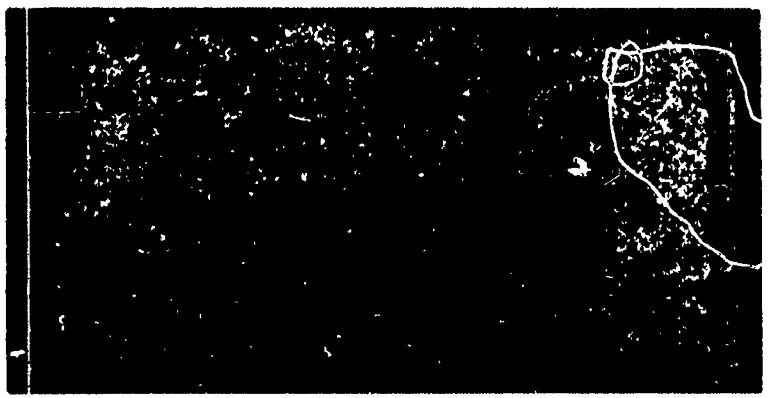


Figure 12. Bath for low-temperature testing of notched bend bars.

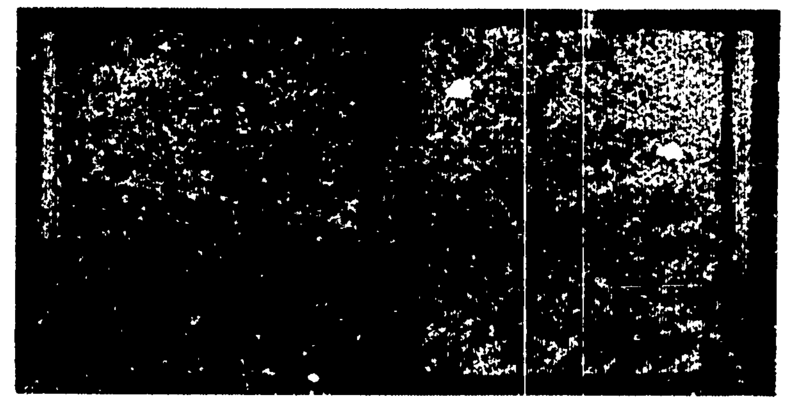
Bend Bar Fractures

Silicon Treated



a. Breaking load - 12,100 lbs.

Aluminum Treated



b. Breaking load - 21,500 lbs.

Notch depth - 0.08 inch
Bar depth - 1 inch
Bar width - 1 inch

Figure 13. Fracture photographs and breaking loads for bars tested at -40°F.

Consultant to the Bureau of Ships, Navy Department. The test is carried out by placing a wedge-shaped specimen in a testing machine and repeatedly dropping a 21-lb. weight on it from a distance of three and one-half feet. The standard size of the test specimen is 1 by 1/2 inch at the base, 1 by 1/16 inch at the top, and 6 inches in length.

Prior to testing, the top of the specimen is bent a small amount to begin the "curl". Succeeding blows with the trip increase the curl. The anvil of the testing machine may be adjusted to shift the specimen laterally so that the trip always falls on the top of the curl.

In order to apply this type of test to hull plate, it would be necessary to establish that the test was capable of separating steels in the same manner as notched-bar impact tests. High-silicon steels, A-2, without aluminum and A-3 with aluminum, were used and wedge specimens were machined from samples of the two steels both in the as-cast condition, where the notched-bar impact resistance was low and did not separate the two steels, and in the 1950°F. normalized condition, where the notched-bar impact resistance of the aluminum-killed steel was markedly superior to that of the steel without aluminum.

The wedge-impact tests were carried out in the laboratory of the Malleable Iron Founders' Society, Cleveland, Ohio. Low-temperature tests were made by immersing the bars in an acetone and dry-ice bath and holding at a temperature 5°F. below the testing temperature for 15 minutes, then quickly transferring the specimen to the testing machine and impacting three times. The specimen was returned to the bath for 5 minutes and the procedure repeated.

