SERIAL NO. SSC-82

Fourth

PROGRESS REPORT

(Project SR-110)

on

THE INFLUENCE OF CARBON AND MANGANESE ON THE PROPERTIES OF SEMIKILLED HOT-ROLLED STEEL

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.

SSC-82

SERIAL NO. **SSC-82**
BuShips Project NS-011-078

October 28, 1954

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

BUREAU OF SHIPS, DEPT. OF NAVY
MILITARY SEA TRANSPORTATION SERVICE, DEPT. OF NAVY
UNITED STATES COAST GUARD, TREASURY DEPT.
MARITIME ADMINISTRATION, DEPT. OF COMMERCE
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

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

October 28, 1954

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee is sponsoring 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 Fourth Progress Report, SSC-82, of the investigation entitled "The Influence of Carbon and Manganese on the Properties of Semikilled Hot-Rolled Steel" by F. W. Boulger, R. H. Frazier 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

FOURTH
Progress Report
(Project SR-100)

on

The Influence of Carbon and Manganese on the Properties of Semikilled Hot-Rolled Steel

by

F. W. Boulger
R. H. Frazier
C. H. Lorig

BATTELLE MEMORIAL INSTITUTE

under

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

for

<u>SHIP STRUCTURE COMMITTEE</u>

INTRODUCTION

The research work on the influence of carbon and manganese on the properties of semikilled steel reported in the Appendix of this report supplements that reported earlier as part of the Second Progress Report of the investigation, SSC-53, November 28, 1952.

Based on the earlier study (SSC-53), a paper has been prepared entitled "The Influence of Carbon and Manganese on the Properties of Semikilled Hot-Rolled Steel". This paper was published in the *Journal of Metals* of the American Institute of Mining and Metallurgical Engineers, May 1954. A reprint of the paper and the Appendix have been combined herein to form the Fourth Progress Report of the investigation in order to unify the report on the influence of carbon and manganese.

The additional tear tests reported in the Appendix were prepared in order to determine the temperature at which the probability of 50% brittle performance is expected and to define this temperature with the same degree of confidence as that obtained for the same steels using the Charpy keyhole specimen.

In reviewing the reprint, your attention is called to the changes in tear test properties of heats made in the laboratory that are occasioned by the additional work reported and discussed in the Appendix.

Heat numbers A and B shown in Table II and elsewhere represent standard heats of the base compositions studied. These heats were made at various times in the course of the investigation to act as checks on the steelmaking procedures used.

The Influence of Carbon and Manganese on The Properties of Semikilled Hot Rolled Steel

by F. W. Boulger and R. H. Frazier

THE performance of welded structures is closely associated with the ductile-to-brittle transition temperature of the steel from which they are made.[1] A low transition temperature is desirable because it indicates that the steel is less likely to fail suddenly at low ambient temperatures. Structures such as bridges, ships, storage tanks, and pipelines are usually made from hot rolled semikilled steel. Changes in rolling practice or chemical composition appear to be the most practical methods for improving the toughness of such materials. This results from the fact that production is likely to be seriously curtailed if improvements were obtained by recourse to heat treatment or complete deoxidation.

This paper discusses the effect of variations in carbon and manganese contents on the properties of semikilled steels. The transition temperature, a property to which considerable importance is attached, varies with specimen configuration, testing method, and criterion of performance. Both the Navy tear test[2] and the keyhole Charpy test were used in the investigation. According to the terms used by Vanderbeck and Gensamer,[3] the tear test was used to measure a fracture transition and the Charpy test to measure a ductility transition. In either case the specimens absorb considerably less breaking energy in tests below the transition temperature than in tests above the transition temperature.

Decreasing the testing temperature of notched-bar specimens seems to be equivalent in its effect to increasing the severity of loading on fabricated structures. Therefore, structures built from steels exhibiting lower transition temperatures in laboratory tests are expected to be less susceptible to sudden brittle fractures in service. Consequently, changes in composition which lowered the transition temperature of the experimental steels were judged desirable.

Materials and Methods

The steels for this study were made in a laboratory induction furnace and rolled to ¾ in. plate, using a finishing temperature of 1850°F. Precautions taken to insure reproducible melting and testing practices are discussed in detail elsewhere.[4] All tests were made on hot rolled steels.

The analyses of the experimental steels are given in Table I. The list includes steels with manganese contents ranging from 0.21 to 1.46 pct, at each of five carbon levels. The phosphorus, silicon, sulphur, and nitrogen contents of the steels are reasonably constant.

Table I. Chemical Analysis of Semikilled Steels Made in the Laboratory

Heat No.*	Mn/C	Composition, Pct					
		C	Mn	P	S	Si	N
7448	1.35	0.17	0.23	0.015	0.021	0.04	0.004
6539	2.73	0.15	0.41	0.017	0.027	0.02	0.004
6586	5.43	0.14	0.76	0.011	0.023	0.07	0.004
7517	8.20	0.15	1.23	0.016	0.021	0.07	0.004
6590	1.16	0.19	0.22	0.015	0.026	0.05	0.003
7532	2.37	0.19	0.45	0.015	0.031	0.03	0.004
B	3.80	0.20	0.76	0.015	0.023	0.05	0.004
7518	5.06	0.19	0.96	0.017	0.028	0.04	0.004
6554	5.17	0.18	0.93	0.016	0.017	0.11	0.005
7516	5.89	0.18	1.06	0.016	0.025	0.08	0.004
6599	7.30	0.20	1.46	0.015	0.022	0.06	0.004
6589	0.92	0.25	0.23	0.016	0.024	0.08	0.004
A	2.09	0.22	0.46	0.014	0.024	0.05	0.004
6547	3.95	0.21	0.83	0.015	0.028	0.05	0.004
6598	5.29	0.24	1.27	0.016	0.026	0.07	0.004
7519	6.23	0.21	1.31	0.017	0.025	0.07	0.005
7520	0.78	0.27	0.21	0.014	0.027	0.02	0.004
7521	1.65	0.26	0.43	0.015	0.029	0.02	0.003
7522	2.36	0.28	0.66	0.016	0.025	0.03	0.004
7533	3.84	0.26	1.00	0.016	0.030	0.03	0.003
7527	0.78	0.31	0.21	0.016	0.027	0.03	0.004
6596	1.44	0.34	0.49	0.015	0.023	0.06	0.003
6597	2.50	0.32	0.80	0.017	0.024	0.06	0.004
7525	2.84	0.31	0.88	0.016	0.025	0.04	0.004
7524	4.48	0.31	1.39	0.018	0.026	0.03	0.005

* Data for *A* steel are averages for eight heats, and data for *B* steel are averages for seven heats.

The tensile and notched-bar properties of the experimental steels are presented in Table II. Both upper and lower yield points are listed, and all values are averages for duplicate specimens.

Transition temperatures based on three criteria are given. The keyhole Charpy transition temperatures are the temperatures at which the energy-temperature curves based on averages of four specimens cross the 20 and 12 ft-lb levels. Both definitions of Charpy transition temperatures have been used by other investigators. Charpy tests were made at intervals of 10°F, using a pendulum with an available striking energy of 220 ft-lb and a velocity of 18.1 ft per sec. The specimens were oriented parallel to the rolling direction and notched normal to the surface of the plates. The tear test transition temperatures are based on the usual[2] criterion of the highest temperature at which at least one of four specimens exhibits brittle behavior.

The dimensions of the tear test specimens are shown in Fig. 1. The specimen is loaded eccentrically in tension, with pin and shackle fixtures, through the large holes while submerged in a liquid bath at the proper temperature. A specimen developing a fracture area with less than 50 pct shear or ductile texture is classed as brittle. Tear tests were made at intervals of 10°F.

F. W. BOULGER and R. H. FRAZIER, Members AIME, are Division Chief and Assistant Division Chief, respectively, Battelle Memorial Institute, Columbus, Ohio.

