SERIAL NO. **SSC-71**

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Third

PROGRESS REPORT

(Project SR-110)

on

THE INFLUENCE OF HEAT TREATMENT ON THE NOTCHED-BAR PROPERTIES OF SEMIKILLED STEEL PLATE

by

R. H. FRAZIER, F. W. BOULGER and C. H. LORIG
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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.

March 15, 1954

SERIAL NO. **SSC-71**
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.

March 15, 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 Third Progress Report, SSC-71, of the investigation, entitled "The Influence of Heat Treatment on the Notched-Bar Properties of Semikilled Steel Plate" 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

THIRD
Progress Report
(Project SR-110)

on

The Influence of Heat Treatment on the Notched-Bar Properties of Semikilled Steel Plate

by

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

BATTELLE MEMORIAL INSTITUTE

under

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

for

SHIP STRUCTURE COMMITTEE

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THE INFLUENCE OF HEAT TREATMENT ON THE NOTCHED-BAR PROPERTIES OF SEMIKILLED STEEL PLATE

INTRODUCTION

Earlier work[1] on ship plate steels indicated that the temperature at which ship plate is finished has a very significant effect on notched-bar properties. Plates rolled in the laboratory, where the finishing temperature can be carefully controlled, showed a 16°F decrease in tear-test transition temperature when the finishing temperature was lowered 200°F. The same plates showed a drop of 10°F in the keyhole Charpy transition temperature from the same decrease in finishing temperature. Commercially finished plates[2] exhibit a similar change in transition temperatures with finishing temperature.

When the ferrite grain size of the laboratory plates was determined, a close relationship was found between the ferrite grain size, as determined by the counting method[3], and the notched-bar transition temperature. Converting the grain counts to ASTM numbers meant changes of 30° and 60°F in keyhole Charpy and tear-test transition temperatures, respectively[4]. The 30°F change in keyhole Charpy transition temperature agrees with the findings on low-carbon steels of Hodge, Manning, and Reichhold[5] despite the differences in composition of the steels.

The cooling rate after rolling varies from one steel plant to another. This variation changes the microstructure[3] and appeared very likely to affect the notched-bar properties of the steel plates. From these facts, a comprehensive study of the effect of austenitizing temperature and cooling rate on notched-bar properties of ship plate steel seemed desirable. Therefore, the study was conducted under the Department of the Navy, Bureau of Ships Contract NObs-53239, Index No. NS-011-078. Results of this study can be used to estimate the effect of rolling temperature and of cooling rates from rolling temperatures on the notched-bar properties of semikilled steel plate.

MATERIAL

The semikilled steel plate used in this investigation was a 3/4-inch, hot-rolled plate from an open-hearth heat. Other plates from this heat have been used on many other studies performed for the Ship Structure Committee[6,7,8], and the heat has been identified as Project Steel "A". The chemical composition of the plate[8] is 0.25 per cent carbon, 0.49 per cent manganese, 0.011 per cent phosphorus, 0.045 per cent sulfur, 0.04 per cent silicon, and 0.004 per cent nitrogen. The tensile strength of the plate is 58,650 psi, with an elongation of 33.4 per cent in eight inches.

The Navy tear-test properties of the as-rolled plate were determined at Battelle using 48 specimens divided into four groups as shown by the diagram in Figure 1. Each group was tested as an individual steel. Four tear-test specimens from each group were broken at +70°, +80°, and +90°F. Test data from individual tests are shown in Table A-1 of the Appendix. The results of these tests are summarized in Table 1. When tested at +90°F, all 16 specimens had fractured surfaces exhibiting more than 50 per cent ductile type of failure. At +70°F, 15 of the 16 specimens showed a 50 per cent or more cleavage fracture. This is a very sudden transition in fracture texture, much sharper than is characteristic of most steels. Half of the specimens were brittle at 80°F; this would be the transition temperature: the temperature corresponding to a probability of 50 per cent brittle tests. Based on the definition of transition temperature as the highest temperature at which one or more specimens out of four are brittle, the transition temperatures of the various groups are 80°, 70°, 80°, and 80°F, respectively. This is the definition recommended by Kahn and Imbembo[8]. Kahn[8] reported the transition temperature of this steel as 70°F.

