SERIAL NO. **SSC-91**

FINAL REPORT
(Project SR-110)

on

INVESTIGATION OF THE INFLUENCE OF DEOXIDATION AND CHEMICAL COMPOSITION ON NOTCHED-BAR PROPERTIES OF SHIP PLATE STEELS

by

F. W. BOULGER, R. H. FRAZIER and C. H. LORIG
Battelle Memorial Institute

Transmitted through

NATIONAL RESEARCH COUNCIL'S
COMMITTEE ON SHIP STEEL

Advisory to

SHIP STRUCTURE COMMITTEE

Division of Engineering and Industrial Research
National Academy of Sciences - National Research Council
Washington, D. C.

July 15, 1955

SERIAL NO. **SSC-91**
BuShips Project NS-011-078

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

July 15, 1955

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee has sponsored an investigation of the influence of deoxidation and composition on properties of semikilled steel ship plate at the Battelle Memorial Institute. Herewith is a copy of the Final Report, SSC-91, of the investigation entitled "Investigation of the Influence of Deoxidation and Chemical Composition on Notched-Bar Properties of Ship Plate Steels" by R. H. Frazier, F. W. Boulger and C. H. Lorig.

The project is being conducted with the advisory assistance of the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

Any questions, comments, criticism or other matters pertaining to the report should be addressed to the Secretary, Ship Structure Committee.

This report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K K Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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under

Department of the Navy
Bureau of Ships NObs-53239
BuShips Project No. NS-011-078

for

<u>SHIP STRUCTURE COMMITTEE</u>

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INVESTIGATION OF THE INFLUENCE OF DEOXIDATION AND CHEMICAL COMPOSITION ON NOTCHED-BAR PROPERTIES OF SHIP PLATE STEELS

INTRODUCTION

Late in 1949, on the recommendation of the Committee on Ship Steel of the National Academy of Sciences-National Research Council, the Ship Structure Committee established Project SR-110 to investigate the effects of variations in composition on the fracture characteristics of ship plate steel. An Advisory Committee was appointed by the Committee on Ship Steel to guide the study and review the findings.

This report summarizes the results of the investigation which included studies on approximately 400 steels. In order to condense the information, references are made to progress reports(1-9) containing original data supporting conclusions drawn in this report. Some technical articles based on these reports have been published.(12-15,30)

The majority of the data was obtained on steels made in 200-lb. melts and processed in the laboratory. All of the laboratory heats were made in an induction furnace using standardized melting practices. Unless otherwise noted, they were rolled to 3/4-in. plate using a finishing temperature of 1850 F. Two base compositions for semikilled steels were investigated. One was similar to ABS Grade B steel in composition (Type B heats). The other was similar to ABS Grade A steel (Type A heats) and resembled the ship steel used during World War II.

The effects of carbon, manganese, phosphorus, nitrogen, and sulfur were investigated on semikilled steels. Silicon and aluminum were the principal deoxidizers studied. The investigation of composition was supplemented by limited studies of the effects of hot working and cooling variables on notched-bar properties and fracture characteristics of ship plate steel.

The effects of variations in composition and deoxidation practice were evaluated by tensile and notched-bar tests. Particular importance was attached to transition temperatures measured by keyhole Charpy and Navy tear tests(19). The transition temperature of a steel is a temperature in the range within which the type of failure for a part or specimen of the steel changes from one that is ductile to one that is brittle. It is well established(16,18) that the transition temperatures obtained with notched-bar specimens classify ship plate steels used during World War II in accordance with the service histories of ships. Steels which otherwise meet ship steel requirements but which have the lower transition temperatures are preferred.

The transition temperature of a steel varies with testing conditions and the criterion chosen for defining it. In this study, the criterion for the keyhole Charpy transition temperature was taken as the temperature where the average energy value was either 12 or 20 ft-lb. By using either energy level, the same general conclusions regarding the ductile to brittle behavior of the steels were obtained. The 12 ft-lb transition temperature criterion was, however, more discriminating for steels which broke with comparatively little deformation at room temperature.

Navy tear test specimens which developed a fracture area with less than 50 per cent fibrous texture were classified as brittle. The transition temperature in the tear test was usually taken as the temperature where the probability of brittle fracture was the same as the probability of ductile fracture.

According to the terms used by Vanderbeck and Gensamer(28), the tear test measured a fracture transition and the Charpy test measured a ductility transition. In either case, the specimens absorbed considerably less breaking energy in tests below the transition temperature than in tests above the transition temperature.

RELIABILITY OF DATA FROM LABORATORY MELTS

The success of the investigation depended to a large extent on controlling laboratory melting and rolling conditions closely so that steels made at different periods would be comparable. This was necessary so that differences noted in properties could be attributed to the composition and processing variables being studied. Table 1 shows that the compositions and properties of control heats were in good agreement even though they were made at intervals over a four-year period. The standard deviations for data on steels

TABLE 1. REPRODUCIBILITY OF COMPOSITION, TENSILE, AND NOTCHED-BAR PROPERTIES* OF SEMIKILLED HOT-ROLLED STEELS MADE AND PROCESSED IN THE LABORATORY

	Type A Heats		Type B Heats	
	No. of Heats	Value	No. of Heats	Value
Carbon, per cent	11	0.22 ± 0.01	9	0.20 ± 0.02
Manganese, per cent	11	0.45 ± 0.02	9	0.76 ± 0.03
Phosphorus, per cent	11	0.015 ± 0.002	9	0.015 ± 0.002
Silicon, per cent	11	0.04 ± 0.01	9	0.05 ± 0.02
Nitrogen, per cent	11	0.004 ± 0.0005	9	0.004 ± 0.0005
Sulfur, per cent	11	0.026 ± 0.002	9	0.025 ± 0.002
Tensile strength, psi	10	61,180 ± 1240	8	62,350 ± 664
Upper yield point, psi	10	36,400 ± 1230	8	36,300 ± 750
Lower yield point, psi	10	34,800 ± 665	8	35,300 ± 575
Elong. in 8", per cent	10	29.0 ± 2.2	8	28.5 ± 2.2
Keyhole Charpy, 20 ft-lb transition temperature	10	21 ± 13.6 F	8	-15 ± 8.0 F
Tear-test transition temp, 10 F below temp where 4 specimens were ductile	10	80 ± 13.7 F	8	70 ± 7.1
Where p of brittle fracture = 0.5	8	73 ± 8 F	8	60 ± 8 F

*Data are shown as averages plus or minus the standard deviation. Subject discussed in greater detail in References 5 and 1.

intended to be alike are small, approaching the limits set by analytical and testing techniques. The data show that the compositions and mechanical properties could be reproduced consistently.

It was also vital to produce laboratory steels with properties matching those of commercial semikilled steels. Some of the evidence showing that the properties of the laboratory plates agree with those of commercial ship plate is presented in Table 2. This

TABLE 2. COMPARISON OF AVERAGE TENSILE AND NOTCHED-BAR PROPERTIES OF LABORATORY* AND COMMERCIAL** 3/4-IN. SEMIKILLED STEEL PLANTS

Property	Commercial	Laboratory
Type A Steels (Mn = 0.40/0.60 %)		
Yield point, psi	37,460	36,400
Ultimate strength, psi	64,000	61,180
Elongation in 8 in., per cent	27.8	29.0
Keyhole Charpy transition (20 ft-lb level)	16 F	21 F
Type B Steels (Mn = 0.60/0.90 %)		
Yield point, psi	36,650	36,275
Ultimate strength, psi	62,315	62,350
Elongation in 8 in., per cent	30.5	28.5
Keyhole Charpy transition (20 ft-lb level)	-5 F	-15 F

*Data for laboratory steels from Table 1.

**Tensile data for commercial steels based on 24 ABS Grade A and 20 ABS Grade B 3/4-in. plates reported by Epstein, Reference 21.

Keyhole Charpy transition temperature data for commercial steels based on 43 ABS Grade A and 46 ABS Grade B 3/4-in. plates, Reference 21.

table compares the average tensile properties and Charpy transition temperatures of the control heats with averages for some commercial 3/4-in. ship plate. In making such comparisons, it must be recognized, of course, that a particular grade of steel is characterized by a range in mechanical properties and transition temperatures. The averages indicate the magnitude of typical values.

INFLUENCE OF COMPOSITION ON PROPERTIES OF SEMIKILLED STEELS

Carbon and Manganese. Because of the importance of carbon and manganese, these elements were varied independently in a series of 25 heats(1,2,4,13). Some of the data obtained from these heats are presented in Table 3. They show that as the carbon content is

TABLE 3. EFFECT OF CARBON AND MANGANESE ON KEYHOLE CHARPY VALUES IN FT-LB FOR SEMIKILLED HOT-ROLLED STEELS TESTED AT 80 F*

Manganese Content, per cent	Carbon Content, per cent				
	0.14/0.17	0.18/0.20	0.21/0.25	0.26/0.28	0.31/0.34
0.20/0.25	44	33	28	23	19
0.40/0.50	38	36	32	24	20
0.65/0.85	55	38	38	28	24
0.86/1.05	--	42	--	31	30
1.06/1.25	57	56	--	--	--
1.26/1.50	--	50	46	--	34

*Values are averages for four specimens. Samples were taken from 3/4-in. plates rolled at 1850 F from laboratory heats.

raised the energy absorbed in Charpy keyhole specimens tested at 80 F decreases, whereas raising the manganese content increases the energy absorption.

The effect of these elements on the transition temperatures is demonstrated in Table 4, which illustrates the fact that carbon raises and manganese lowers the Charpy transition temperature. Multiple-correlation analyses of the data obtained on the series of 25 laboratory steels resulted in the formulas listed in Table 5. These equations summarize the information obtained on the effects of carbon and manganese and put it in quantitative form. Calculations

TABLE 4. EFFECT OF CARBON AND MANGANESE ON 20 FT-LB KEYHOLE CHARPY TRANSITION TEMPERATURES FOR HOT-ROLLED SEMIKILLED STEELS*

Manganese Content, per cent	Carbon Content, per cent				
	0.14/0.17	0.18/0.20	0.21/0.25	0.26/0.28	0.31/0.34
0.20/0.25	21 F	26 F	36 F	67 F	90 F
0.40/0.50	10 F	12 F	21 F	61 F	75 F
0.65/0.85	-24 F	-15 F	-11 F	22 F	19 F
0.86/1.05	--	-23 F	--	-9	16 F
1.06/1.25	-41 F	-38 F	--	--	--
1.26/1.50	--	-38 F	-29 F	--	34 F

*Values determined by testing 20 specimens taken from 3/4-in. plates rolled at 1850 F from laboratory heats.

TABLE 5. EQUATIONS FOR CALCULATING THE EFFECTS OF CARBON AND MANGANESE ON THE PROPERTIES OF HOT-ROLLED SEMIKILLED STEELS FINISH ROLLED AT 1850 F IN THE LABORATORY.

Average Ferrite Grain Size of ASTM Number 7.4

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1. Upper Yield Point, psi $= 23{,}000 + (39{,}200 \times \%\ C) + (7200 \times \%\ Mn)$
   Standard Error of Estimate $= 1500$ psi
2. Lower Yield Point, psi $= 20{,}700 + (39{,}800 \times \%\ C) + (8400 \times \%\ Mn)$
   Standard Error of Estimate $= 1300$ psi
3. Tensile Strength, psi $= 30{,}800 + (104{,}000 \times \%\ C) + (13{,}000 \times \%\ Mn)$
   Standard Error of Estimate $= 2200$ psi
4. Elongation in 8 in., $\% = 38.2 - (32.6 \times \%\ C) - (3.2 \times \%\ Mn)$
   Standard Error of Estimate $= 2.4\%$ elongation
5. Tear Test Transition Temperature, F
   (For 1 of 4 brittle) $= 17 + (330 \times \%\ C) - (23 \times \%\ Mn)$
   Standard Error of Estimate $= 10$ F
6. Tear Test Transition Temperature, F:
   (For Probability of Brittle fracture $= 0.5$) $= -7 + (386 \times \%\ C) - (18 \times \%\ Mn)$
   Standard Error of Estimate $= 9$ F
7. Keyhole Charpy Transition Temperature, F:
   (For 12 ft-lb level) $= -15 + (225 \times \%\ C) - (68 \times \%\ Mn)$
   Standard Error of Estimate $= 12$ F
8. *Keyhole Charpy Transition Temperature, F:
   (For 20 ft-lb level) $= K - 19 + (349 \times \%\ C) - (74 \times \%\ Mn)$
   Standard Error of Estimate $= 10$ F

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*The factor "K" in Equation [8] varies with the manganese level as follows:

% Mn	K
0.20	+6F
0.40	+1F
0.60	-3F

% Mn	K
0.80	-8F
1.00	-5F
1.20	+2F

based on these formulas agreed quite well with experimental data for other laboratory steels rolled to 3/4-in. plates. For instance, the differences in average transition temperatures resulting from the differences in average compositions of the A and B steels listed in Table 1 are:

Test Specimen	Criterion for Transition Temperature	Calculated Difference	Experimental Difference
Keyhole Charpy	12 ft-lb	25 F	--
	20 ft-lb	37 F	36 F
Tear Test	(Probability of brittle fracture = 0.5)	13 F	13 F
	1 brittle out of 4	13 F	10 F

These and other checks indicated that the formulas develop adequately the relation among transition temperature, carbon, and manganese within the range of compositions covered by this investigation.

The formula in Table 5 for tensile strength gives good agreement with results developed from data for commercial steels(20). This is additional confirmation that the laboratory semikilled steels had properties matching those of commercial plates.

Fig. 1 illustrates the effect of carbon on the tensile strengths and transition temperatures of laboratory steels containing 0.05 per cent silicon and hot rolled at 1850 F. The chart is based on data for experimental steels after correcting to a common manganese content of 0.75 per cent. The points show moving averages* for groups

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*The moving average, as used for Figures 1 and 2, is a device for obtaining a series of figures which indicate the trend of data better than individual observations because fluctuations in the individual readings are averaged out in the calculations. The process can be illustrated for hypothetical observations forming the Series 2,6,4,7, 8,6,9; the moving averages for groups of three are 4.0, 5.7, 6.3, 7.0, and 7.7.