Discussion on this paper, TP 3733E, may be sent, 2 copies, to AIME by Jan. 1, 1955. Manuscript, Oct. 9, 1953. Chicago Meeting, November 1954.

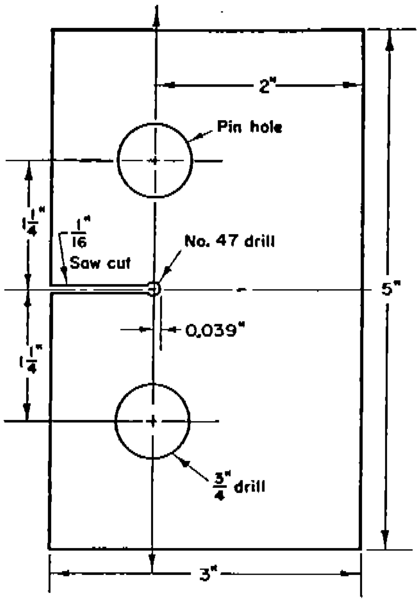


Fig. 1—Navy tear test specimen utilizing full plate thickness.

Effect of Carbon and Manganese on Tensile Properties

Since the carbon and manganese contents were varied independently, the steels cover a range in tensile strengths. The influence of these two elements on tensile properties is shown by the equations in Table III. The equations were obtained by multiple correlation analyses on the steels representing the 25 compositions listed in Table I. The relative effects of carbon and manganese can be summarized as shown in Table IV. The data show that, pound for pound, carbon raises the ultimate strength of steel about eight times as much as manganese. The effect on reducing the elongation values is even more pronounced. The tensile-elongation values of these hot rolled steels were lowered by increases in either carbon or manganese. For equal increases in strength, however, the loss in elongation values was about three-fourths as large when manganese was used as the strengthening element. On the other hand, carbon is only about five times as effective as manganese in raising the yield strength; hence, raising the manganese level of mild steels increases the ratio of yield strength to tensile strength.

The equations in Table III were obtained by correlation analysis of data obtained on semikilled steels made in the laboratory and hot rolled to ¾ in. plate with a finishing temperature of 1850°F. However, the equations give calculated properties in good agreement with those reported by Quest and Washburn[5] for commercial steels.

Effect of Manganese and Carbon on Tear Test Properties

Table II shows that the composition of the steels influenced the maximum load and the energy required to start and to propagate fracture in tear tests at temperatures 10°F above the transition temperature. Kahn has shown that the maximum load and the energy required to start the fracture are practically unaffected by the mode of fracture over a wide range in temperature.[6]

The data on these laboratory steels indicate that the energy required to start a fracture in the tear test decreases with increasing carbon content for steels with the same manganese content. On the other hand, the energy associated with crack initiation increased with manganese, though this change was less marked and less consistent. Thus, combining the individual effects of carbon and manganese is equivalent to showing a beneficial effect of higher Mn-C ratios in raising the energy required to start a failure. This should not be confused with the influence, which will be discussed later, of the effect of manganese on the transition temperature where the mode of fracture changes from ductile to brittle.

Table II. Properties of Semikilled Steels Made in the Laboratory*

	Tensile Properties†				Tear Test Properties††				Charpy Properties†† Transition Temperature, °F	
	Elongation in 8 In.,	Yield Strength, Psi		Tensile Strength,	Maximum Load,	Energy to Start Fracture,	Energy to Propagate Fracture,	Transition Temperature,		
Heat No.**	Pct	Upper	Lower	Psi	Lb.	Ft-Lb	Ft-Lb	°F	12 Ft-Lb	20 Ft-Lb
7448	35.0	33,300	28,700	50,700	33,500	950	670	50	+4	+21
6539	30.5	31,850	30,750	53,300	35,650	930	690	60	−1	+18
6586	28.5	33,000	32,000	54,400	38,500	1270	1130	40	−35	−24
7517	29.5	37,150	36,000	61,400	42,570	1180	870	30	−44	−32
6590	30.5	33,100	31,450	55,100	34,100	840	740	90	+15	+26
7532	32.5	31,700	31,450	56,100	36,900	870	770	70	−6	+12
B	28.0	36,350	35,350	62,250	39,500	870	750	73	−28	−15
7518	33.0	36,200	35,350	61,700	40,100	960	820	50	−33	−21
6554	29.5	38,550	37,100	64,900	40,900	890	800	70	−54	−45
7516	31.5	36,200	34,700	59,600	40,800	1220	840	40	−54	−38
6599	24.5	43,850	43,400	72,400	46,800	970	850	60	−50	−38
6589	29.5	34,050	32,800	58,400	35,200	820	670	100	+14	+36
A	28.0	37,000	35,200	61,900	37,000	780	660	75	+3	+14
6547	26.5	36,900	36,000	65,400	39,200	760	730	80	−36	−27
6598	23.0	42,900	42,200	74,200	45,500	950	830	70	−76	−60
7519	29.0	37,700	37,000	64,200	43,600	980	810	50	−44	−29
7520	29.0	34,250	32,000	58,600	35,000	670	710	90	+46	+67
7521	30.0	36,450	33,900	62,300	36,800	720	710	100	+15	+50
7522	25.5	38,450	36,950	68,500	37,800	600	560	90	−2	+22
7533	27.5	41,900	39,250	73,600	43,200	950	830	70	−29	−9
7527	30.0	34,650	33,800	63,000	35,700	590	640	120	+57	+90
6596	21.0	41,300	38,600	72,900	36,500	520	570	120	+29	+75
6597	24.5	40,900	40,100	75,100	41,000	640	610	90	+5	+19
7525	27.0	40,500	40,100	76,300	43,800	670	540	90	−6	+16
7524	26.5	45,800	45,450	80,800	47,300	740	660	100	−37	−4

* Compositions are given in Table I, tests made on ¾ in. hot rolled plates.
** Data for steels *A* and *B* are averages for eight and seven heats, respectively.
† Tensile data are averages for duplicate specimens.
†† Tear test values are for four specimens tested 10°F above transition temperature. Four Charpy keyhole specimens were tested at each temperature of interest.

Table III. Equations for Calculating the Effects of Carbon and Manganese on the Properties of Hot Rolled, Semikilled Steels

1—Upper Yield Strength, psi = 23,000 + (39,200 x pct C) + (7,200 x pct Mn)
Standard Error of Estimate = 1500 psi
2—Lower Yield Strength, psi = 20,700 + (39,800 x pct C) + (8,400 x pct Mn)
Standard Error of Estimate = 1300 psi
3—Tensile Strength, psi = 30,800 + (104,000 x pct C) + (13,000 x pct Mn)
Standard Error of Estimate = 2200 psi
4—Elongation in 8 in., pct = 38.2 − (32.6 x pct C) − (3.2 x pct Mn)
Standard Error of Estimate = 2.4 pct elongation
5—Maximum Load in Tear Test, lb = 29,000 + (13,800 x pct C) + (9,820 x pct Mn)
Standard Error of Estimate = 900 lb
6—Tear Test Transition Temperature, °F = 17 + (330 x pct C) − (23 x pct Mn)
Standard Error of Estimate = 10°F
7—Keyhole Charpy Transition Temperature, °F = K* − 19 + (349 x pct C) − (74 x pct Mn)
(For 20 ft-lb level) Standard Error of Estimate = 10°F
8—Keyhole Charpy Transition Temperature, °F = − 15 + (225 x pct C) − (68 x pct Mn)
(For 12 ft-lb level) Standard Error of Estimate = 12°F

* Values of *K* are given in Table VI, or can be taken from the two curves in Fig. 6.