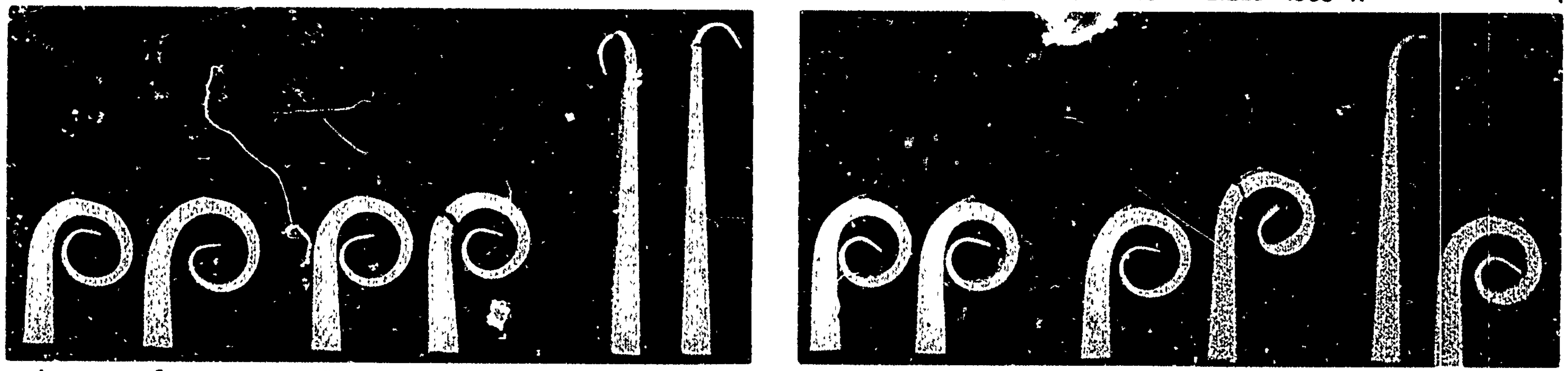
Figure 14 gives test data and shows photographs of the specimens after testing. The as-cast test bars had less resistance to these impact conditions than the normalized test bars, but it was not possible to separate the aluminum-treated steel from the nonaluminum steel and there was considerable scatter in test results. An additional series of wedge-impact specimens is being prepared for testing.

SUMMARY

The problem of developing a fairly simple but reliable method for evaluating the quality of hull plate before the steel is rolled into plate is outlined. Notch sensitivity as judged by notched-bar impact resistance over a suitable range of testing temperatures is taken as a standard of steel quality.

Two series of melts of hull plate-type steels with low silicon (less than 0.12%) and high silicon (0.25% addition to melt) were made, with and without aluminum additions. Sound samples, for test purposes, may be obtained from ingot castings of the high-silicon steel, but the only means thus far found for obtaining sound test specimens from unkilled, low-silicon steel (the major source of hull plate) is to hot work the cast samples.

Charpy V-notch impact values for the high-silicon steels, with and without aluminum, are low and not significantly different. When the same steels are normalized at 1600°F., 1800°F., or 1950°F., the notched-bar impact resistance of the aluminum-treated steel is markedly superior.



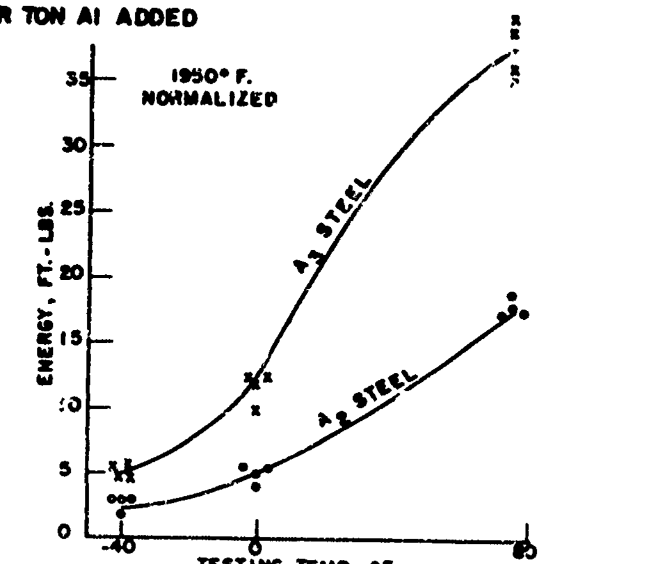
* CURL OF TEST TOUCHED ANVIL OF TESTING MACHINE

STEEL COMPOSITIONS

STEEL	C	Mn	Si	S	P	Al
A_2	.24	.40	.06	.038	.032	NO Al ADDED
A_3	.23	.40	.13	"		3 LBS. PER TON Al ADDED

DATA TABLE

NO.	STEEL	STEEL CONDITION	TESTING TEMP.	NO. BLOWS
1	A_2	AS CAST	75°F.	20*
2	A_3	" "	75°F.	14*
3	A_2	" "	0°F.	18*
4	A_3	" "	0°F.	18*
5	A_2	" "	-10°F.	2
6	A_3	" "	-10°F.	2
7	A_2	1950°F. NORMALIZE	-20°F.	23*
8	A_3	" "	-20°F.	22*
9	A_2	" "	-40°F.	21*
10	A_3	" "	-40°F.	13
11	A_2	" "	-40°F.	3
12	A_3	" "	-40°F.	20*