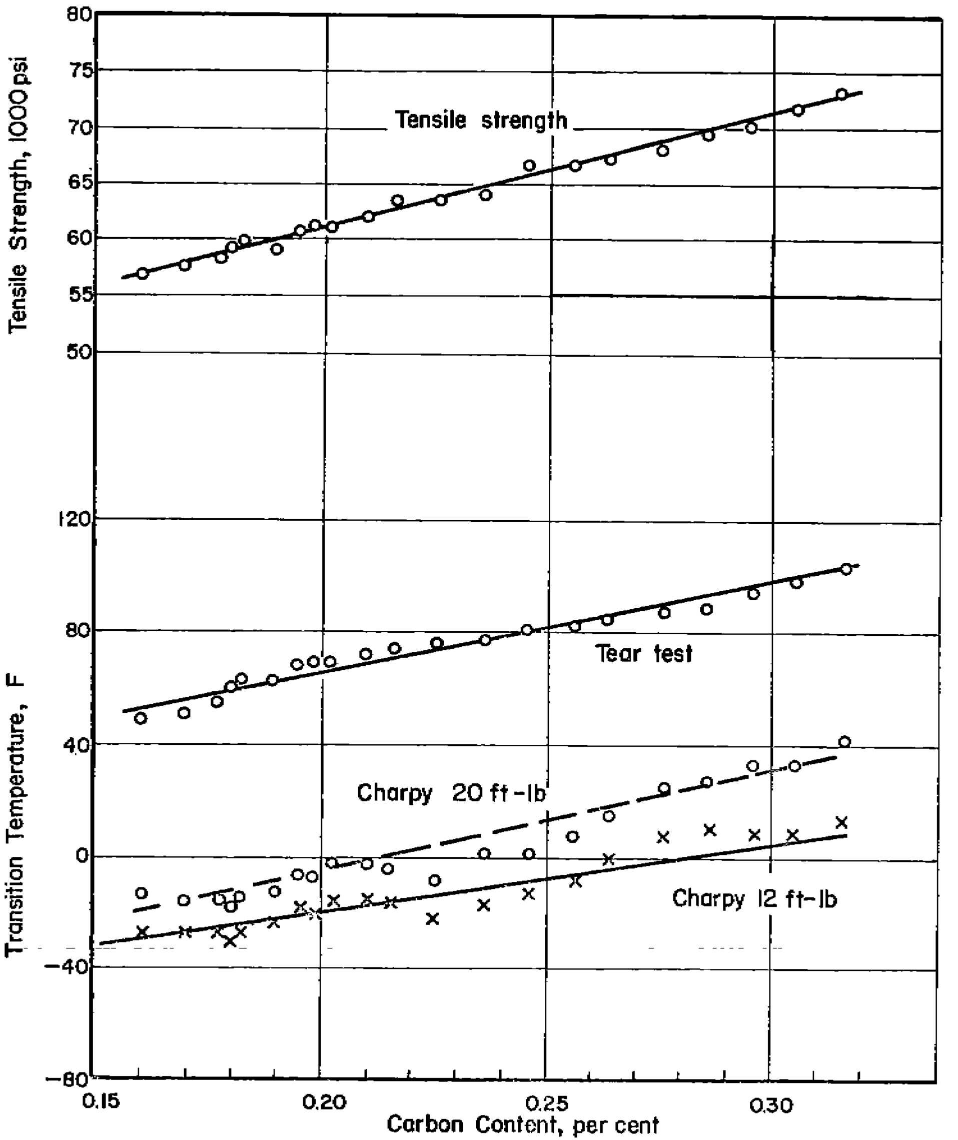

FIGURE 1. INFLUENCE OF CARBON ON PROPERTIES OF HOT-ROLLED SEMIKILLED STEELS MADE AND PROCESSED IN THE LABORATORY

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POINTS REPRESENT MOVING AVERAGES OF FIVE MEASURED VALUES CORRECTED TO 0.75% MANGANESE.

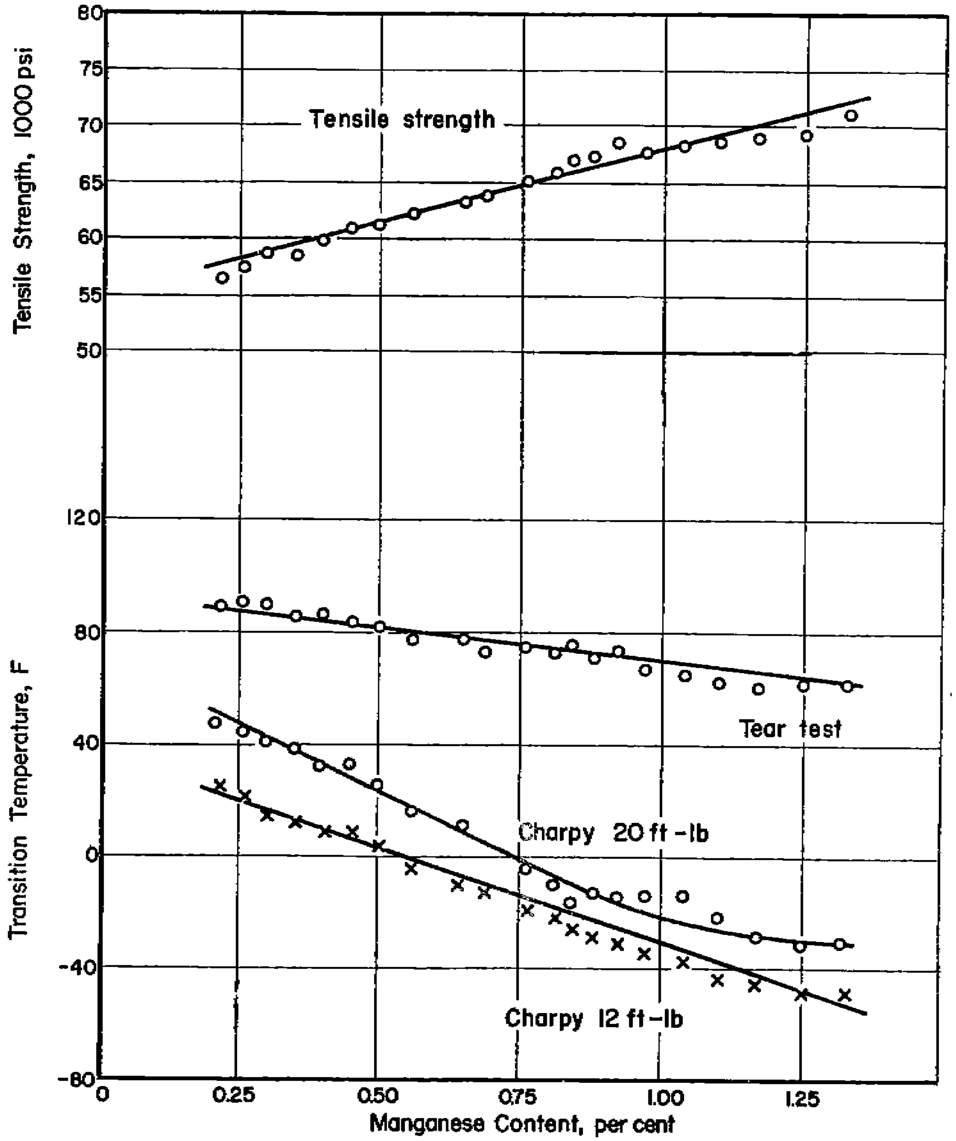


FIGURE 2. INFLUENCE OF MANGANESE ON PROPERTIES OF HOT-ROLLED SEMIKILLED STEELS MADE AND PROCESSED IN THE LABORATORY

A-14559

POINTS REPRESENT MOVING AVERAGES OF FIVE MEASURED VALUES CORRECTED TO 0.23% CARBON.

of five steels after the data were arranged in increasing order of carbon contents. The trend lines were obtained from the formulas given in Table 5. All of the points are close to the trend lines because they are averages for observations on five steels. The close fit at all locations indicates that the equations hold equally well over the range of carbon contents investigated.

Fig. 2 is a similar chart (see note on page 9) showing the influence of manganese on the strengths and notched-bar transition temperatures of the hot rolled experimental steels. To show the effect of manganese, the experimental data were adjusted by the factors given in Table 5 to a common carbon content of 0.23 per cent. The chart shows the effects of manganese in raising the strength and lowering the transition temperature. The data for the 20 ft-lb Charpy transition temperature give some evidence that the effect of manganese in lowering the transition temperature becomes less at higher manganese levels. Above about 0.80 per cent manganese, the relationship differs enough from a straight line to justify the inclusion of the factor "K" in Equation[8]of Table 5. The change in transition temperatures for each unit of manganese using the other two criteria also becomes less pronounced at high manganese levels. The effect is less marked, however, so less complicated equations are used in Table 5 to show the influence of manganese on the tear test and 12 ft-lb Charpy transition temperatures.

It was concluded that the equations in Table 5 gave reliable estimates of the effects of carbon and manganese. Therefore, the factors were used to correct for unintentional variations in carbon and manganese contents when other variables were under study. Transition temperatures were adjusted by the formulas when carbon and manganese varied less than 0.03 or 0.10 per cent, respectively, from the intended amounts. Steels, with actual analyses differing by more than these amounts from the level desired in a series, were remade.

The formulas indicate that replacing 0.01 per cent carbon with sufficient manganese to maintain the same tensile strength lowers the Charpy transition temperature about 10 F. The comparable change in transition temperature for tear tests is about 5 F. The laboratory data confirm the experience that increasing the manganese content and lowering the carbon content by going from ABS Class A steel to ABS Class B steel improved the toughness of semikilled ship plate. That is, for equal tensile strengths, semikilled steels with higher manganese-carbon ratios usually have lower notched-bar transition temperatures.

Although transition temperature data indicate that steels with lower carbon contents or strengths offer advantages, some metallurgists questioned whether brittle cracks might not propagate at lower stresses in such materials. Information on the stresses which can initiate and propagate a rapidly spreading crack is meager. Even less is known about the effect of composition on brittle strength.

To add to this knowledge, the effect of lowering the carbon content and strength was investigated using the Standard Oil Development (SOD) Test(29,30). In this test, the stress necessary to produce a brittle fracture is measured in a notched tensile test on a plate sample. In carrying out this test, a test plate with a crack at one edge is cooled to the testing temperature and loaded in tension. A chisel is then driven into the crack with an impact gun. If the tensile load is above a critical value, the plate breaks with a brittle fracture. If the load is less than critical, the crack progresses only a short distance. In that case, the test is repeated using a higher tensile load.

The data obtained from four plates tested by the Standard Oil Development Company are shown in Table 6. The tensile properties and notched-bar transition temperatures of these steels are listed in Table 11, page 36. All plates were tested at -50 F, which is well below the transition temperature in the SOD test. The results obtained on the second specimen of each steel are considered most reliable and seem to determine the critical stress required for producing a brittle fracture to within about 1000 psi. The data suggest that the manganese content of the steel has little influence on this stress value even though manganese lowers the transition temperature. On the other hand, lowering the carbon content may increase the stress necessary for producing a brittle fracture in this test.

TABLE 6. EFFECT OF CARBON AND MANGANESE ON NOMINAL STRESS FOR BRITTLE FRACTURE IN "SOD" NOTCHED-TENSILE TESTS ON 3/4 IN. SEMIKILLED STEEL PLATES TESTED AT -50 F*

Heat No.	Test No.	Carbon, %	Manganese, %	Tensile Stress, psi	
				No Fracture	Brittle Frac.
B 801	1	0.15	0.45	8,800	10,500
	2			10,000	11,000
B 803	1	0.25	0.42	7,000	8,000
	2			8,000	8,500
B 802	1	0.16	0.77	9,000	10,000
	2			10,500	11,000
B 804	1	0.21	0.74	8,000	9,500
	2			9,500	10,000

*Testing procedures are described in detail in Reference 29.

These few notched tensile tests support the opinion based on transition temperature data that semikilled ship plate can be improved by lowering the carbon content. Lowering the carbon without raising the manganese content would lower the tensile strength below the requirements of present specifications. Whether or not lower tensile strengths would necessitate design changes would have to be evaluated by naval architects.

<u>Phosphorus</u>, <u>Sulfur</u>, <u>and</u> <u>Nitrogen</u>. ABS specifications for hull plate steel state that the phosphorus content of hull plate shall be less than 0.040 per cent. In the present study, the effect of increasing the phosphorus content of semikilled steel plate

from 0.01 to 0.06 per cent was determined. Data obtained from eight steels(1,2) indicate that each increase of 0.01 per cent phosphorus produces the following effects:

Raises the 20 ft-lb Charpy transition temperature ..8 F

Raises the tear test transition temperature ....11 F

Raises the ultimate tensile strength ....1700 psi

The possibility of producing a better steel by substituting phosphorus for carbon was considered. However, replacing carbon with phosphorus while maintaining a constant tensile strength raises the transition temperature. It was established that the transition temperature for a steel containing 0.13 per cent carbon and 0.10 per cent phosphorus(2) was higher than would be expected for a steel of normal phosphorus content and of equal tensile strength. Similarly, low-carbon, high-phosphorus steels with 0.02 per cent vanadium or 0.06 per cent molybdenum did not exhibit promising low-temperature notched-bar properties(2).

The ABS specification for hull plate steel requires that the sulfur content be less than 0.050 per cent. Data on steels containing from 0.023 to 0.050 per cent sulfur but otherwise of the same composition showed sulfur to have no effect on either the Charpy or tear test transition temperatures(1).

The nitrogen content of most basic open-hearth steels is approximately 0.003 to 0.005 per cent. Other methods of making steel can give nitrogen contents much higher than 0.005 per cent.