If all steels deformed the same amount up to the point of maximum load in the tear test, then the energy used in starting a crack would depend only on the maximum load. This appears to be approximately true. The nominal stress at maximum load in the tear test is less than the ultimate strength in tension because of the notch and eccentric loading characteristic of the test method. The sensitivity to these two stress-concentrating factors is influenced by strength and by composition, as shown in Fig. 2.

Fig. 2 is based on tensile strengths measured at room temperature and maximum loads measured in tear tests 10°F above the transition temperature. This difference in testing temperatures is unimportant because the maximum load in a tear test is almost independent of mode of fracture, or temperature in the range covered. Fig. 2 shows that increasing the carbon content by 0.05 pct increased the strength reduction factor by 0.17. For this discussion the strength-reduction factor is considered to be the nominal strength in tensile tests at room temperature divided by the nominal strength in tear tests made 10°F above the transition temperature. This can also be deduced from the equations in Table III. Large variations in manganese content among steels at the same carbon level had comparatively little effect on the strength-reduction factor. However, manganese tended to decrease the sensitivity to the notch and eccentric loading.

Table IV. Relative Effects of Carbon and Manganese

Property	Relative Effect	
	C	Mn
Lower yield strength	+4.7	+1
Upper yield strength	+5.4	+1
Ultimate tensile strength	+8.0	+1
Elongation in 8 in.	−10.2	−1

The data for these hot rolled steels indicate that greater notch sensitivity is not a necessary consequence of increased strength. The equations in Table III show that manganese raised the notched strength in the tear test about half as much as it raised the tensile strength. This contrasts with carbon, which raised the notched strength only one-tenth as much as it did the ultimate strength. The disparate effects of carbon and manganese on the strength of tear test specimens may result from their effects on notched ductility. In this regard, Ripling concluded that the strength of notched tensile bars depends on their ductility as evidenced by contraction in area, a point which was not investigated in the current studies. However, it should be emphasized that tear test specimens show at least 10 pct contraction in area at the root of the notch when tested at the temperature separating fractures which have predominantly shear textures from those with predominantly cleavage textures. This is true for specimens showing either type of fracture. Temperatures about 100°F below those of current interest are necessary to produce tear test fractures with no measurable deformation at the base of the notch.

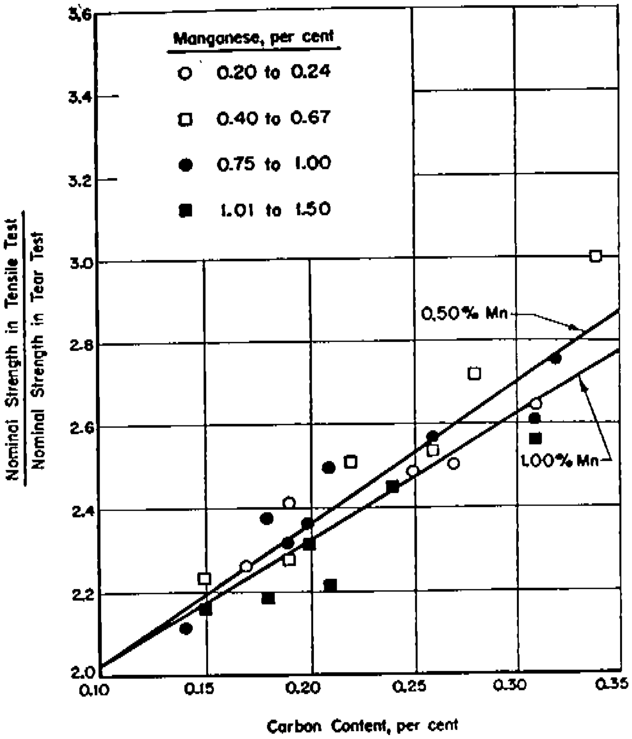


Fig. 2—Influence of carbon on the strength reduction factor resulting from the notch and eccentric loading in the tear test.

The equations in Table III also show the influence of carbon and manganese on the transition temperature in tear tests. Manganese lowers the transition temperature in addition to improving the notched strength at temperatures above the transition temperature. Carbon, on the other hand, raises the transition temperature. This harmful effect of car-

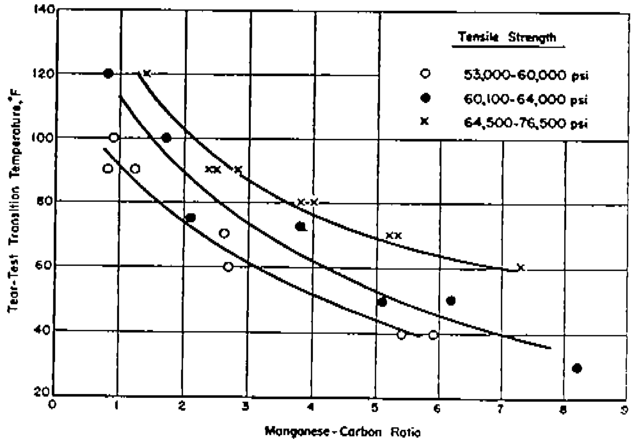


Fig. 3—Influence of Mn-C ratio on the tear test transition temperature of semikilled steels.

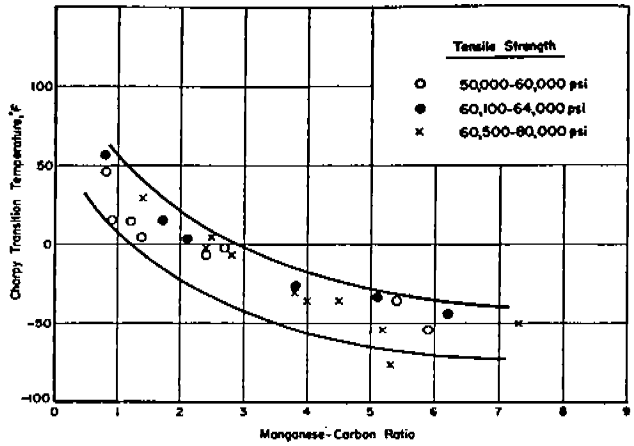


Fig. 4—Influence of Mn-C ratio on the 12 ft-lb keyhole Charpy transition temperature of semikilled steel.

bon would seem to reflect its potent influence on notch sensitivity.

The equations indicate that carbon and manganese have independent effects on tear test transition temperatures. Within the range of carbon contents studied, increasing the manganese content by 0.20 pct lowered the tear test transition temperature approximately 4.6°F. Nevertheless, it is convenient to compare steels with equal strengths on the basis of their Mn-C ratios. Fig. 3 shows that steels with higher Mn-C ratios have lower transition temperatures in tear tests. The improvement amounted to about 30°F, for steels of similar strengths, when the Mn-C ratio increased from two to five.

The graphs also show a range of about 25°F in transition temperatures for steels with the same Mn-C ratio, but with tensile strengths varying from 53,000 to 76,500 psi. With equal Mn-C ratios, the stronger steels have poorer transition temperatures in the tear test, despite their higher manganese contents. This results from the fact that the accompanying increase in carbon overcomes the beneficial effect of manganese in the stronger steels.

Fig. 3 indicates that increasing the Mn-C ratio from two to four, for steels of equal strengths, corresponds to an improvement in tear test transition temperature of approximately 20°F. These Mn-C ratios are typical of those for ABS class *A* and class *B* ship plate, respectively.

Effect of Manganese and Carbon on Charpy Properties

Since the carbon and manganese contents were varied independently, the experimental steels cover a range in tensile strength. Table V shows that strengthening hot rolled steels of this kind by increasing the carbon content lowered the room temperature Charpy value. On the other hand, raising the manganese content at a constant carbon level raised the Charpy values of specimens tested above the transition temperature. These observations agree with the conclusions of Rinebolt and Harris[8] from their studies on killed steels. They reported that carbon changes the shape of the temperature-energy curves in Charpy tests, while the principal effect of manganese is to increase the energy values of ductile specimens.