NOTCH TOUGHNESS CURVES OF STEELS USED IN WEDGE TESTS

FIGURE 14 . WEDGE TEST DATA

TABLE 8. SUMMARY OF METAL TREATMENTS AND RESULTS FOR NOTCH-BAR IMPACT TESTS

			Tested As Cast				Tested After Forging				
					Impact Energy, Ft./Lbs.					Impact Energy, Ft./Lbs.	
Steel*	Al Addition	Cast Into	Heat Treatment, °F.	Tests	75°F.	0°F.	Rolling	Finishing Temperature, °F.	Tests	75°F.	0°F.
A_2	None	165-lb. Ingots	Normalize 1500	V-Notch Charpy	20-24	5-7					
			" 1350	" "	24-26	4-7					
			" 1800	" "	20-22	5					
			" 1950	" "	18-19	4-5					
A_3	1½ lbs./ton	165-lb. Ingots	Normalize 1500	V-Notch Charpy	10-20	5-6					
			" 1650	" "	32-33	7-16					
			" 1800	" "	27-38	8-12					
			" 1950	" "	35-40	10-12					
G	None	100-lb. Ingots	None --	V-Notch Charpy	8-9	4-6	1-inch square	1500	Round Charpy	46-68	16-23
			Normalize 1600	" "	27-30	5-8	to 9/16-inch	1600	" "	43-45	17-17.5
			" 1950	" "	15-21	4-5	square	1800	" "	36-47	9-16
			" 1600	Round Charpy	28-31	10-13	(68.3% red.)	1950	" "	46-44	13-17
H	2 lbs./ton	100-lb. Ingots	None --	V-Notch Charpy	6-11	3-5	1-inch square	1500	Round Charpy	90-91	27-28
			Normalize 1600	" "	47-50	9-12	to 9/16-inch	1600	" "	110+	41-46
			" 1950	" "	25-39	5-6	square	1800	" "	110+	25-30
			" 1600	Round Charpy	39-47	20-15	(68.3% red.)	1950	" "	33-55	9.5-8.5
I	None	Core sand molds 1" dia.					1-inch round	1500	Round Charpy	30-51	12-19
							to 9/16-inch	1600	" "	17-25	11-15
							square	1800	" "	35-33	13-14
							(59.5% red.)	1950	" "	15-23	9-14
J	2 lbs./ton	Core sand molds 1" dia.					1-inch round	1500	Round Charpy	55-73	18-19
							to 9/16-inch	1600	" "	36-83	20-21
							square	1800	" "	20-23	10-15
							(59.5% red.)	1950	" "	16-17	8-12
O	None	-					1-inch round to 9/16-inch	1600	Round Charpy	40-79	15-21
							square (59.5% red.)	1800	" "	35-78	7-10
P	6 lbs./ton	-					1-inch round to 9/16-inch	1600	Round Charpy	83-97	45-50
							square (59.5% red.)	1800	" "	75-108	34-37

* See Table 1 for chemical compositions.

CONCLUSIONS

At present, it is believed possible to evaluate the quality of hull plate steel by casting a 1-inch-round bar, hot rolling to approximately 9/16 inch at a temperature corresponding to the mill practice, strain aging, and testing as round notched-bar impact specimens. This procedure provides sound samples from unkilled steel and introduces the plate-processing variables. Other simpler test methods which may possibly be developed should be shown to be capable of distinguishing between steels variously deoxidized and processed. It appears that as-cast samples do not provide an adequate distinction of notch sensitivity unless normalized or hot worked and prestrained.

FUTURE WORK

Further attempts will be made to obtain sound as-cast samples from unkilled steel. A deoxidation addition which could be made to the sample without changing its notch sensitivity, relative to the rest of the melt, would be suitable, and the influence of small additions of silicon in this respect will be investigated. An attempt will be made to cast sound samples of unkilled steel by centrifuging.

Arrangements are being made with two steel companies to obtain several ladle samples together with samples of finished plate from the same heat for inclusion in the test program.

Further investigation of the wedge-impact test will be carried out in the near future. The investigation of a fatigue-type test at stress levels considerably above the endurance limit is being considered.

The original data from which this report was written are recorded in B.M.I. Notebook, No. 2756, pages 1 to 43, inclusive.

WGNH/SAH/CHL:am
August 11, 1947

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13. ABSTRACT

A simple but reliable method for evaluating the notch sensitivity of hull steel before the steel has been rolled into plate is sought. The notch sensitivity of steel is believed to depend principally on deoxidation practice, temperature of hot rolling, rate of cooling following hot rolling, and susceptibility to strain aging.

At present, no method is known for obtaining sound test smaples in the as-cast condition from low-silicon hull steel. Sound smaples for test purposes may be obtained from ingot castings of steel with relatively high (about .25%) silicon additions. Sound samples were obtained from unkilled low-silicon steel by hot working the cast smaples.

Several series of both the low- and high-silicon steels were made both with and without aluminum deoxidation and tested by standard V-notch Charpy impact tests and by a round Charpy impact bar, which was developed to save maching time and cost.

Notched-bar impact values of the high-silicon steels with or without aluminum deoxidation, are low and not significantly different. A marked superiority of the aluminum-killed steels is apparent when these steels are properly normalized and also when these or the low-silicon steels are hot rolled at proper temperatures. Specimens hot rolled and then subjected to strain-aging show a further decrease in notched-bar impact

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resistance of the nonaluminum as compared with the aluminum-killed steels.

A series of notched-bar tests qualitatively indicated the same trands by fracture appearance and manner of breaking, but no quantitative evaluations were obtained from static bend tests.

On the suggestion of Mr. E.G. To[illegible], a series of wedge-impact tests of the type used by the malleable iron industry were made. Results obtained to date with this test are not conclusive and further work is planned. Future work will also include further attempts to abtain sound as-cast samples from semi-killed steels.

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	ROLE	WT	ROLE	WT	ROLE	WT
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