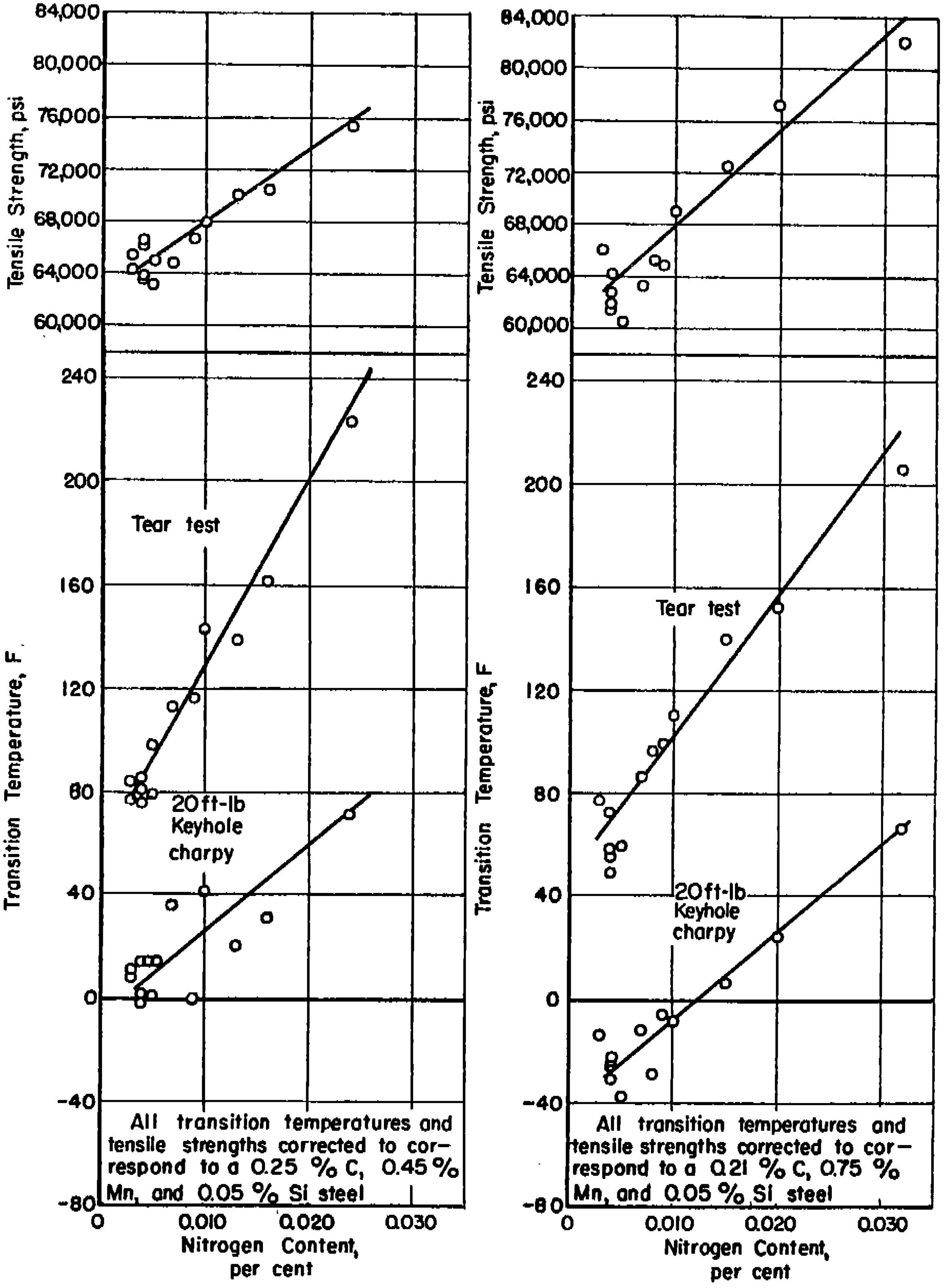
Therefore, it was pertinent to determine the influence of nitrogen on the properties of semikilled steels(2). Fig. 3 shows the effects of nitrogen on tensile strength and transition temperatures of 3/4-in. plate.

The transition temperature data indicate that the tear test is more sensitive than the Charpy test to changes in nitrogen content. Fig. 3 shows that each increase of 0.005 per cent nitrogen has the following effects:

	In Steels With 0.45% Mn	In Steels With 0.75% Mn
Raises the 20 ft-lb Charpy transition temperature	16 F	18 F
Raises the tear test transition temperature	35 F	28 F
Raises the ultimate tensile strength	2900 psi	3900 psi

There is little doubt that low nitrogen contents are desirable for good notched-bar properties. The data show that if the carbon content were reduced to maintain a constant tensile strength, the harmful effects of nitrogen would be less marked in steels with the higher manganese contents. These data also indicate that nitrogen has a more pronounced strengthening effect on steels with higher manganese contents.

Silicon. Many of the experimental steels used to study the effects of silicon and aluminum would be classified as killed steels.



All transition temperatures and tensile strengths corrected to correspond to a 0.25 % C, 0.45 % Mn, and 0.05 % Si steel

All transition temperatures and tensile strengths corrected to correspond to a 0.21 % C, 0.75 % Mn, and 0.05 % Si steel

FIGURE 3. INFLUENCE OF NITROGEN ON TENSILE STRENGTH AND NOTCHED-BAR PROPERTIES OF SEMIKILLED STEELS

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Semikilled steels usually contain about 0.05 per cent silicon and less than 0.01 per cent aluminum. The presence of sufficient quantities of silicon or aluminum produces a strongly deoxidized or killed steel. Killed ingots are characterized by a shrinkage cavity or pipe. As a consequence, killed steel is usually made in hot-top molds, and this practice results in lower ingot yields and production rates.

To determine the effect of variations in silicon content, 57 laboratory steels with silicon contents up to 0.54 per cent were processed and tested(6). The five types of steels listed at the top of Table 7 were studied in this investigation.

The silicon content of the steel plate did not change the ferrite grain size or microstructure when the plates were finish rolled at 1850 F and air cooled. The average ferrite grain size was 7.3 on the ASTM scale.

Each increase of 0.01 per cent silicon raised the tensile strength about 155 psi. Within the ranges investigated, silicon had no effect on the elongation values in tensile tests.

Silicon had no appreciable effect on the room-temperature notched-bar properties. It did, however, affect the transition temperatures, as shown in Figs. 4 and 5. Fig. 6 presents some supplementary data obtained on a few steels with other manganese contents. The transition temperatures for each steel were corrected for small unintentional differences in carbon or manganese content.

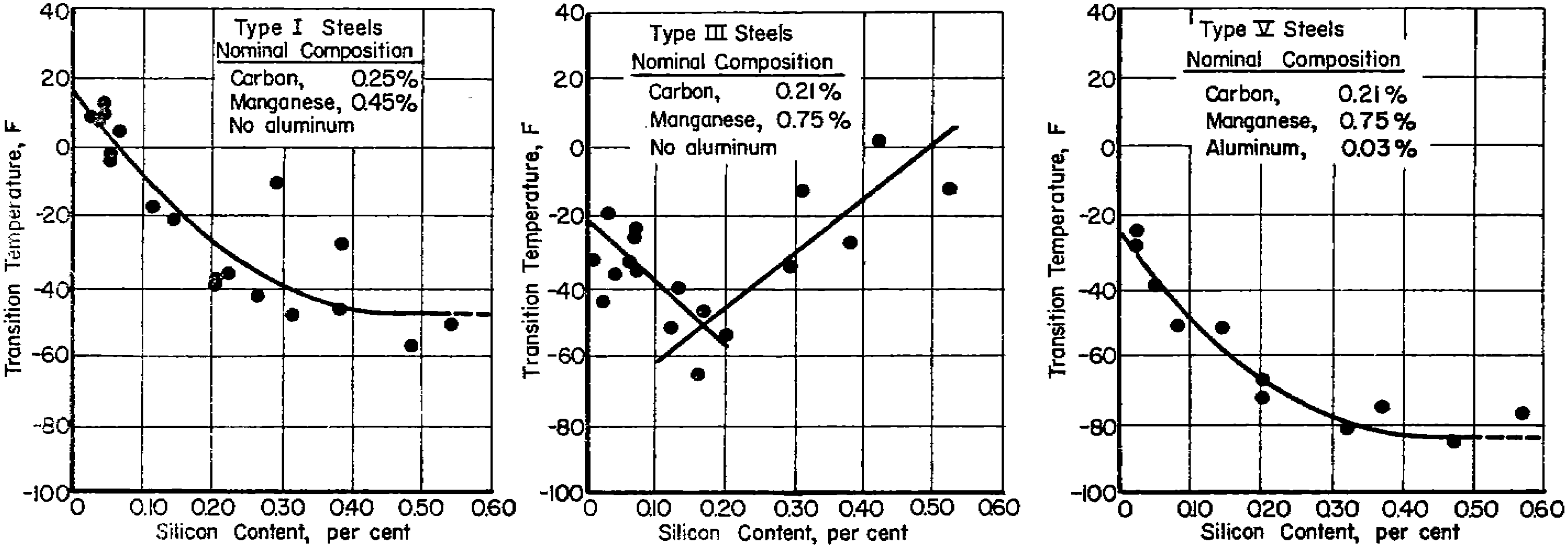


FIGURE 4. INFLUENCE OF SILICON ON THE 12-FOOT-POUND KEYHOLE CHARPY TRANSITION TEMPERATURES OF THREE TYPES OF STEEL

All transition temperatures corrected to correspond to the nominal composition of each steel.

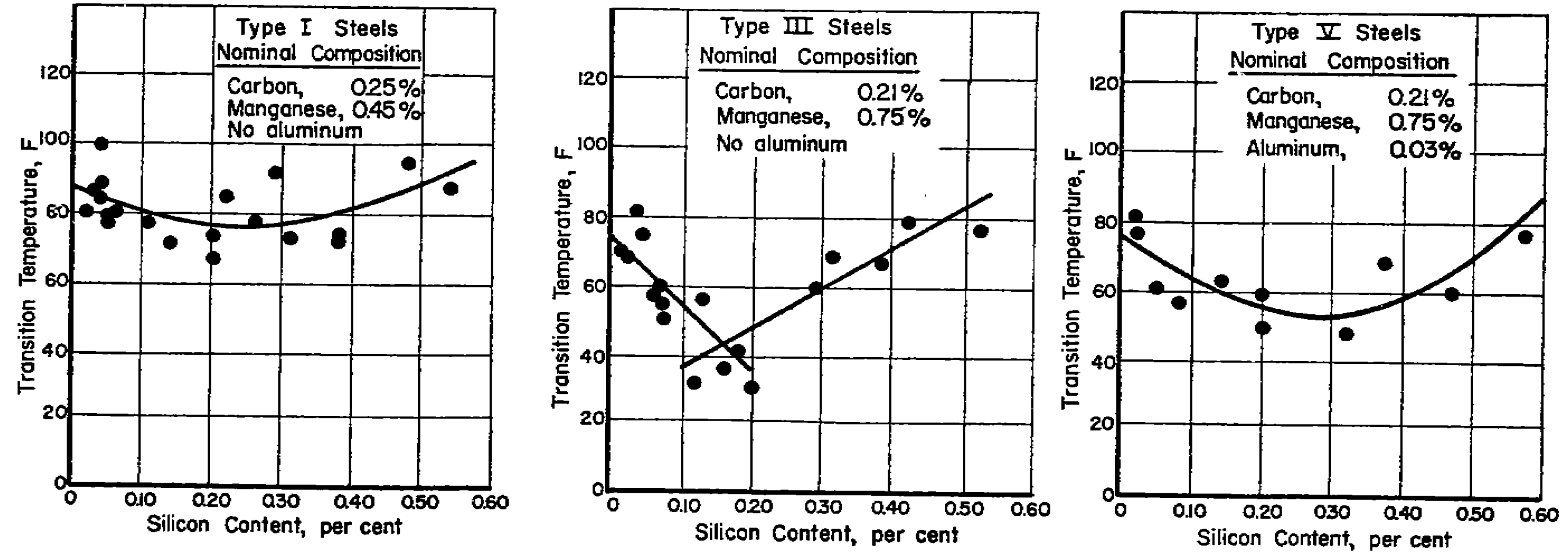
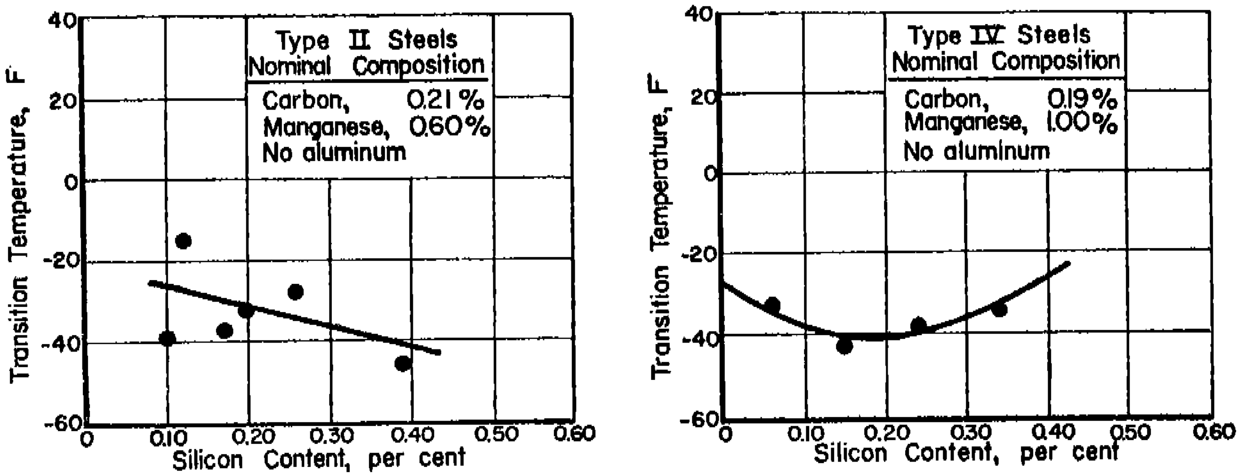
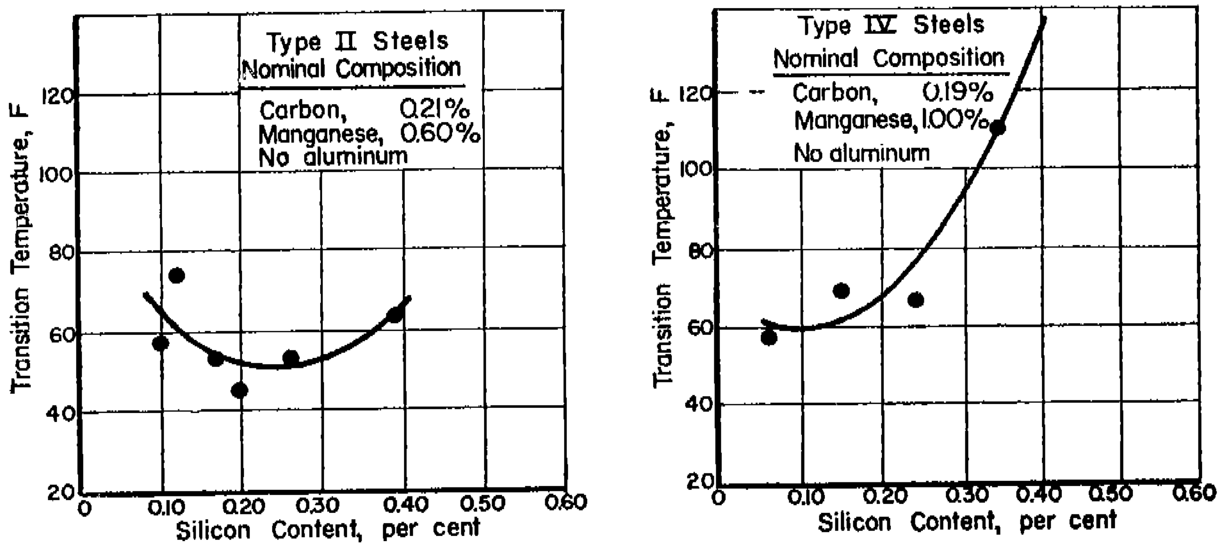