Figs. 4 and 5 show the influence of the Mn-C ratio on the Charpy transition temperatures of the experimental steels. Unlike the tear test data in Fig. 3, these charts indicate that the Charpy transition temperature is relatively independent of tensile strength in the range from 50,000 to 80,000 psi. Steels with the higher Mn-C ratios usually have lower Charpy transition temperatures, regardless of their strength. The fact that stronger steels do not necessarily have inferior Charpy properties has also been noted in tests on heat-treated steels tempered at various temperatures.[8]

Barr and Honeyman[10] were among the first to attach importance to the Mn-C ratio as a factor affecting the notched-bar properties of steel. Their data indicated the benefits of higher Mn-C ratios, but were too few to establish the independent effects of manganese and carbon on Charpy transition temperatures. This could be done in the present investigation because the larger number of experimental heats covered a wider range in composition and tensile strength.

Carbon raises and manganese lowers the transition temperature of notched bars and the elements seem to act independently. The separate effects of carbon and manganese on the Charpy transition temperatures of semikilled laboratory steels are shown by the equations in Table III. Combining Eqs. 3, 7, and 8 indicates that replacing carbon with manganese while maintaining the same strength should 1—lower the 20 ft-lb transition temperature 11°F, and 2—lower the 12 ft-lb transition temperature 8°F for each 0.01 pct C replaced. The improved toughness results from the combined benefits of adding manganese and of removing carbon. Such changes in composition alter the Mn-C ratio by amounts which depend on the original analysis of the steel. The change in the Mn-C ratio accompanying the replacement of carbon with manganese is more noticeable at low carbon or high manganese levels. This accounts for the curvilinear relationship between the Mn-C ratios and the transition temperatures in Figs. 4 and 5. The Mn-C ratio does not seem to have any intrinsic importance, although it is a convenient device for distinguishing between steels of comparable strengths.

Fig. 6 illustrates an important point concerning the beneficial effects of manganese. The effect of this element in lowering the 20 ft-lb Charpy transition temperature decreases appreciably at higher levels. The chart is based on data for the experimental steels corrected to 0.23 pct C. The points show moving averages* for groups of five steels after

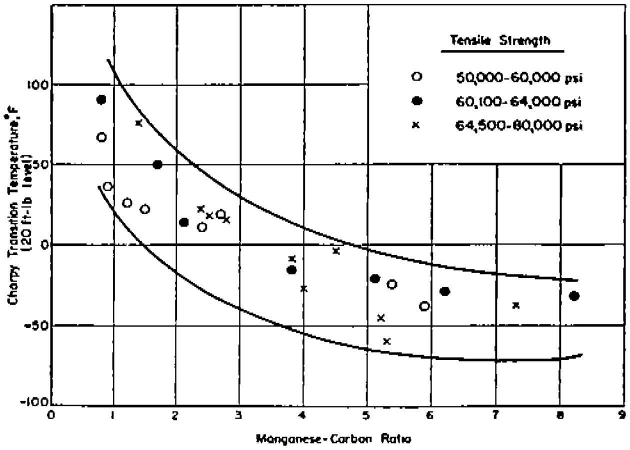


Fig. 5—Influence of Mn-C ratio on the 20 ft-lb keyhole Charpy transition temperature of semikilled steel.

---

* The moving average is a device for obtaining a series of figures which represent the general 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 corresponding moving averages for groups of three are 4.0, 5.7, 6.3, 7.0, and 7.7.

Table V. Keyhole Charpy Values in Foot-Pounds of Hot Rolled, Semikilled Steels, Differing in Carbon or Manganese Contents, Tested at 75° to 80°F.*

Mn Content, Pct	C Content, Pct				
	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

* Most of the values quoted are averages for four specimens.
† These values are averages for eight or more specimens.

the data were arranged in order of manganese content. These values differ enough from a straight line to justify inclusion of the factor *K* in Eq. 7 of Table III. Suitable values of *K* for calculating transition temperatures of steels with different manganese contents are given in Table VI. The change in transition temperature 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 little would be gained by using more complicated equations for expressing the influence of manganese on the tear test or 12 ft-lb Charpy transition temperatures.

The standard errors of estimate of Eqs. 5, 7, and 8 are small compared to the precision of notched-bar data. This suggests that transition temperatures of the experimental steels can be estimated almost as well by calculations as by experiments.

Agreement Between Calculated and Experimental Transition Temperatures

The regression equations for estimating the tear test transition temperature and the Charpy 20 ft-lb transition temperature from carbon and manganese analyses were tested both on the laboratory steels and on a series of commercial steels. Fig. 7 is a correlation plot of the experimental and calculated transition temperatures for the 25 laboratory steels. The amount of scatter is normal and all values but one (98 pct) fall within the limits of twice the standard errors of estimate.

Table VII compares calculated transition temperatures for 25 commercial steels with actual data obtained by Kahn[11] and Battelle Memorial Institute. For about two-thirds of the materials, the experimental and calculated values agree within twice the standard errors of estimate given in Table III. This is much poorer agreement than for the steels made and rolled under controlled conditions in the laboratory. Most of the calculated temperatures are lower than the transition temperatures determined experimentally. This is invariably true for the materials giving the poorest correlations.

Apparently, for the same composition, commercial steels are likely to have slightly higher transition

Table VI. Values for *K* in Eq. 7 of Table III, Showing the Effect of Manganese on the 20 Ft-Lb Charpy Transition Temperature.

Mn, Pct	*K*, °F	Mn, Pct	*K*, °F
0.20	+6	0.90	−8
0.30	+3	1.00	−5
0.40	+1	1.10	−2
0.50	−1	1.20	+2
0.60	−3	1.30	+5
0.70	−6	1.40	+8
0.80	−8	1.50	+12

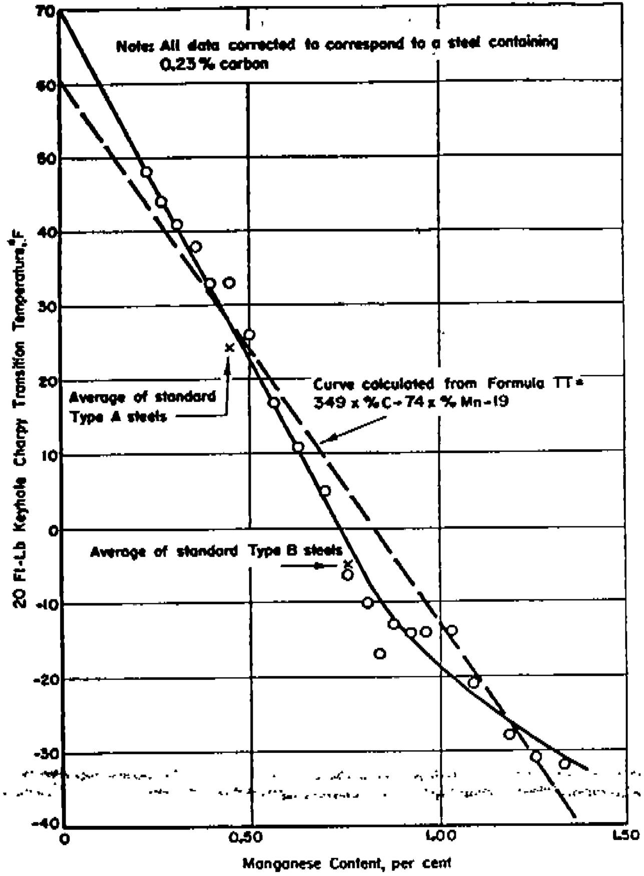


Fig. 6—Influence of manganese on the Charpy transition temperature of semikilled steels.