FIGURE 5. INFLUENCE OF SILICON ON P=0.5 TEAR-TEST TRANSITION TEMPERATURES OF THREE TYPES OF STEEL

All transition temperatures corrected to correspond to the nominal composition of each steel.



a. 12 Ft-Lb Keyhole Charpy Transition Temperatures



b. Tear-Test Transition Temperatures

FIGURE 6. EFFECT OF SILICON ON TRANSITION TEMPERATURES OF TWO KINDS OF ALUMINUM-FREE STEEL

A-14562

TABLE 7. NOMINAL COMPOSITIONS OF STEELS USED FOR THE STUDIES ON THE EFFECTS OF SILICON AND ALUMINUM

Type of Steel	No. of Heats	Chemical Composition, per cent			
		C	Mn	Al	Si
I	20	0.25	0.45	Nil	0.02/0.54
II	6	0.21	0.60	"	0.10/0.39
III	18	0.21	0.75	"	0.01/0.52
IV	4	0.19	1.00	"	0.06/0.34
V	9	0.21	0.75	0.03	0.02/0.57
VI	10	0.25	0.45	0/0.13	0.01
VII	12	0.25	0.45	0/0.21	0.05
VIII	6	0.25	0.45	0/0.26	0.10
IX	5	0.21	0.75	0/0.06	0.01
X	11	0.21	0.75	0/0.19	0.05
XI	7	0.21	0.75	0/0.27	0.10

Data from each group with comparable base composition were used for multiple-correlation analyses. The trend lines were obtained by accepted mathematical procedures. The choice of plotting curved or straight lines from the data was made on the basis of best fit and least standard error. The types of curves tried were arbitrarily limited to one straight line, two straight lines, or a second order curve.

Increasing the silicon content in the range from 0.01 to about 0.20 per cent lowered the transition temperature as determined by both types of tests. The effect of increasing the silicon content above 0.20 per cent on transition temperature depended on the carbon and manganese contents of the steel and the type of test.

Fig. 4 shows the results obtained on Type B steels with 0.03 per cent aluminum. The data indicate that this amount of aluminum does not have a significant effect when the silicon content is under 0.20 per cent but lowers the transition temperature of the steels with higher silicon.

Some of the formulas obtained by multiple-correlation analysis of data from the silicon series are given in Table 8. For the aluminum-free steels with 0.21 per cent carbon and 0.75 per cent manganese, i.e., Type III, each increase of 0.01 per cent silicon up to 0.20 per cent lowered the transition temperature about 1.9 F in both the Charpy and tear tests. For the Types I and V steels, the reduction was more marked in the Charpy tests and averaged about 2.3 F. Thus, it appears that increasing the silicon content of semikilled steels by 0.01 per cent will decrease the transition temperature an average of 2 F. Commercial ship plate steels have an average silicon content of about 0.05 per cent(21,25). Some benefits could be gained if the average silicon content could be raised without introducing difficulties in producing steels of semikilled grades.

TABLE 8. EQUATIONS FOR CALCULATING THE EFFECTS OF SILICON IN THE RANGE FROM 0.01 TO 0.2 PER CENT ON THE PROPERTIES OF HOT-ROLLED STEELS*

Type of Steel	Base Composition, % C	Mn	Al	Equation	Standard Error
I	0.25	0.45	--	Yield Point, psi = 36,701 + 6,389 x % Si	1,579 psi
III	0.21	0.75	--	" " " = 36,313 + 11,217 x % Si	1,258 psi
V	0.21	0.75	0.03	" " " = 36,233 + 13,475 x % Si	698 psi
I	0.25	0.45	--	Tensile Strength, psi = 63,464 + 15,311 x % Si	1,385 psi
III	0.21	0.75	--	" " " = 62,476 + 16,624 x % Si	1,497 psi
V	0.21	0.75	0.03	" " " = 62,964 + 15,637 x % Si	920 psi
				<u>Keyhole Charpy Transition Temperature</u>	
I	0.25	0.45	--	20 ft-lb CTT, F = 37 - (263 x % Si) + 333 $(\% \text{ Si})^2$	11.1 F
III	0.21	0.75	--	20 ft-lb CTT, F = -7 - (158 x % Si)	9.0 F
V	0.21	0.75	0.03	20 ft-lb CTT, F = -8 - (308 x % Si) + 429 $(\% \text{ Si})^2$	5.7 F
I	0.25	0.45	--	12 ft-lb CTT, F = 16 - (274 x % Si) + 296 $(\% \text{ Si})^2$	10.6 F
III	0.21	0.75	--	12 ft-lb CTT, F = -21 -(183 x % Si)	9.0 F
V	0.21	0.75	0.03	12 ft-lb CTT, F = -25 -(284 x % Si) + 335 $(\% \text{ Si})^2$	4.9 F
				<u>Tear Test Transition Temperature</u>	
I	0.25	0.45	--	p = 0.5 TTTT = 88 - (93 x % Si) + 189 $(\% \text{ Si})^2$	7.7 F
III	0.21	0.75	--	p = 0.5 TTTT = 71 - (178 x % Si)	9.9 F
V	0.21	0.75	0.03	p = 0.5 TTTT = 74 - (154 x % Si) + 286 $(\% \text{ Si})^2$	7.7 F

*Compositions of the different types of steels are given in Table 7. The tear test equations are for the temperature corresponding to a probability of 0.5 for brittle fracture.

The limit on benefits obtained by raising the silicon content suggests that silicon is beneficial as a deoxidizer but harmful as an alloying element. Rinebolt and Harris(26) reported that increasing the silicon content in the range above 0.50 per cent raises the transition temperature of killed steels containing aluminum.

It is common practice to specify that ship plate containing 0.15 to 0.30 per cent silicon be made by fine-grained practice. Such steels usually contain about 0.03 per cent aluminum. This amount of aluminum produces a fine austenitic or McQuaid-Ehn grain size but has little effect on the ferritic or actual grain size of hot-rolled steels. The laboratory series of steels made with this aluminum content had a minimum Charpy transition temperature about 30 F below that for aluminum-free steels. However, the tear test transition temperature was lower for the aluminum-free steels. The beneficial effect of 0.03 per cent aluminum on the Charpy transition was most noticeable at high silicon levels. Fig. 3, for instance, shows that the 12 ft-lb Charpy transition temperature was lowered 70 F by aluminum in steels with 0.45 per cent silicon. On the other hand, tear tests made for steels containing 0.45 per cent silicon did not suggest important improvements in transition temperatures when 0.03 per cent aluminum was added.

Aluminum. It seemed appropriate to determine the effect of aluminum on the properties of ship plate steels because it is widely used in the production of both semikilled and killed steels. Fifty-one experimental heats with the nominal compositions listed in Table 7 (Types VI through XI) were made for this study. Within the range investigated, aluminum had no significant effect on the tensile properties of the hot-rolled steels. The six types of steel used to study the effect of aluminum contained 0.10 per cent silicon or less.

Figs. 7 and 8 show the effects of aluminum on the transition temperatures of steels of various base compositions. The aluminum-containing series of steels covered two manganese-carbon combinations at each of three silicon levels. Multiple-correlation analyses led to the equations listed in Table 9 and to the trend lines shown in the charts. The points on the graphs were corrected for small unintentional variations in base composition.

Aluminum additions were effective in the six types of steels investigated. With one exception, the transition temperatures decreased in both Charpy and tear tests as aluminum contents increased up to 0.25 per cent. Only in the case of a steel with 0.27 per cent aluminum (Type XI) was the transition temperature higher than for similar steels containing less aluminum. No ready explanation can be offered for the behavior of this steel.

The reduction in transition temperature derived from a particular increase in aluminum content varied slightly in steels with different silicon contents. Aluminum was most effective in steels

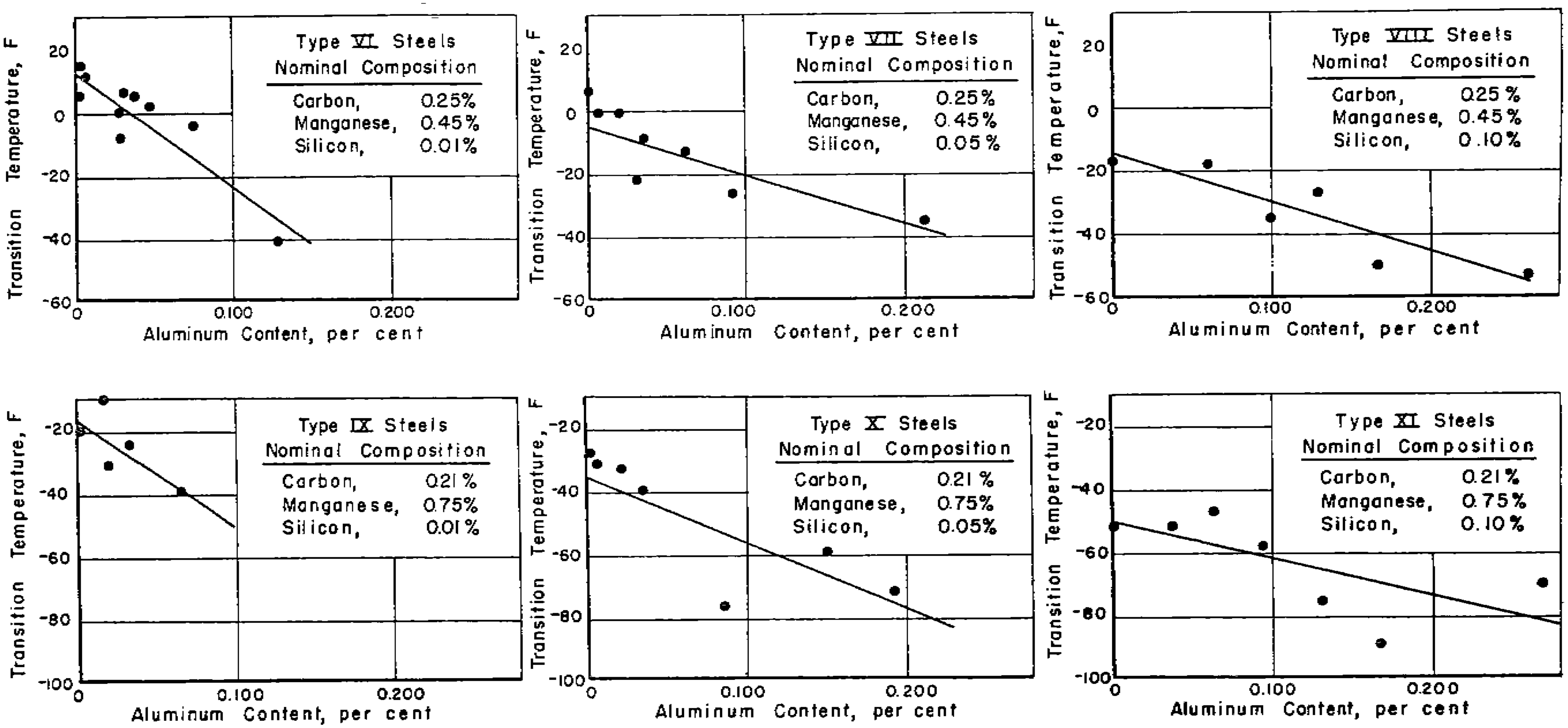


FIGURE 7. INFLUENCE OF ALUMINUM ON THE 12-FOOT-POUND KEYHOLE CHARPY TRANSITION TEMPERATURES OF SIX TYPES OF STEEL

All transition temperatures corrected to correspond to the nominal composition of each type of steel.

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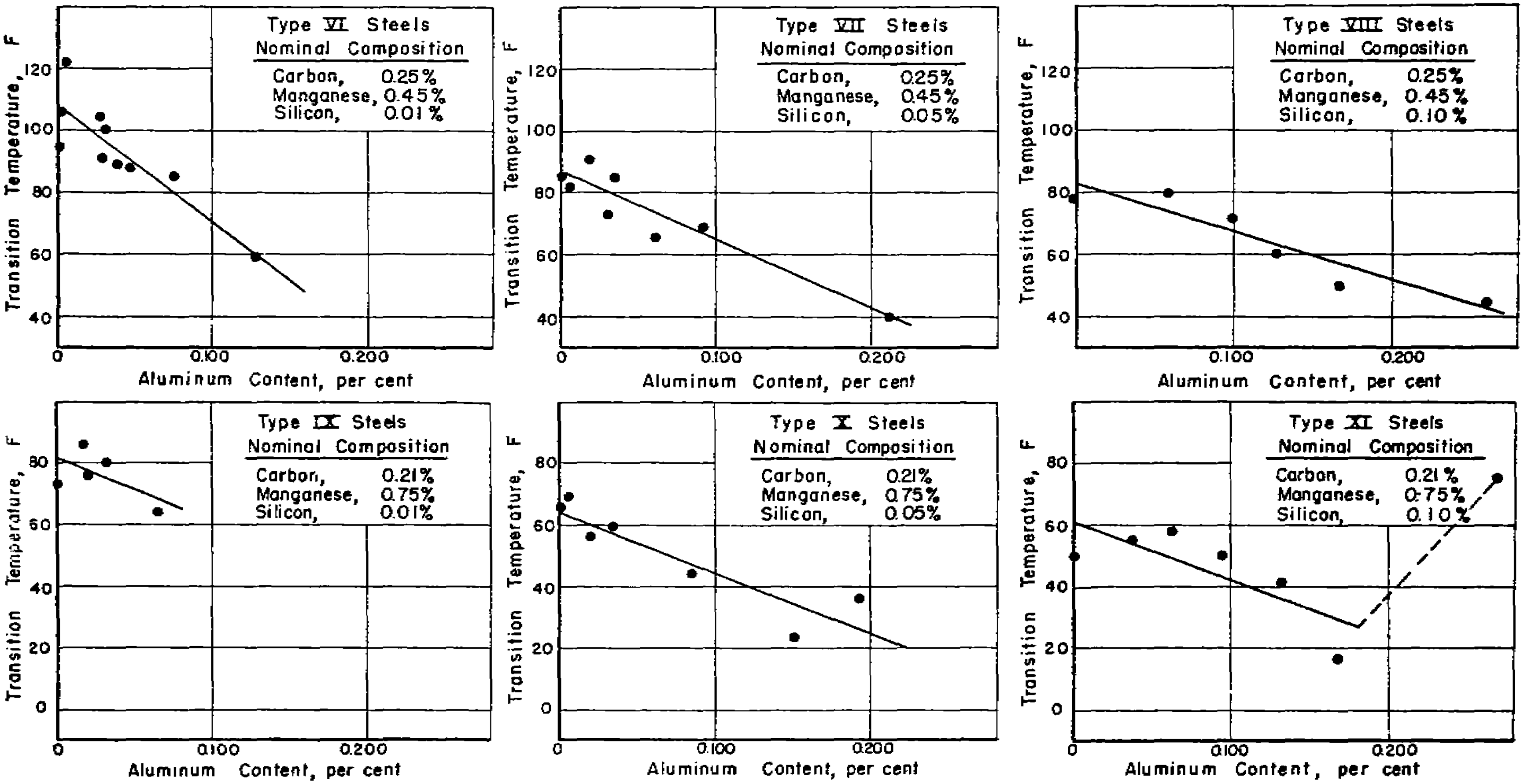

FIGURE 8. INFLUENCE OF ALUMINUM ON THE P = 0.5 TEAR-TEST TRANSITION TEMPERATURES OF SIX TYPES OF STEEL

All transition temperatures corrected to correspond to the nominal composition of each type of steel.

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TABLE 9. EQUATIONS FOR CALCULATING THE EFFECTS OF ALUMINUM ON TRANSITION TEMPERATURES OF HOT-ROLLED STEELS*

Type of Steel	Base Composition, %			Equation	Standard Error
	C	Mn	Si		
	20 Ft-Lb Keyhole Charpy Transition Temperature, F				
VI	0.25	0.45	0.01	32.1 - (380 x % Al)	4.9 F
VII	0.25	0.45	0.05	12.6 - (175 x % Al)	5.9 F
VIII	0.25	0.45	0.10	6.6 - (147 x % Al)	6.3 F
IX	0.21	0.75	0.01	-3.5 - (384 x % Al)	9.2 F
X	0.21	0.75	0.05	-22.7 - (191 x % Al)	14.5 F
XI	0.21	0.75	0.10	-32.1 - (143 x % Al)	10.2 F
	12 Ft-Lb Keyhole Charpy Transition Temperature, F				
VI	0.25	0.45	0.01	12.5 - (363 x % Al)	7.2 F
VII	0.25	0.45	0.05	-5.3 - (155 x % Al)	7.5 F
VIII	0.25	0.45	0.10	-14.7 - (157 x % Al)	7.3 F
IX	0.21	0.75	0.01	-16.3 - (345 x % Al)	8.8 F
X	0.21	0.75	0.05	-35.4 - (211 x % Al)	13.2 F
XI	0.21	0.75	0.10	-50.7 - (117 x % Al)	12.0 F
	Tear Test Transition Temperature, F				
VI	0.25	0.45	0.01	108 - (377 x % Al)	8.4 F
VII	0.25	0.45	0.05	87 - (222 x % Al)	6.9 F
VIII	0.25	0.45	0.10	82 - (156 x % Al)	5.8 F
IX	0.21	0.75	0.01	81 - (203 x % Al)	7.7 F
X	0.21	0.75	0.05	64 - (196 x % Al)	8.6 F
XI	0.21	0.75	0.10	61 - (189 x % Al)	10.4 F

*Compositions of the different types of steels are given in Table 7. The tear test equations are for the temperatures corresponding to a probability of 0.5 for brittle fracture.

containing 0.01 per cent silicon. The smallest reduction in transition temperature was in steels with 0.10 per cent silicon. These factors apply to hot-rolled steels similar to conventional ship plate in nominal composition. Equations for estimating the effects of aluminum on transition temperatures for steels of various compositions are given in Table 9.

Figs. 7 and 8 show that increasing either silicon or aluminum in the range up to 0.10 per cent lowered the Charpy and tear test transition temperatures. Based on the charts, the effects of the two elements can be summarized by the average values given below:

Type of Steel Composition, %			12 ft-lb Keyhole Charpy Transition Temperature, F			Tear Test Transition Temperature, F		
C	Mn	Al	.01% Si	.05% Si	.10% Si	.01% Si	.05% Si	.10%Si
0.25	0.45	0.00	12	-5	-15	105	85	82
0.25	0.45	0.05	-5	-12	-22	90	75	75
0.25	0.45	0.10	-22	-20	-30	70	65	68
0.21	0.75	0.00	-18	-35	-50	81	63	60
0.21	0.75	0.05	-30	-40	-52	70	54	50
0.21	0.75	0.10	-50	-55	-62	60	45	42

Titanium and Zirconium. Titanium and zirconium are deoxidizing elements which are not ordinarily used in producing semikilled steels. However, they were not overlooked as possibilities for lowering the transition temperatures of the grades of steel under investigation. Small amounts of titanium and zirconium were added to experimental steels to determine their effects on the transition temperature.

Table 10 lists transition temperatures and compositions of eleven heats containing various amounts of titanium. Transition temperatures calculated on the basis of the carbon, manganese, and silicon contents of the steel provided a basis for judging the influence of titanium. Accordingly, the presence of 0.08 or 0.10 per cent titanium raised the transition temperature about 45 F in Charpy tests and 80 F in the tear tests(2). This amount of titanium deoxidized the steel and raised its tensile strength about 9000 psi(2). Smaller quantities of titanium apparently have no outstanding effect on the transition temperatures of steels of ship plate grades.

Data for six laboratory steels containing zirconium are listed in Table 10. In amounts up to 0.04 per cent, this element did not affect the transition temperatures markedly. Charpy tests suggest that slightly larger quantities of zirconium might be beneficial. Zirconium is a strong deoxidizer, and larger amounts would be expected to fully deoxidize the steel.

<u>Vanadium and Molybdenum</u>. Vanadium is being used as an element to impart nonaging qualities to rimmed steels. Molybdenum is frequently used to minimize temper brittleness in quench and tempered steels. A few heats were therefore made to determine whether

TABLE 10. TRANSITION TEMPERATURES OF LABORATORY STEELS CONTAINING VARIOUS AMOUNTS OF ZIRCONIUM AND TITANIUM

Composition, per cent					Transition Temperatures, F			
					Calculated for C, Mn, Si*		Measured	
C	Mn	Si	Ti	Zr	Charpy**	Tear Test	Charpy**	Tear Test
0.23	0.44	0.02	0.002	--	32	83	+21	90
0.23	0.46	0.03	0.003	--	30	82	+24	90
0.25	0.44	0.03	0.02	--	38	90	+40	90
0.23	0.45	0.07	0.03	--	25	82	+41	110
0.23	0.45	0.09	0.08	--	22	82	+51	120
0.23	0.47	0.10	0.10	--	19	83	+64	160
0.20	0.75	0.03	0.002	--	-8	83	-9	70
0.19	0.76	0.02	0.003	--	-11	80	-3	70
0.19	0.76	0.04	0.02	--	-14	62	-15	50
0.19	0.76	0.05	0.04	--	-15	62	-13	60
0.19	0.79	0.10	0.10	--	-25	65	+37	150
0.25	0.57	0.07	--	0.03	20	86	-5	60
0.23	0.50	0.10	--	0.02	14	82	+5	100
0.25	0.55	0.08	--	0.06	20	86	-17	70
0.19	0.85	0.05	--	0.04	-23	66	+2	50
0.21	0.85	0.12	--	0.05	-27	66	-42	50
0.21	0.87	0.17	--	0.06	-36	66	-43	90

*These transition temperatures were calculated by the equations in Table 5. Adjustments were also made to 0.05% Si using a factor of 2.0 F per 0.01% Si for Charpy transition temperatures. All steels contained approximately 0.025% S, 0.017% P, and 0.004% N.

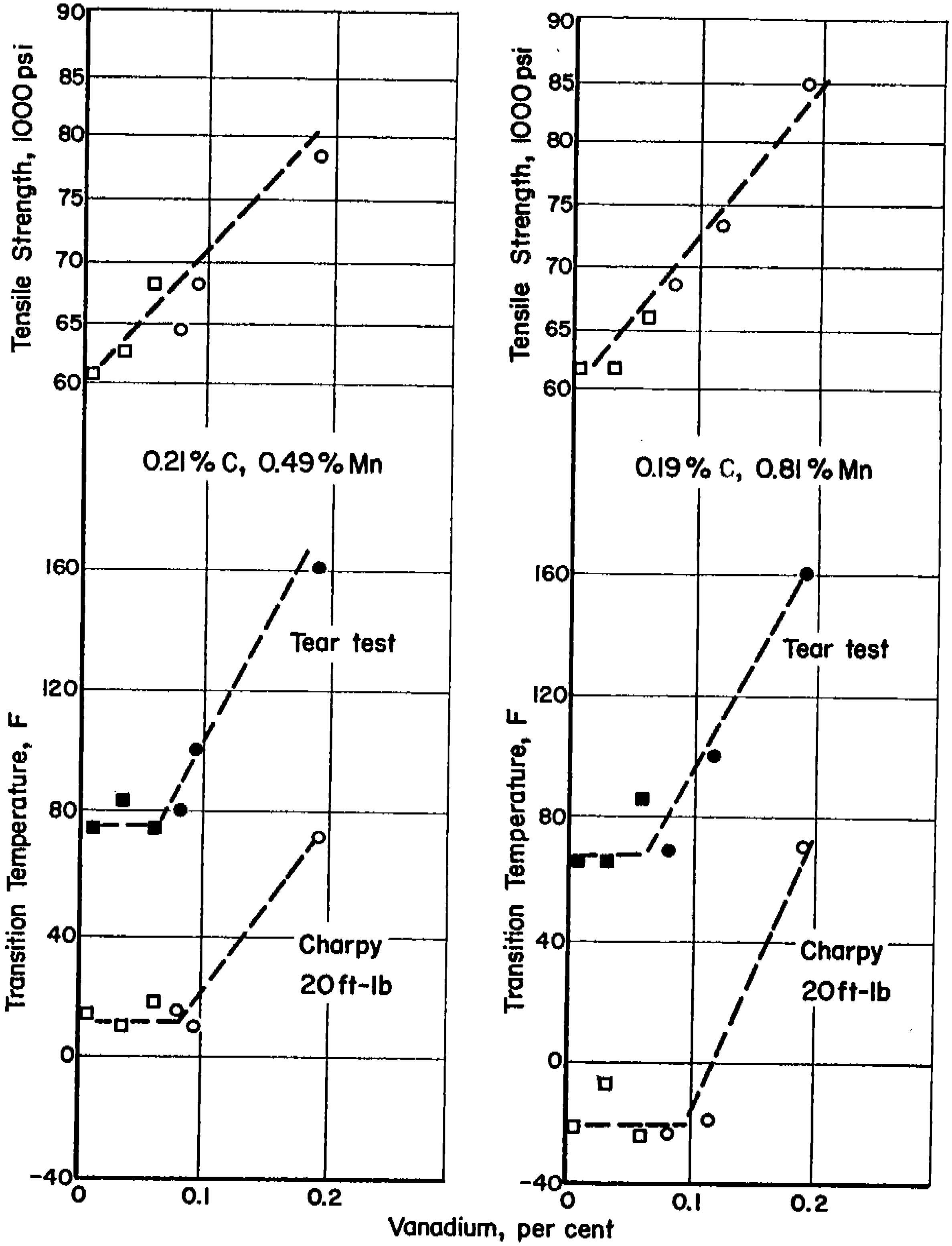
**Temperature corresponding to the 20 ft-lb level for keyhole specimens.

or not either of these elements would improve the properties of hot-rolled semikilled steels.

Ten laboratory heats were made to explore the effects of vanadium on the properties of ship plate. Fig. 9 shows that vanadium in amounts exceeding 0.10 per cent raises the transition temperature. Smaller amounts have no effect on the notched-bar properties. Charpy transition temperatures, based on the 12 ft-lb criterion, follow the same pattern as for the tear test and the Charpy test using the 20 ft-lb criterion. The scanty data indicate that the tensile strength increases 1050 psi for each 0.01 per cent vanadium. The transition temperatures increase about 80 F when the vanadium content is raised from 0.1 to 0.2 per cent.

Four of the steels used in plotting Fig. 9 were made with lower carbon contents to compensate for the strengthening effect of vanadium. The experiments indicated that substituting vanadium for carbon is not likely to lower the transition temperatures of semikilled steels(2).

Only two laboratory heats containing 0.10 per cent molybdenum were tested to determine the effect of molybdenum on the notched-bar properties. Data from these two laboratory heats showed no unusual notched-bar properties. It appears that small amounts of molybdenum are not effective in altering the transition temperatures of semikilled steels.



Square symbols indicate data adjusted to the given carbon and manganese.

FIGURE 9. EFFECT OF VANADIUM ON STRENGTH AND TRANSITION TEMPERATURES OF SEMIKILLED STEELS

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POSSIBILITIES FOR IMPROVED SEMIKILLED STEELS

Increasing the manganese and lowering the carbon appears to be one of the most practical methods for improving the notched-bar properties of semikilled steels. A significant improvement was obtained in certain gage ranges of ship steel by specifying manganese in the range of 0.60--0.90 per cent. This range is currently specified for ABS Class B steels for ship plate over 1/2 in. and up to and including 1 in. in thickness. The Navy specification for hull plates (MIL-S-16113B) sets a maximum of 0.90 per cent manganese for plates over 3/16 in. and under 7/8 in. in thickness.