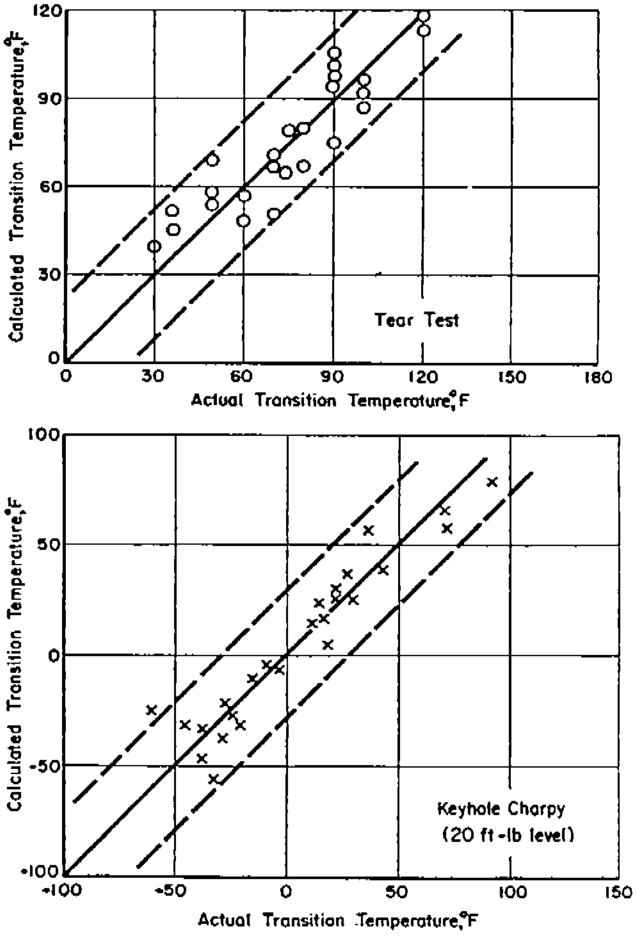
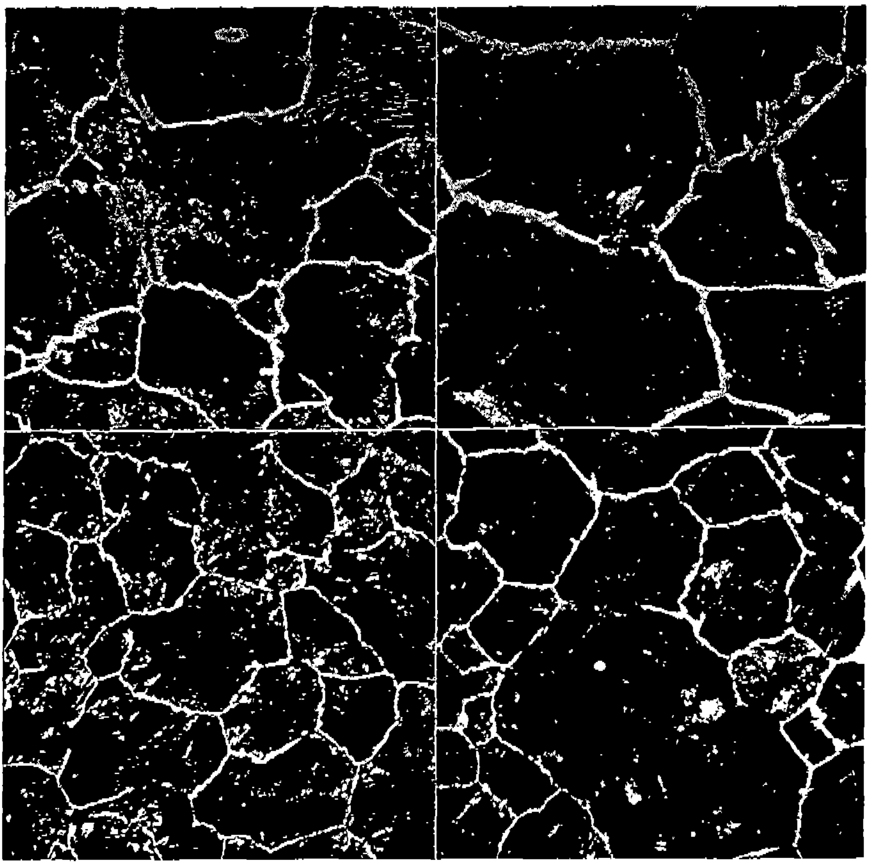


Fig. 7—Correlation of actual and calculated transition temperatures of experimental steels.


a—0.31 pct C-0.21 pct Mn alloy.

b—0.31 pct C-1.39 pct Mn alloy.

c—0.19 pct C-0.22 pct Mn alloy.

d—0.15 pct C-1.23 pct Mn alloy.

Fig. 8—Effect of manganese and carbon on the McQuaid-Ehn grain size of experimental ship-plate steels. X100.

temperatures than the laboratory steels made and processed in this investigation. This is probably an effect of rolling temperature. The laboratory steels on which the equations are based were rolled at 1850°F, while some of the commercial steels were probably finished at higher temperatures. It has been demonstrated previously[4] that increasing the temperature of the last rolling pass raises notched-bar transition temperatures. Increasing the finishing temperature 100°F raises the transition temperature in tear tests about 20°F. The same increase in finishing temperature raises the Charpy transition temperature about 5°F for steels containing 0.22 pct C and 0.50 pct Mn, and 10°F for steels containing 0.18 pct C and 0.76 pct Mn. If appropriate corrections are made to the calculated temperatures on the assumption that most of the commercial steels were rolled at 1950°F, the agreement is better than indicated by data in Table VII.

Relationships Among Carbon, Manganese, Grain Size, and Notched-Bar Properties

Various investigators have shown that heat treatments which refine the ferritic grain size of a particular semikilled steel improve its notched-bar properties.[4,12,13] The available information indicates that the Charpy transition temperature decreases approximately 25°F when the number of grains per unit volume of steel is doubled. This change in grain size corresponds to an increase of one number on the ASTM scale. On the other hand, it has also been demonstrated that semikilled steels with the same ferritic grain size can differ significantly in notched-bar properties. There is also some evidence[4] indicating that a relationship exists between the prior austenitic grain size of ship steels and their transition temperatures.

For these reasons it seemed desirable to measure the grain size of the experimental steels. Therefore, McQuaid-Ehn tests and ferrite grain counts were made on each steel with the results shown in Table VIII.

The grain counts show the average number of ferrite grains per 0.0001 sq in. of steel. For steels with equal amounts of ferrite, larger numbers indicate smaller ferrite grain sizes. Although it would be expected that increasing the manganese content would decrease the amount of ferrite, Table VIII indicates that the grain counts were independent of the manganese contents of these experimental steels. Therefore, manganese must have refined the ferritic grain size of these steels.

Table VIII also indicates that the number of ferrite grains per 0.0001 sq in. usually increased with carbon content. Since the total amount of ferrite decreased as the carbon content increased from 0.15 to 0.34 pct, the increase in carbon was obviously accompanied by a decrease in size of the ferrite

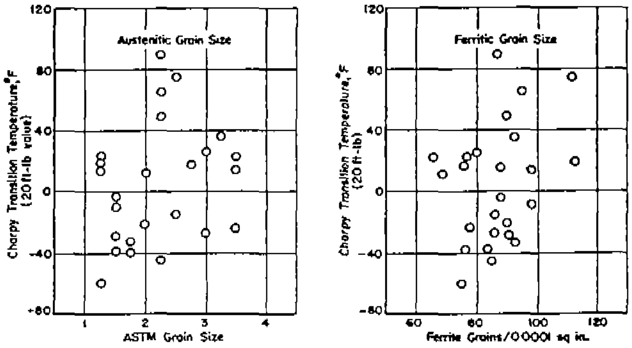


Fig. 9—Poor correlation between austenitic or ferritic grain sizes and Charpy transition temperatures.