This investigation suggests that further improvements could be gained by raising the manganese limits. Increasing the average manganese content by 0.20 per cent and lowering the carbon content to maintain the same strength would be expected to lower the transition temperature about 20 F in the Charpy test and 13 F in the tear test.

Another possibility for lowering the transition temperature of semikilled steel would be to lower the tensile strength requirements to permit lower carbon contents with current manganese levels. The formulas in Table 5 indicate that decreasing the carbon content enough to reduce the tensile strength by 6000 psi should lower the Charpy and tear test transition temperatures about 20 F.

Eight laboratory steels were produced and tested to check this prediction. The data for the lower carbon, lower strength steels are compared with the properties of standard steels in Table 11. The experimental data for the changes in tensile strength and transition temperatures resulting from the lower carbon contents agree closely with those expected from the factors given in Table 5.

INFLUENCE OF COMPOSITION ON AUSTENITIC GRAIN GROWTH

In many applications, a relationship exists between the austenitic grain size existing in a steel during the final heating operation and its properties at room temperature. However, comparatively little information is available on the influence of prior austenitic grain size on the properties of steels in the hot-rolled condition. Therefore, some data were obtained on austenitic grain size and grain-growth characteristics of the experimental steels.

The dividing line between coarse and fine grain sizes is generally agreed to lie between Numbers 4 and 5 on the ASTM scale. Consequently, the temperature at which the austenitic grain size exceeded ASTM No. 4.5 was determined for a large number of samples. Specimens were heated for four hours in a temperature-gradient furnace, similar to the one described by Halley(10). The effect of variations in composition on the grain-coarsening temperature is illustrated by Table 12.

The data for the two types of "standard" steels indicate that the variations in carbon and manganese contents investigated have no effect on low-silicon, aluminum-free steels. The average coarsening temperatures for the two types of "standard" steels

TABLE 11. PROPERTIES OF LOWER CARBON, LOWER STRENGTH, SEMIKILLED STEELS* MADE AND PROCESSED IN THE LABORATORY

Heat No.	Composition, %			Tensile Strength, psi	Yield Point, psi		Elong in 8" %	Transition Temp., F	
	C	Mn	Si		Upper	Lower		Charpy (20 ft-lb)	Tear** Test
Type A Steel									
B803	0.25	0.42	0.02	61,250	35,600	35,000	27.0	21	100
Avg of 11	0.22	0.45	0.04	61,190	36,400	34,800	29.0	21	80
Lower Carbon, Type A Steel									
A6539	0.15	0.41	0.01	53,300	31,850	30,750	30.5	10	60
B801	0.15	0.45	0.04	56,100	32,150	32,050	31.0	-9	80
B805	0.15	0.42	0.04	55,450	32,900	32,150	28.0	-5	70
B807	0.14	0.47	0.04	53,750	31,800	31,150	30.0	-8	70
Average	0.15	0.44	0.03	54,650	32,180	31,530	30.1	-3	70
				Improvement Due to Lower Carbon				24 F	10F
Type B Steel									
B804	0.21	0.74	0.03	63,800	37,500	36,300	27.0	-16	70
Avg of 9	0.20	0.76	0.05	62,350	36,260	35,250	28.8	-15	70
Lower Carbon, Type B Steel									
A6586	0.14	0.76	0.07	54,400	33,000	32,000	28.0	-24	40
B802	0.16	0.77	0.04	57,450	35,850	34,300	29.0	-39	50
B806	0.15	0.76	0.02	57,450	35,550	35,000	29.5	-39	60
B808	0.13	0.80	0.03	56,050	35,400	34,050	30.5	-28	60
Average	0.15	0.77	0.04	56,450	34,950	33,840	29.3	-33	53
				Improvement Due to Lower Carbon				18 F	17F

*The steels contained 0.015--0.019% P, 0.024--0.031% S, and 0.003--0.005% N.

**The tear test transition temperature is the highest temperature where one or more of four specimens broke with less than 50 per cent of the fracture area exhibiting a dull or fibrous texture.

TABLE 12. SUMMARY OF AUSTENITIC GRAIN-COARSENING TEMPERATURES OF LABORATORY STEELS*

Number of Steels	Composition, per cent				Austenite Grain-Coarsening Temperature, F**	
	C	Mn	Si	Al	Average	Range
Standard Steels						
9	0.25	0.45	0.05	None	1514	1500--1540
7	0.21	0.75	0.05	None	1517	1506--1533
Silicon Series						
10	0.25	0.45	0.02--0.48	None	1527	1510--1562
7	0.21	0.75	0.02--0.38	None	1524	1515--1530
Fine-Grained Silicon Series						
6	0.21	0.75	0.02--0.32	0.03	1762	1747--1775
Aluminum Series						
10	0.25	0.45	0.01	0.001--0.127	1657	1540--1785
8	0.25	0.45	0.05	0.006--0.211	1630	1490--1710
4	0.25	0.45	0.10	0.000--0.260	1634	1520--1725
5	0.21	0.75	0.01	0.001--0.064	1679	1490--1750
5	0.21	0.75	0.05	0.004--0.194	1689	1510--1765
4	0.21	0.75	0.10	0.000--0.167	1646	1520--1765

*All steels contained approximately 0.02% P, 0.025% S, and 0.004% N.

**Samples were heated for four hours. The temperature listed is half way between the temperature where the grains started to coarsen and the temperature where the grains were all coarser than ASTM 4.5.

agree within 3 F.

Studies on aluminum-free steels indicated that variations in silicon content from 0.02 to 0.48 per cent have no effect on austenitic grain-growth characteristics. The presence of 0.03 per cent acid-soluble aluminum, on the other hand, raises the average grain-coarsening temperature about 235 F. This increase is independent of the silicon content. Steels with compositions similar to ABS Class C ship plate have coarsening temperatures around 1760 F. This is below the ordinary finishing temperature for hot rolling.

Fig. 10 shows the influence of acid-soluble aluminum on grain coarsening of austenite. The maximum coarsening temperature is associated with the presence of about 0.05 per cent aluminum. The coarsening characteristics of aluminum killed steels are not affected by variations in silicon contents between 0.01 and 0.10 per cent. The levels of carbon and manganese seem to exert some influence, the steels with lower carbon and 0.75 per cent manganese having the higher coarsening temperatures. Table 12 indicates that the difference in austenite grain-coarsening temperatures between the lower carbon, higher manganese, and the higher carbon, lower manganese steels in the "aluminum series" is about 25 F.

INFLUENCE OF FINAL ROLLING TEMPERATURE

The 3/4-in. plates rolled in the laboratory were heated at a predetermined temperature before receiving the last pass which reduced the thickness 17 per cent. The plates were then cooled,

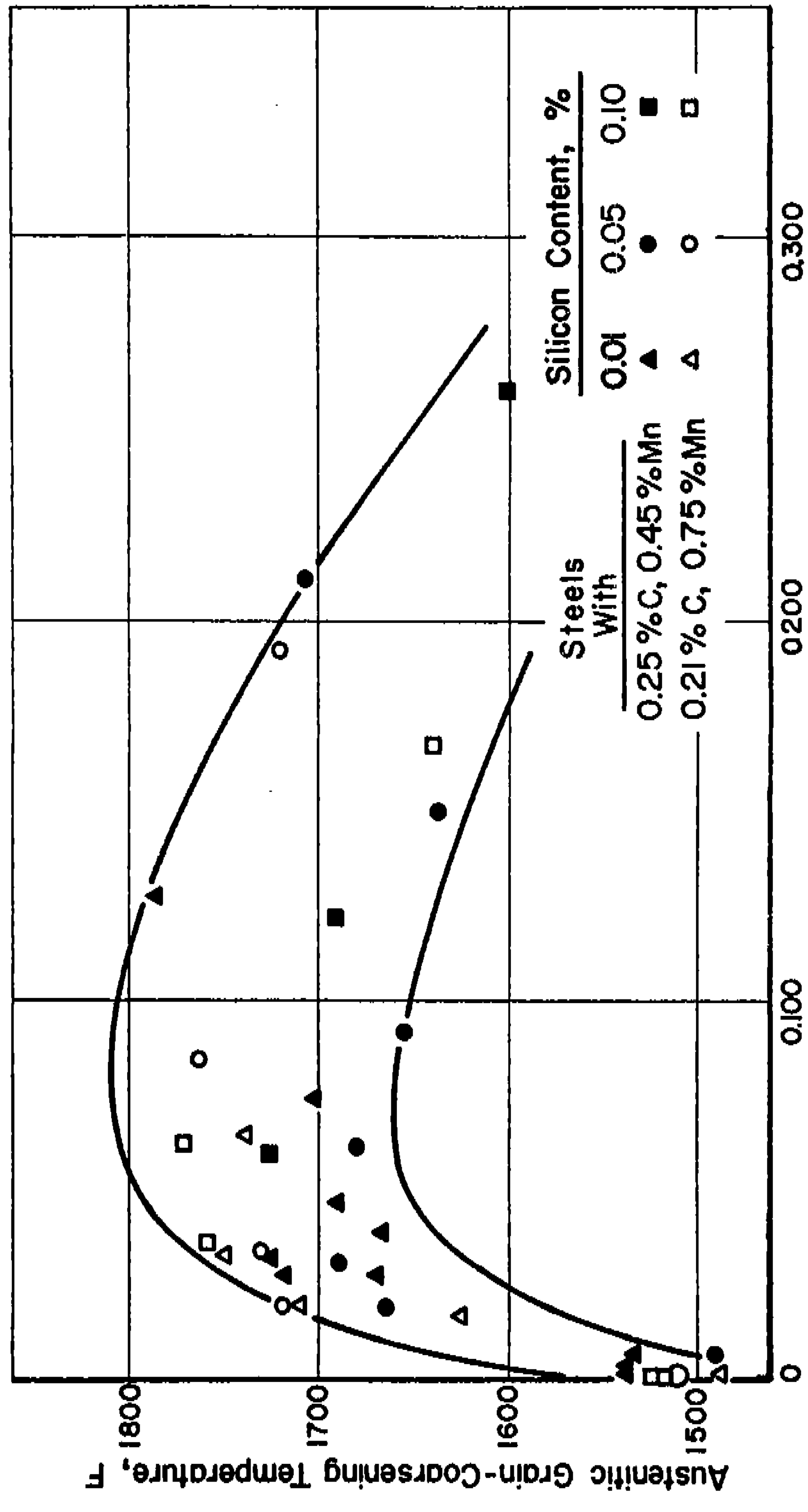

FIGURE 10. INFLUENCE OF ACID-SOLUBLE ALUMINUM ON AUSTENITIC GRAIN-COARSENING TEMPERATURE

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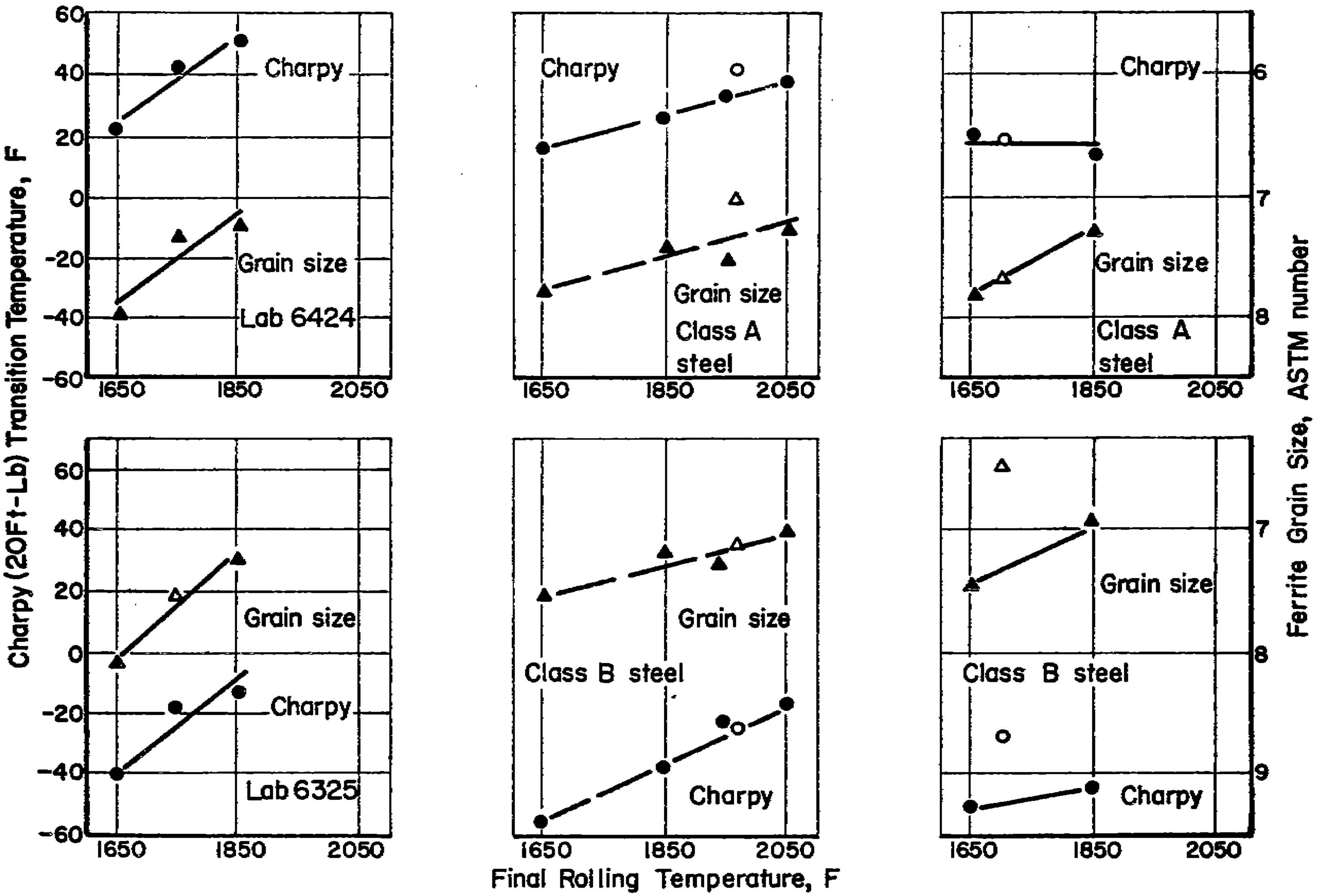
on edge, to room temperature in still air. Some of the early laboratory steels were hot rolled, using a finishing temperature of 1650 F. Such steels had significantly lower transition temperatures than steels hot rolled at a finishing temperature of 1850 F(1). This increase of 200 F in finishing temperature raised the transition temperature about 33 F in the tear test and 13 F in the Charpy test. These estimates are based on data obtained on 12 steels rolled at each of the finishing temperatures.