Table VII. Transition Temperatures of Commercial Semikilled ¾ in. Ship Plate

	Composition, Pct		Tear Test Transition Temperature, °F		20 Ft-Lb Keyhole Charpy Transition Temperature, °F	
Plate Code	C	Mn	Actual	Calculated*	Actual	Calculated*
G-3	0.25	0.42	100	90	—	—
A	0.25	0.49	70	89	+10	+31
C	0.25	0.51	135	88	+15	+30
S-7	0.21	0.49	120	75	+17	+17
S-6	0.20	0.55	100	71	+14	+8
S-9	0.18	0.50	80	65	+10	+6
S-10	0.19	0.54	90	68	0	+6
S-11	0.20	0.55	90	71	+36	+8
S-8	0.14	0.46	90	53	+22	−4
58x428	0.33	0.55	130	114	+43	+55
5779	0.25	0.44	80	91	+20	+36
Average	0.22	0.50	99	80	+19	+19
G-6	0.18	0.96	50	55	—	—
S-2	0.17	0.60	110	60	+7	−7
S-21	0.22	0.81	70	71	−5	−10
S-23	0.20	0.75	100	66	+12	−12
S-1	0.17	0.66	100	58	+19	−13
S-13	0.17	0.68	90	58	−1	−16
S-22	0.19	0.77	100	62	+8	−17
S-20	0.18	0.73	80	60	+1	−16
S-19	0.19	0.78	80	62	+10	−18
S-18	0.17	0.73	100	57	−8	−20
B	0.16	0.76	60	53	−34	−27
S-5	0.17	0.90	70	53	+5	−35
50x426	0.21	0.78	80	69	−24	−12
1046	0.20	0.77	50	66	−28	−14
Average	0.18	0.76	81	60	−3	−17

* These transition temperatures were calculated according to the equations in Table III.

grains. Therefore, it appears that the influence of carbon on ferritic grain size tends to minimize its harmful effect on notched bar toughness.

The grain counts indicate that the ferritic grain sizes of the experimental steels ranged less than one number on the ASTM scale. This would also be true if the counts were corrected for the pearlite contents of the steels. Previous data[4,12,13] indicate that such a change in grain size would correspond to a shift of about 25°F in Charpy transition temperature. Therefore, very little of the 150°F range in transition temperature of these steels could be caused by variations in ferritic grain size.

Fig. 9 shows that the correlation between ferrite grain count data and Charpy transition temperature is very poor. Apparently, the minor differences in grain sizes of these steels were too small to have any marked effect on transition temperature. The rolling practice, which was the same for all steels, apparently controlled the ferritic grain size in these experiments.

Table VIII. Grain Size Data for ¾ In. Laboratory Steels Differing in Carbon and Manganese Contents

	Carbon, Pct				
Manganese, Pct	0.14-0.17	0.18-0.20	0.21-0.25	0.26-0.28	0.31-0.34
ASTM Grain Size*					
0.20-0.25	3.5	3	3.3	2.3	2.3
0.40-0.50	2.8	2	3.5	2.3	2.5
0.65-0.85	3.5	2.5	3.0	1.3	1.3
0.86-1.05	—	2†	2.3	1.5	1.3
1.06-1.25	1.8	1.8	—	—	—
1.26-1.50	—	1.5	1.4†	—	1.5
Ferrite Grains per 0.0001 Sq In.					
0.20-0.25	66	80	93	95	87
0.40-0.50	77	69	93	90	112
0.65-0.85	78	86	86	77	113
0.86-1.05	—	87†	—	98	91
1.06-1.25	93	76	—	—	—
1.26-1.50	—	84	83†	—	88

* Measured after McQuaid-Ehn tests involving carburizing for 8 hr at 1700°F.
† Averages for more than one steel.

The McQuaid-Ehn data show that all steels were coarse grained after carburizing for 8 hr at 1700°F. This indicates, that all experimental steels had a coarse austenitic grain size during hot rolling at 1850°F. Both carbon and manganese influenced the austenitic grain size developed in the standard carburizing test. Table VIII shows that increasing the amount of either element while holding the other at a constant level resulted in coarser austenite grains. These effects on the carburized grain size are illustrated by the micrographs in Fig. 8. The mechanism of this effect on grain size is obscure, although increasing either manganese or carbon would be expected to decrease the oxygen level of steel. It is well known, of course, that manganese lowers the grain coarsening temperature of aluminum-free steels, but the effect of carbon was not anticipated.

Fig. 9 also shows the poor correlation found between austenitic grain sizes and Charpy transition temperatures. The variations in austenite grain sizes were much larger than those noted in ferrite grain counts. This resulted from the grain coarsening produced in the McQuaid-Ehn tests, attributable to higher carbon or manganese contents. Although both elements coarsened the austenite, only carbon raised the Charpy transition temperature. Hence, the poor correlation.

Summary

Semikilled steels covering a range from 0.14 to 0.34 pct C and from 0.20 to 1.50 pct Mn were made and rolled in the laboratory. The effects of these elements on grain size, tensile properties, and notched-bar properties were evaluated. The following conclusions seem justified from the data examined.

Carbon raised and manganese lowered the transition temperature of semikilled steels. The effects of a particular change in composition differ quantitatively with the criterion used to define the notched-bar transition temperature. The transition temperature of semikilled steels in notched-bar tests can be improved by decreasing the carbon content. Manganese can be used to replace carbon in order to maintain the desired tensile strength. For equal strengths, steels with higher Mn-C ratios have better notched-bar properties.

Equations derived by multiple correlation of the experimental data provide satisfactory predictions of changes in strengths and notched-bar properties resulting from differences in manganese and carbon contents. The agreement between calculated and experimental values for semikilled steels is improved by taking rolling temperatures into consideration.

The McQuaid-Ehn grain size of semikilled steels increases significantly with increases in either carbon or manganese contents.

Carbon and manganese tend to refine the ferritic grain size of semikilled steels hot rolled at 1850°F, but these effects on notched-bar properties were not large enough to be important in this study.

No correlation was found between the notched-bar transition temperatures and either austenitic or ferritic grain sizes of the hot rolled steels studied. This does not mean that grain size has no effect on notched-bar toughness.

Acknowledgment

The data for this paper were obtained from experiments conducted under Contract NObs 53239, Index No. NS-011-078. Grateful acknowledgment is made to the Ship Structure Committee and the Bureau of Ships for permission to publish the results. We also wish to express our appreciation to the Advisory Committee, of the National Academy of Sciences, National Research Council, on the project, T. S. Washburn, Samuel Epstein, Finn Jonassen, M. W. Lightner, T. T. Watson, and S. L. Hoyt, and to the investigator, C. H. Lorig, for advice and counsel.

References

[1] M. L. Williams, M. R. Meyerson, G. L. Kluge, and L. R. Dale: Investigation of Fractured Steel Plates Removed from Welded Ships. Ship Structure Committee (June 1, 1951).

[2] N. A. Kahn and E. A. Imbembo: A Method of Evaluating Transition from Shear to Cleavage Failure in Ship Plate. *Welding Journal* (1951) **30**, No. 2, pp. 79s-90s.

[3] R. W. Vanderbeck and M. Gensamer: Evaluating Notch Toughness. *Welding Journal* (1950) **29**, pp. 37s-48s.

[4] R. H. Frazier, F. W. Boulger, and C. H. Lorig: An Investigation of the Influence of Deoxidation and Chemical Composition on Notched Bar Properties of Semi-killed Ship Steel: Ship Structure Committee Report. Serial No. SSC-53 (Nov. 28, 1952).

[5] C. F. Quest and T. S. Washburn: Tensile Strength and Composition of Hot-Rolled Plain Carbon Steels. *Trans.* AIME (1940) **140**, pp. 489-496.

[6] N. A. Kahn and E. A. Imbembo: Notch Sensitivity of Steel Evaluated by Tear Tests. *Welding Journal* (1949) **28**, pp. 153s-166s.

[7] E. J. Ripling: How to Determine Toughness of Steels from Notched Bar Tests. *Materials and Methods* (September 1951) **34**, No. 3, p. 81.

[8] J. A. Rinebolt and W. J. Harris, Jr.: Effect of Alloying Elements on Notch Toughness of Pearlitic Steels. *Trans.* ASM (1951) **43**, pp. 1175-1214.

[9] J. H. Hollomon and L. D. Jaffe: *Ferrous Metallurgical Design.* (1947) New York. John Wiley and Sons, Inc.

[10] W. Barr and A. J. K. Honeyman: Effect of Mn-C Ratio on the Brittle Fracture of Mild Steel. *Journal* Iron and Steel Inst. (1947) **157**, pp. 239-246.

[11] N. A. Kahn and E. A. Imbembo: Further Study of the Navy Tear Test. *Welding Journal* (1950) **29**, No. 2, pp. 84s-96s.

[12] S. Epstein: Discussion on Article by J. E. Campbell, R. H. Frazier, and H. O. McIntire. *Welding Journal* (1952) **31**, No. 2, pp. 78s-94s.

[13] J. M. Hodge, R. D. Manning, and H. M. Reichhold: The Effect of Ferrite Grain Size on Notch Toughness. *Trans.* AIME (1949) **185**, pp. 233-239; JOURNAL OF METALS (March 1949).

The opinions expressed herein are those of the authors. They do not necessarily represent those of the Ship Structure Committee, the Bureau of Ships, the Dept. of the Navy, or of the Advisory Committees of the National Academy of Sciences, National Research Council.

APPENDIX

APPENDIX

The transition temperatures for tear tests listed in SSC-53 were determined by the usual method; that is, testing at a particular temperature was stopped when one brittle specimen was encountered. In some cases the transition temperature corresponds to a temperature where only one of four specimens was brittle. This was true if the first three specimens behaved in ductile fashion. In other instances the first specimen exhibited a brittle fracture, so no more specimens were tested at the transition temperature.

Some additional tear tests were made after the preparation of the original draft of SSC-53. The new data permit the determination of tear test transition temperatures based on a P = 0.5 probability of brittle fracture. From a scientific standpoint this definition of transition temperature is preferable to the one used in SSC-53 and the AIME paper. The reasons for this opinion are discussed in a forthcoming publication.*

The additional tear test data are given in Table A-2. In the complete series of tear tests, four observations were made at each temperature of interest. By using all of the data, new transition temperatures corresponding to P = 0.5 for brittle fracture were determined for the experimental steels.

---

*Frazier, R. H., Spretnak, J. W., and Boulger, F. W., "Reproducibility of Keyhole Charpy and Tear Test Data on Laboratory Heats of Semikilled Steel", ASTM Preprint 91 d (1953).

The transition temperatures defined by the two criteria, for the steels with different manganese and carbon contents, are compared in Table A-1. The probability criterion changed the transition temperatures by +5°to -18°F from those reported previously. On the average use of the P = 0.5 probability of brittle fracture to define the transition temperature resulted in values lower by 9°F.

An equation for calculating the tear test transition temperature defined on the probability basis was determined. This formula is:

$$\text{Tear Test Transition Temperature, F} = -7 + (386 \text{ x } \%\text{ C}) - (18 \text{ x } \%\text{ Mn})$$

Standard error of estimate = 9°F.

As would be expected, this formula differs from Equation 6 of Table III (AIME paper).

The standard error is small, indicating that the revised formula fits the data very well. For instance, the transition temperatures calculated for Steels A and B are 70°F and 58°F, respectively, compared to the experimentally determined values of 73°F and 55°F listed in Table A-1. The small standard error of estimate indicates that considerable reliance can be placed on calculations based on the equation.

TABLE A-1. REVISED COMPILATION OF TEAR-TEST TRANSITION TEMPERATURES OF SEMI-KILLED STEELS MADE IN THE LABORATORY

Heat	Transition Temperature, F 1 of 4	 P = 0.5
7448	50	42
6539	60	50
6586	40	30
7517	30	20
6590	90	72
7532	70	64
B	73	55
7518	50	55
6554	70	55
7516	40	26
6599	60	60
6589	100	86
A	75	73
6547	80	67
6598	70	67
7519	50	39
7520	90	85
7521	100	90
7522	90	95
7533	70	73
7527	120	113
6596	120	116
6597	90	95
7525	90	86
7524	100	96

TABLE A-2. ADDITIONAL$^{(a)}$ NAVY TEAR-TEST DATA FOR STEELS IN THE CARBON-MANGANESE SERIES

Heat	Specimen	Testing Temp, F	Maximum Load, lb	Energy to Start Fracture	Energy to Propagate Fracture	Per Cent Shear in Fracture
			0.15 Per Cent Carbon Series			
A7448	T-2	40	34,350	1040	83	5
	U-1	40	35,600	1140	142	10
	U-2	40	34,500	1050	83	5
	S-2	50	35,050	1170	75	4
	T-1	50	33,800	1040	58	5
A6586	C-1	10	40,150	1583	342	45
	C-2	10	39,400	1416	108	5
	D-1	10	40,050	1516	125	7
	D-2	10	39,950	1533	108	10
	B-1	20	40,300	1500	750	94
	B-2	20	39,750	1425	142	5
	A-1	30	40,600	1649	757	92
	A-2	30	38,650	1240	541	47
	Q-2	30	39,150	1374	842	100
	L-2	40	38,200	1367	775	85
	M-2	40	38,650	1425	860	98
	N-2	40	38,250	1342	175	18
A7516	V-1	0	44,750	1913	158	3
	V-2	0	43,600	1539	216	10
	W-1	0	43,800	1466	117	2
	W-2	0	44,150	1591	117	3
	B-1	10	43,000	1300	833	95
	B-2	10	42,750	1275	525	47
	C-1	10	43,300	1327	117	3
	C-2	10	42,050	1175	193	10
	R-1	20	42,950	1308	860	93
	R-2	20	42,900	1350	450	40
	S-1	20	43,150	1327	815	95
	S-2	20	43,450	1358	142	5

TABLE A-2. (Continued)

Heat	Specimen	Testing Temp, F	Maximum Load, lb	Energy to Start Fracture	Energy to Propagate Fracture	Per Cent Shear in Fracture
			0.15 Per Cent Carbon Series (Continued)			
A7516	U-1	30	43,750	1441	58	4
	U-2	30	43,000	1342	92	3
	T-1	40	41,450	1210	891	100
	T-2	40	41,400	1170	117	5
A7517	A-1	0	46,450	1466	167	2
	A-2	0	47,250	1530	142	2
	B-1	0	46,150	1258	150	3
	B-2	0	47,200	1491	117	2
	U-1	10	45,300	1475	125	5
	U-2	10	44,650	1358	142	7
	V-1	10	43,700	1258	800	95
	V-2	10	44,800	1250	150	3
	S-2	20	44,200	1225	891	100
	T-2	20	44,000	1190	984	100
	T-1	20	44,750	1250	940	100
	S-1	30	44,150	1275	860	100
			0.20 Per Cent Carbon Series			
A6590	A-1	50	34,750	766	58	2
	A-2	50	35,800	860	100	7
	B-1	50	36,350	900	75	3
	B-2	50	37,000	961	100	3
	V-1	60	33,150	808	658	100
	V-2	60	34,700	875	100	7
	W-1	60	34,100	734	642	100
	W-2	60	34,300	658	500	5
	T-1	70	33,950	833	642	95
	T-2	70	33,400	866	92	6
	U-1	70	34,350	900	715	100
	U-2	70	33,950	824	92	5

TABLE A-2. (Continued)