The effect of the final rolling temperature on the Charpy transition temperature for two laboratory heats is illustrated by the charts at the left of Fig. 11. The data also show that the size of the ferrite grains increases regularly with increasing finishing temperature.

The possibility of improving the notched-bar properties of ship plate by using lower finishing temperatures was of such interest that the matter was investigated further. Slabs of open-hearth steel 1 3/4 in. in thickness were procured from three plants(2,8) for this study. These slabs were rerolled in the laboratory to 3/4-in. plates, using different finishing temperatures. Properties of these plates were then compared with those of 3/4-in. plates rolled from the same ingots in commercial mills. Data from this study are shown in Figs. 11 and 12. Values shown in Fig. 12 are averages from tests on three plates. The steels received small aluminum additions in the mold which apparently had no effect on



Open symbols indicate plates produced in commercial plants

FIGURE 11. INFLUENCE OF FINISHING TEMPERATURE ON TWO LABORATORY STEELS (LEFT) AND FOUR OPEN-HEARTH STEELS

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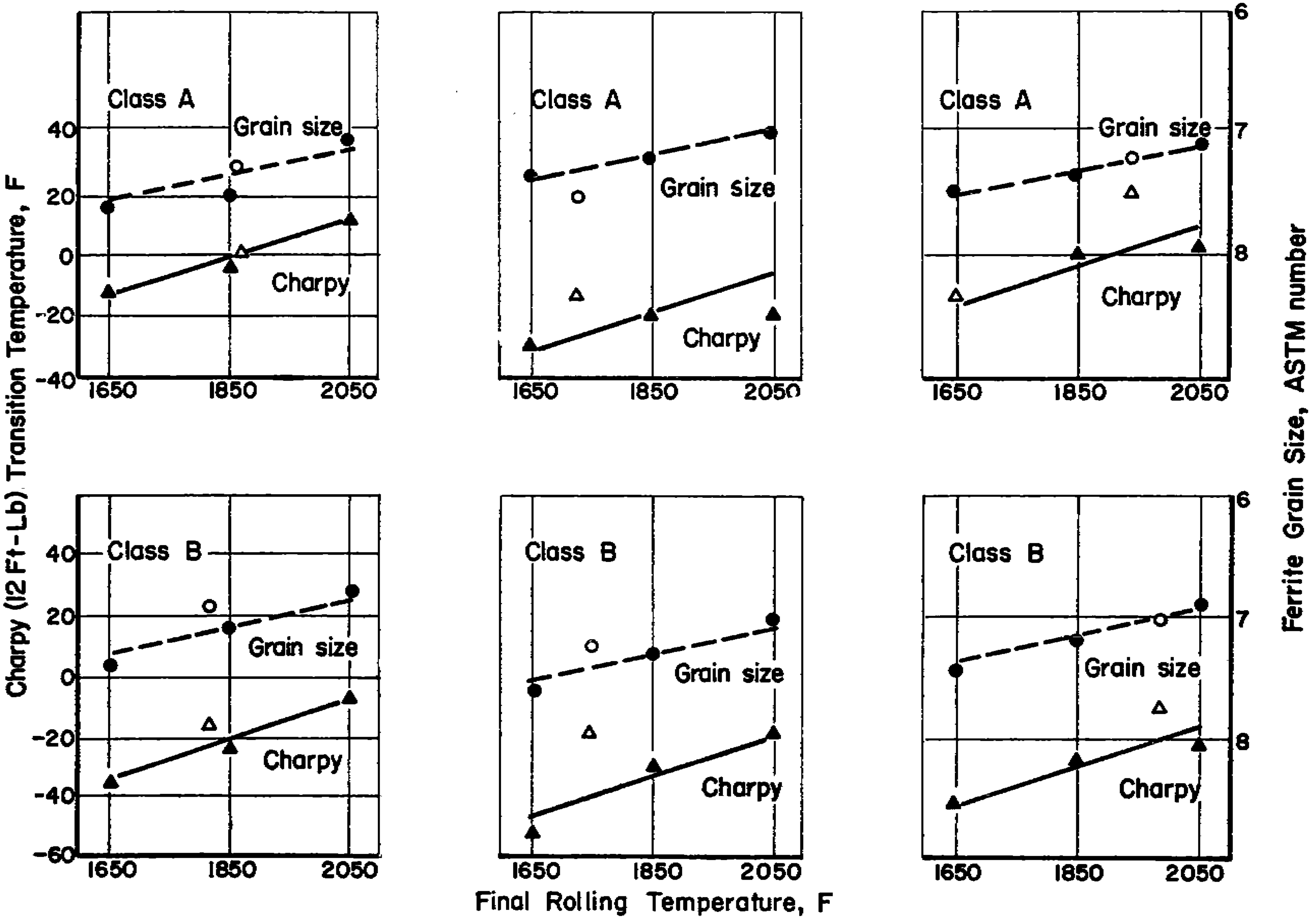

Open symbols indicate plates from commercial mills.

FIGURE 12. INFLUENCE OF FINISHING TEMPERATURE ON OPEN-HEARTH STEELS PRODUCED BY THREE PLANTS AND ROLLED IN THE LABORATORY AND IN STEEL PLANTS

grain size or transition temperature.

The data for the open-hearth steels rerolled in the laboratory show the same influence of final rolling temperature as was indicated by the induction-furnace steels. On the average, increasing the temperature 200 F increased the Charpy transition temperature of the open-hearth steels 14 F and the tear-test transition temperature 23 F. The higher finishing temperature resulted in a larger ferrite grain size; the grain size changed 0.25 on the ASTM scale.

Plates rolled in the laboratory, at various temperatures, show that a change of one ASTM number corresponds to a change in transition temperature of 56 F and 96 F in the Charpy and tear tests, respectively(2,8). On the other hand, results on air-cooled plates indicate that simple heat treatments which change the ferrite grain size by one ASTM number change both the Charpy and tear test transition temperature by only 30 F. This information suggests that rolling at lower finishing temperatures, followed by air cooling, has a greater effect on the transition temperature than would be expected from the change in grain size. Apparently, small differences in ferrite grain size are more important when they result from variations in rolling practice than when they result from heat treatment. Consequently, the relations observed between grain size and transition temperatures indicate that ferrite grain size is only one of several variables. Variations in both grain size and transition temperatures may be symptoms of a more fundamental change in microstructure.

Figs. 11 and 12 also permit a comparison of properties of plates rolled in the laboratory with those of plates rolled under commercial conditions. Almost invariably the ferrite grain sizes of the commercial plate showed the same relation to finishing temperature as did the ferrite grain sizes of the plate rolled in the laboratory from commercial slabs. The Charpy transition temperatures of these plates were, however, not in good agreement. This was illustrated by the fact that seven of the ten steels rolled commercially had transition temperatures 6 to 20 F above those indicated by trend line for plates rolled in the laboratory. This deviation suggests that factors in addition to the finishing temperature may be important; among these may be the amount of reduction during the finishing passes and the temperature prior to these passes. The lower notch toughness of the commercial plates may indicate several other factors being involved, including segregation of elements and slower cooling after rolling. The transition temperatures and the finishing temperatures reported by the mills for 22 plates of experimental open-hearth steel are shown in Fig. 13. Charpy data on the steels were adjusted to compensate for small variations in carbon and manganese contents. Such data for the ten Type A steels made and rolled in steel plants fit the trend line based on the laboratory studies of the effect of finishing temperature. On the other hand, data for the Type B steels from the same

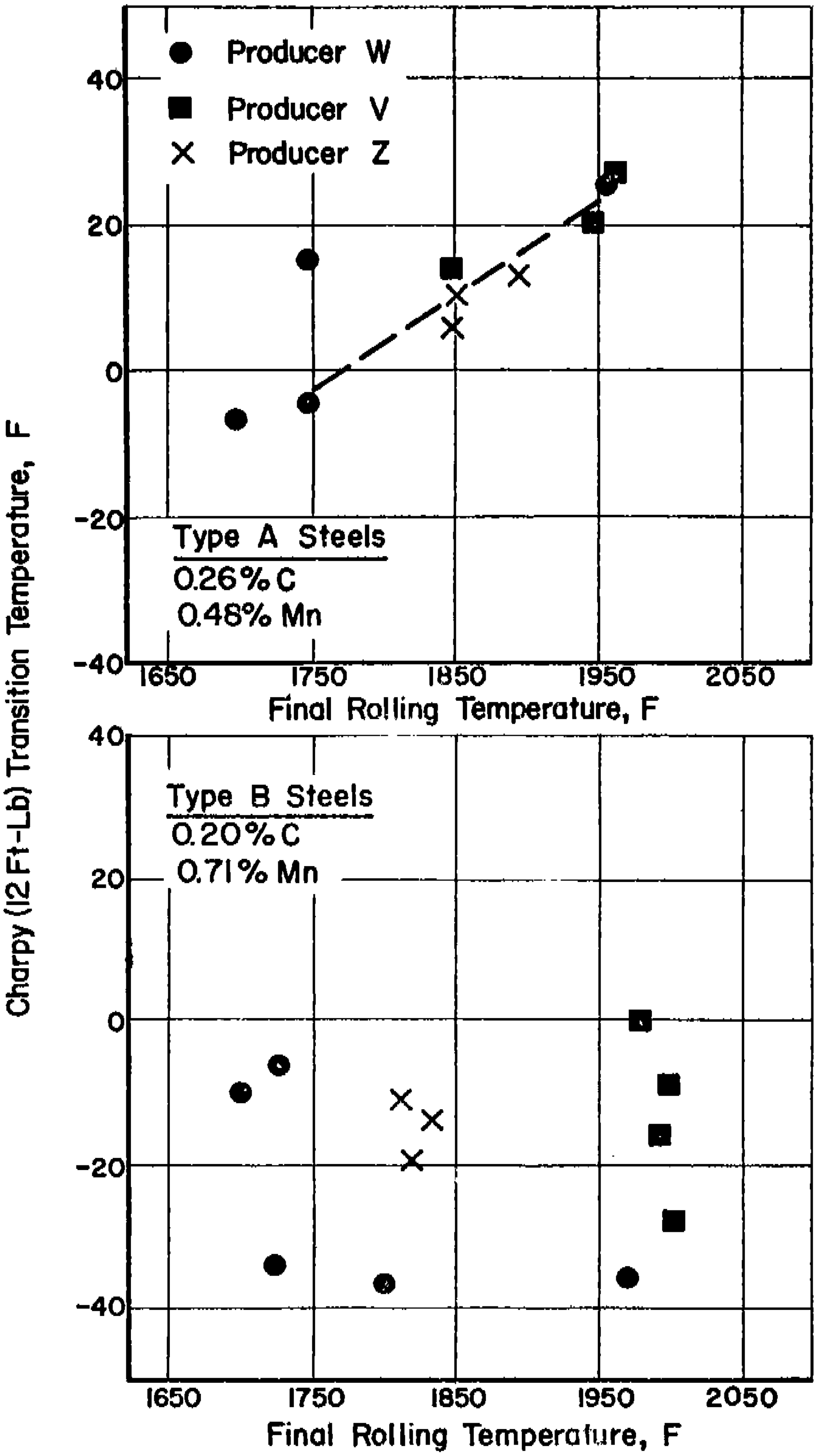

FIGURE 13. RELATIONSHIP BETWEEN FINISHING TEMPERATURE AND TRANSITION TEMPERATURES OF EXPERIMENTAL OPEN-HEARTH STEELS ROLLED IN COMMERCIAL PLANTS

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plants show so much scatter that an effect of finishing temperature could not be determined. No reason can be given for this wide variation for the Type B steels.

INFLUENCE OF AUSTENITIZING TEMPERATURE AND COOLING RATE ON PROPERTIES OF SEMIKILLED STEEL

As mentioned in the preceding section, the ferrite grain size and the transition temperatures of plates processed in the laboratory decreased with a decrease in the final rolling temperature(1,2,11). The transition temperatures of commercial plates were affected similarly(21). Since it is commonly asserted that normalizing may improve the notched-bar properties of ship plate and hence lower the transition temperature, it was considered appropriate to determine the effect of several heat treatments on the properties of semikilled steel(3,7).

A 3/4-in. thick plate from an open-hearth heat, "Project Steel A", was used for this study. Other plates of the same steel had been studied by other investigators(19,22,23). The plate contained 0.25 per cent carbon, 0.49 per cent manganese, 0.04 per cent silicon, 0.011 per cent phosphorus, and 0.004 per cent nitrogen. In the as-rolled condition, the tensile strength was 58,650 psi, and the elongation 33.4 per cent in eight inches. The plate received for the study had Charpy transition temperatures of 11 and 31 F for the 12 and 20 ft-lb criteria, respectively. In the tear test, the transition temperature was 78 F.

To study the effect of ferrite grain size, samples of the 3/4-in. plate were austenitized at various temperatures and cooled to room temperature at four different rates. The times required for the center of the samples to cool from 1400 to 1000 F ranged from about 11 minutes when cooled in an air blast to 500 minutes when cooled in the furnace. Regardless of the cooling rate, austenitizing at 1800 or 1900 F produced coarser ferrite grains than were typical for hot-rolled plate. Austenitizing from these temperatures increased the transition temperature. Plates cooled from 1600 F or 1700 F in air or in an air blast had smaller ferrite grains and lower transition temperatures than the hot-rolled steel.