Heat	Specimen	Testing Temp, F	Maximum Load, lb	Energy to Start Fracture	Energy to Propagate Fracture	Per Cent Shear in Fracture
			0.20 Per Cent Carbon Series (Continued)			
A6590	G-2	80	34,400	815	684	100
	H-2	80	35,400	925	642	100
	J-1	80	35,200	860	1077	100
	J-2	80	35,850	961	707	100
A7532	A-1	50	36,250	833	67	3
	A-2	50	37,100	935	142	8
	B-1	50	37,750	1033	75	5
	B-2	50	37,900	990	42	3
A7518	U-1	30	43,700	1175	117	8
	U-2	30	43,450	1125	83	2
	V-1	30	42,950	1020	408	26
	V-2	30	42,800	1050	167	10
	S-1	40	42,600	1090	133	10
	S-2	40	42,300	1125	459	45
	T-1	40	42,750	1110	108	2
	T-2	40	41,550	1010	984	100
	R-1	50	42,750	1170	784	96
	R-2	50	42,050	1060	133	8
A7519	X-2	20	45,300	925	238	20
	A-1	20	45,450	1040	250	10
	A-2	20	46,300	1110	283	12
	B-1	20	48,200	1342	125	5
	B-2	20	46,850	1077	158	5
	V-2	30	46,350	1160	133	3
	W-1	30	45,750	1080	242	13
	W-2	30	44,350	1120	150	7
	X-1	30	46,050	1175	559	67
	V-1	40	44,850	1080	815	100
	T-2	40	45,600	1170	234	15
	U-1	40	44,250	975	650	70
	U-2	40	45,000	No curve		100

TABLE A-2. (Continued)

Heat	Specimen	Testing Temp, F	Maximum Load, lb	Energy to Start Fracture	Energy to Propagate Fracture	Per Cent Shear in Fracture
		0.20 Per Cent Carbon Series (Continued)				
A7519	S-1	50	44,700	1077	842	100
	S-2	50	44,450	1100	808	100
	T-1	50	44,550	1170	750	100
A6599	T-1	50	48,850	1234	92	3
	T-2	50	49,100	1250	125	1
	U-1	50	48,850	1125	367	25
	P-2	60	47,150	1140	83	3
	S-2	60	47,400	1125	875	100
		0.25 Per Cent Carbon Series				
A6589	S-1	70	35,900	740	67	3
	S-2	70	34,900	725	50	3
	T-1	70	35,700	740	50	3
	T-2	70	35,300	766	75	2
	Q-1	80	35,050	725	600	85
	Q-2	80	35,100	707	67	8
	R-1	80	35,450	757	616	98
	R-2	80	35,250	734	559	100
	B-1	100	34,000	700	659	100
	D-1	100	35,300	808	935	100
A6547	U-2	50	42,950	1020	125	5
	V-1	50	41,600	866	83	3
	V-2	50	42,600	935	117	7
	W-1	50	43,150	866	83	3
	B-1	60	40,000	833	433	55
	B-2	60	41,050	875	715	100
	C-1	60	40,400	850	715	100
	W-2	70	42,200	958	665	90
	T-2	70	39,200	740	734	100
	U-1	70	41,500	875	125	10
	T-1	80	39,700	766	734	100

TABLE A-2. (Continued)

Heat	Specimen	Testing Temp, F	Maximum Load, lb	Energy to Start Fracture	Energy to Propagate Fracture	Per Cent Shear in Fracture
			0.25 Per Cent Carbon Series (Continued)			
A6554	Y-1	40	44,150	1050	108	3
	Y-2	40	44,200	1040	142	3
	W-1	50	44,550	1125	559	85
	W-2	50	43,850	958	358	30
	X-1	50	43,600	1020	590	73
	X-2	50	43,500	975	850	100
	R-1	60	42,900	975	757	100
	R-2	60	43,200	1010	875	100
	S-1	60	42,450	940	700	93
	S-2	60	42,550	975	775	100
	P-2	70	41,700	824	800	100
	Q-1	70	42,250	984	850	100
	Q-2	70	42,900	975	784	100
A6598	M-1	60	45,050	885	175	5
	N-2	60	46,900	984	183	15
	P-1	60	45,750	885	484	52
	S-1	70	46,150	1010	216	12
			0.30 Per Cent Carbon Series			
A7520	U-1	70	35,450	740	50	2
	U-2	70	35,200	750	67	3
	V-1	70	36,450	766	67	3
	V-2	70	36,200	815	75	5
	S-2	80	36,200	824	92	10
	T-1	80	35,600	775	550	92
	T-2	80	35,600	734	92	5
	R-2	90	35,800	766	541	100
A7521	H-1	70	37,250	740	83	3
	H-2	70	37,800	734	58	2
	J-1	70	37,700	740	42	2
	J-2	70	37,300	690	33	1

TABLE A-2. (Continued)

Heat	Specimen	Testing Temp, F	Maximum Load, lb	Energy to Start Fracture	Energy to Propagate Fracture	Per Cent Shear in Fracture
0.30 Per Cent Carbon Series (Continued)						
A7521	T-2	80	37,800	766	92	5
	U-1	80	37,750	757	625	100
	U-2	80	37,500	734	58	5
	S-1	90	36,250	665	58	10
	S-2	90	36,400	725	550	100
	T-1	90	37,200	766	67	5
A7522	P-2	90	39,050	707	83	15
	Q-1	90	39,800	715	100	12
	Q-2	90	38,300	633	108	15
A7533	V-1	60	44,550	757	117	2
	V-2	60	43,800	740	193	15
	W-1	60	44,200	757	75	2
	W-2	60	43,800	766	175	5
	T-2	70	43,850	648	625	100
	U-1	70	43,550	650	633	100
	U-2	70	43,200	642	658	100
	T-1	80	42,700	633	616	100
A7524	V-1	80	48,850	766	108	3
	V-2	80	50,800	808	133	3
	W-1	80	47,750	650	75	3
	V-1	90	48,100	775	308	20
	V-2	90	48,650	815	142	10
	T-2	90	48,800	850	650	100
	S-1	100	47,350	725	367	45
	S-2	100	48,400	866	616	100
	T-1	100	49,350	875	725	100
0.35 Per Cent Carbon Series						
A7527	S-2	100	36,550	650	100	5
	T-1	100	36,050	600	50	2
	T-2	100	35,900	633	142	5

TABLE A-2. (Continued)

Heat	Specimen	Testing Temp, F	Maximum Load, lb	Energy to Start Fracture	Energy to Propagate Fracture	Per Cent Shear in Fracture
			0.35 Per Cent Carbon Series (Continued)			
A7527	R-1	110	36,000	616	525	97
	R-2	110	35,300	600	466	95
	S-1	110	36,500	658	508	100
A6596	T-2	100	38,500	559	125	12
	U-1	100	37,150	516	108	10
	U-2	100	37,500	541	234	27
	B-2	110	37,450	650	541	100
	T-1	110	37,300	550	142	20
	Q-1	110	36,600	584	383	47
	M-1	120	36,400	633	534	100
	P-1	120	37,400	625	525	100
	P-2	120	36,100	642	283	35
A6597	H-2	90	41,950	665	183	33
	J-1	90	43,700	725	108	15
	K-1	90	42,450	707	108	15
A7525	S-1	70	44,300	665	167	10
	S-2	70	45,650	707	158	10
	T-1	70	45,600	707	108	3
	R-2	80	44,500	658	466	80
	A-1	80	44,400	665	108	8
	A-2	80	44,400	700	67	10
	Q-2	90	45,000	642	334	440
	R-1	90	44,300	675	342	25

(a) Other test data were reported in the Second Progress Report, "An Investigation of the Influence of Deoxidation and Chemical Composition on Notched-Bar Properties of Semikilled Ship Steel", Serial No. SSC-53.