Figs. 14 and 15 show a reasonably good correlation between ferrite grain sizes and the transition temperatures of the heat-treated samples of "Project Steel A". The tear test transition temperature decreased about 30 F for a reduction in grain size of one ASTM number. Variations in the rate of cooling had very little effect in this case. Fig. 14 indicated, however, that the relationship between ferrite grain size and Charpy transition temperature was influenced by the rate at which plates were cooled to room temperature. The change in Charpy transition temperature was about 20 F per grain-size number for the slowly cooled samples and about 30 F for samples cooled in air or in an air blast. The effect of grain size on transition temperature shown by this study agreed with observations of other investigators including those who studied

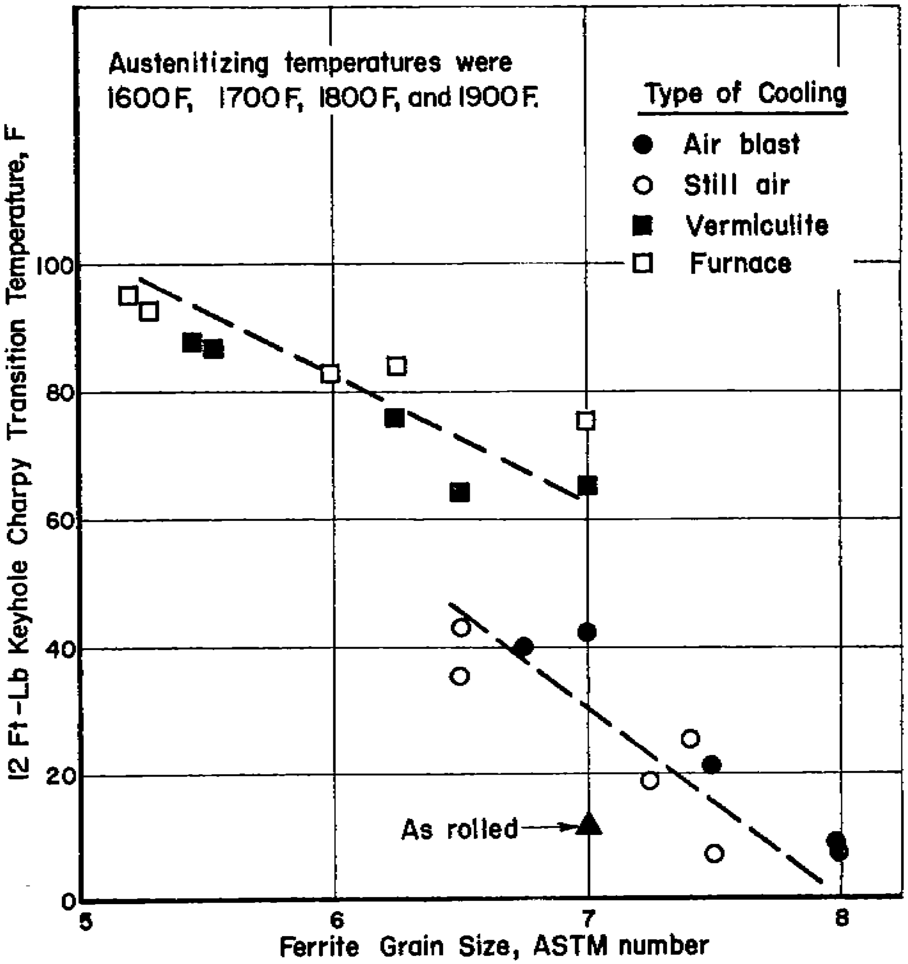

FIGURE 14. RELATIONSHIP BETWEEN CHARPY TRANSITION TEMPERATURES AND FERRITE GRAIN SIZES PRODUCED BY HEAT TREATMENT OF $\frac{3}{4}$-INCH PLATES OF PROJECT STEEL "A" (ABS CLASS A STEEL)

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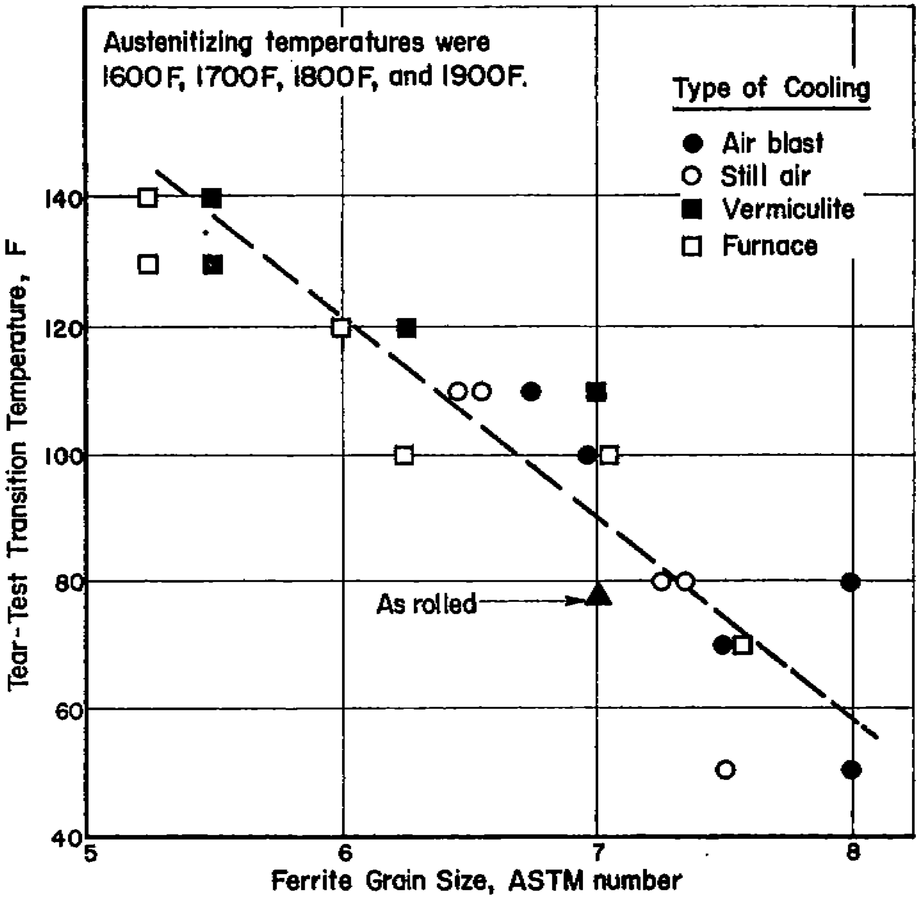

FIGURE 15. RELATIONSHIP BETWEEN TEAR-TEST TRANSITION TEMPERATURES AND FERRITE GRAIN SIZE PRODUCED BY A HEAT TREATMENT OF $\frac{3}{4}$-INCH PLATES OF PROJECT STEEL "A" (ABS CLASS A STEEL)

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steels with extremely low carbon contents(24).

These data indicate that normalizing from temperatures around 1650 F can reduce the transition temperatures of ship plate. The reduction expected can be estimated from the change in ferrite grain size produced by heat treatment. The change in grain size depends on the finishing temperature during rolling, the plate thickness, the composition of the steel, and the normalizing treatment.

To obtain information on the effect of normalizing, 14 hot-rolled open-hearth steels were heated one hour at 1650 F and air cooled. Seven of these steels were of Class B type and were plates 3/4 to 1-in. thickness, with an average hot-rolled ferrite grain size of 6.8 on the ASTM scale. The other seven steels were of the aluminum-treated Class C type in plate thicknesses ranging from 3/4 to 1 15/16 in. The average grain size in the hot-rolled condition was the same as for the Class B steel. After normalizing, the Class C steel had a much finer grain size (ASTM 8.6) than the Class B steel (ASTM 7.8). These results suggested that normalizing should decrease the transition temperature of both but should be most effective for the aluminum treated Class C steels.

The data obtained in this study indicate that normalizing should reduce the average transition temperature of the semikilled Class A steels about 30 F. This is in line with a difference between normalized and as-rolled samples from 32 Class A steels of

27 F found by Kahn and Imbembo(25) in tear tests. Furthermore, Epstein(21) reported that normalizing lowered the average Charpy transition temperature 38 F for Class B steels and 65 F for Class C steels.

EFFECT OF ACCELERATED COOLING FROM HOT-ROLLING TEMPERATURES

The notched-bar properties of steels reheated to temperatures above 1500 F are affected by the rate at which they cool to room temperature. Cooling in an air blast produces better properties than slower cooling rates. Therefore, the effect of accelerating the rate of cooling from the final rolling pass was investigated(3).

Slabs 1 3/4 in. thick were rolled to 0.9 inch at 2250 F and then to 3/4 in. at 1850 F. These slabs were obtained from two heats of semikilled open-hearth steel. Some of the 3/4-in. plates were time quenched in water immediately after rolling. In the range from 1850 to 1300 F, the average rate of cooling on water quenching was 20 F per second in contrast to 0.7 F per second for air cooling. After water quenching the plates for the desired time, they were cooled in air to room temperature. Data obtained from these experiments are given in Table 13(7).

Quenching in water for six seconds or more increased the surface hardness of the plates, and quenching in water for ten seconds or more also increased the hardness at the center.

Using the 12 ft-lb Charpy value as a criterion, the time quenching treatments lowered the Charpy transition temperatures of

TABLE 13. SUMMARY OF CHARPY* AND TEAR TEST** DATA FOR 3/4-INCH PLATES COOLED IN DIFFERENT WAYS FROM THE LAST ROLLING PASS

Type of Cooling From Last Rolling Pass	Hardness, Rockwell B		Charpy at 80 F, ft-lb	Maximum Load Tear Test lb	Transition Temperature, F		
	Center	Surface			Charpy 12 ft-lb	Charpy 20 ft-lb	Tear Test
				Steel W-1			
Air-cooled	69	69	34.5	38,490	-10	+6	90
Water quenched							
For 6 seconds	70	95	42.0	42,600	-30	-25	80
For 10 seconds	88	105	44.0	60,620	-36	-15	60
For 25 seconds	88	105	25.5	56,480	-45	-6	130
				Steel W-5			
Air-cooled	71	71	37.0	39,940	-23	-11	60
Water quenched							
For 6 seconds	67	90	31.5	38,790	-26	-14	--
For 10 seconds	78	95	31.5	51,690	-31	-20	50
For 25 seconds	88	100	37.0	51,030	-35	-26	20

*Four keyhole Charpy specimens from each plate were broken at intervals of 10 F.

**Sixteen tear tests were made on stock from plates representing each condition. The maximum load listed is the average for all specimens. The transition temperature is the highest temperature where at least one of four specimens exhibited more than 50 per cent brittle texture.

the steels studied. The reduction, in this case, appeared to be significant. The effect of time quenching was less consistent for the 20 ft-lb and the tear test criteria. In all cases but one the plates quenched for a short time in water showed lower transition temperatures than plates cooled in air from the rolling temperature. The plate with 0.52 per cent manganese quenched for 25 seconds before air cooling was the exception in that its tear test transition temperature was higher than the transition temperature of the air-cooled plate. Like the hardnesses, the maximum loads before fracture in the tear tests were higher for the quenched specimens. However, the time quenched plates deformed less so they absorbed less energy before fracture started.

These experiments indicate that the notched-bar transition temperatures of semikilled steels can be lowered somewhat by accelerating the rate at which plates cool from the last rolling pass.

CONCLUSIONS

The killed and semikilled steels made and processed in the laboratory had consistent and reproducible properties. These steels have attributes similar to those of ship plate made and processed in steel plants. Therefore, the data from laboratory prototype steels can be used to predict the effects of changing the composition or processing of commercial ship plate.

Increasing the manganese content decreases the transition temperature and consequently increases the resistance of hot-rolled steels to brittle fracture.

Increasing the carbon, phosphorus, or nitrogen contents increases the transition temperature and consequently the susceptibility to brittle fracture. Although nitrogen was observed to be detrimental in semikilled steel, it is not necessarily detrimental in heat treated aluminum killed steels(31). Formulas indicating quantitatively the effects of these elements on strength and notched-bar transition temperatures are given in this report.

Sulfur up to 0.06 per cent, and titanium or zirconium in amounts permissible in semikilled steels have no effect on notched-bar transition temperatures. Titanium above 0.04 per cent increases the transition temperature. Zirconium above 0.04 per cent might be beneficial.

Small amounts of molybdenum or vanadium apparently do not influence the transition temperatures. When the vanadium content was increased from 0.10 to 0.20 per cent, the transition temperature was raised 80 F.

Increasing the degree of deoxidation with silicon and aluminum usually lowers the transition temperature of ship-plate steel. However, only small amounts of these deoxidizers can be present in semikilled steels. Possible reductions of transition temperature from increases of silicon or aluminum in semikilled steels are thus inherently limited. These deoxidizers had no significant effect on the ferritic grain size of hot-rolled plates.

In killed steels, the transition temperatures are lowered by increases of aluminum content up to approximately 0.20%. This effect is valid for steel with .01, .05, and .10% silicon.

The effect of silicon in the range present in killed steels varies with the base metal composition and the type of notched-bar test. In general, silicon lowers the transition temperature as determined by both the Charpy keyhole and tear test in the case of killed steels with silicon contents up to 0.15%. Above this percentage, the effect of increasing amounts of silicon depends on the amounts of manganese and aluminum present.

If current tensile strength requirements are maintained, it would be desirable to use steels with more manganese and less carbon. If a decrease in the minimum tensile strength were permissible, then the carbon content could be lowered. These changes in composition would result in lower transition temperatures and consequently improved low-temperature characteristics of ship plate.

Accelerating the rate of cooling from the last rolling pass tended to improve the notched-bar properties of semikilled steel. Laboratory studies indicated that reducing the temperature of the final hot-rolling pass (17% reduction) lowered the notched-bar transition temperatures of semikilled steels. The ABS Class A steels rolled in commercial mills showed the same response to finishing temperature. Data for 13 commercial Class B ship plates, on the other hand, were inconclusive. Additional studies on the effects of rolling-mill practice seem, therefore, desirable.

Heat treatments such as normalizing which refine the ferrite grain size reduce the transition temperatures of hot-rolled semikilled steel. A change of one ASTM number in ferrite grain size is associated with a change of about 30 F in keyhole Charpy and tear test transition temperature. The indications are that normalizing from a suitable temperature lowers the transition temperatures of Class C steels, made by fine-grained practice, more than it does the transition temperatures of semikilled steels.

ACKNOWLEDGMENT

The Committee on Ship Steel appointed a Committee to help in planning and to review the findings of this research program. This Committee consisted of Samuel Epstein, S. L. Hoyt, Finn Jonassen, M. W. Lightner, T. T. Watson, and the Chairman, T. S. Washburn. The investigators are sincerely grateful for the invaluable contributions in time, counsel, and criticisms made by the Committee members during the course of the work. In particular, the efforts of the Advisory Committee in procuring experimental open-hearth steels and in interpreting the usefulness of laboratory data in the light of commercial practices were especially helpful.

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