The keyhole Charpy transition curve as determined at Battelle for this steel in the hot-rolled condition is shown in Figure 2. The properties in two directions were determined

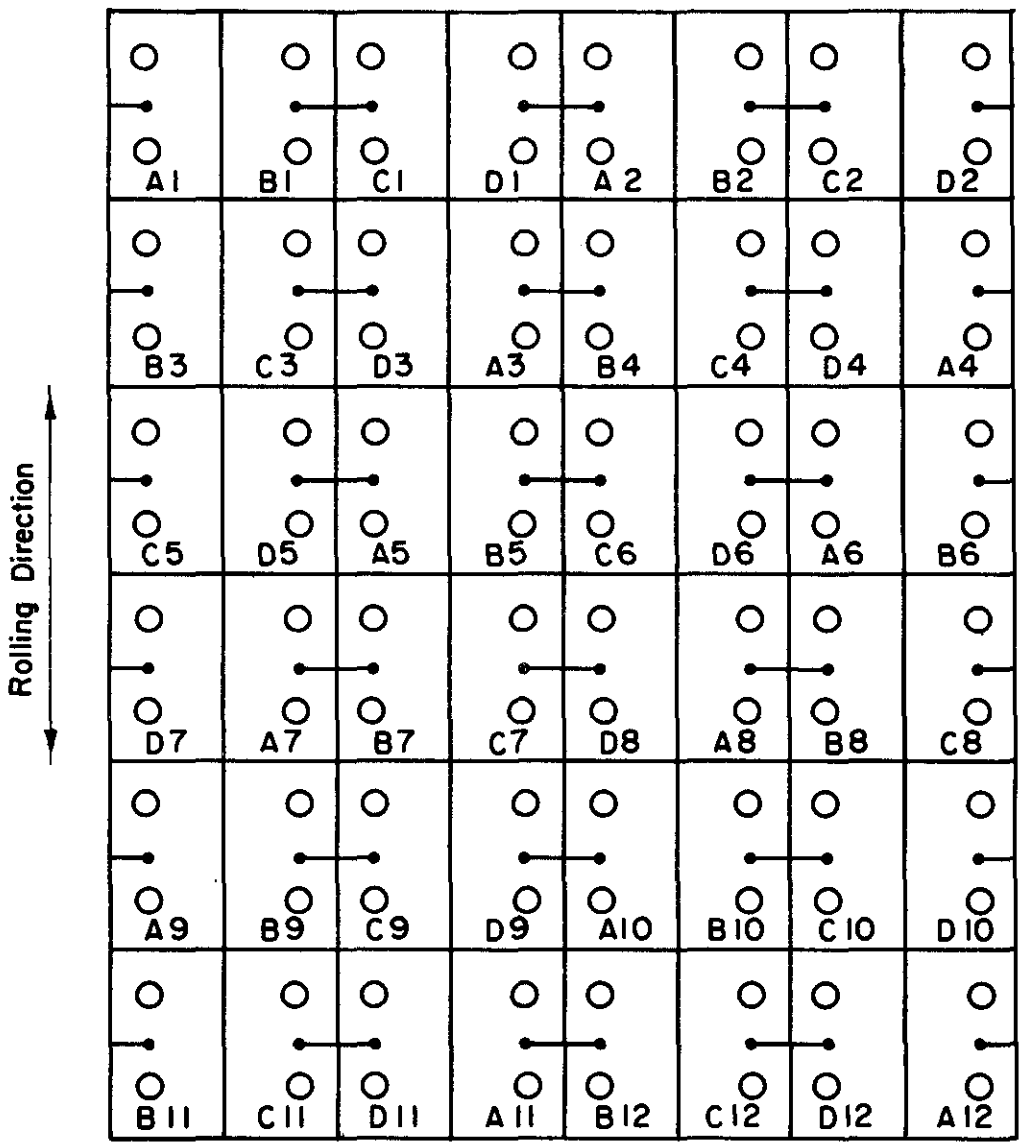


FIGURE 1. LOCATION OF TEAR-TEST SPECIMENS FROM AS-ROLLED PROJECT STEEL "A"

A-6664

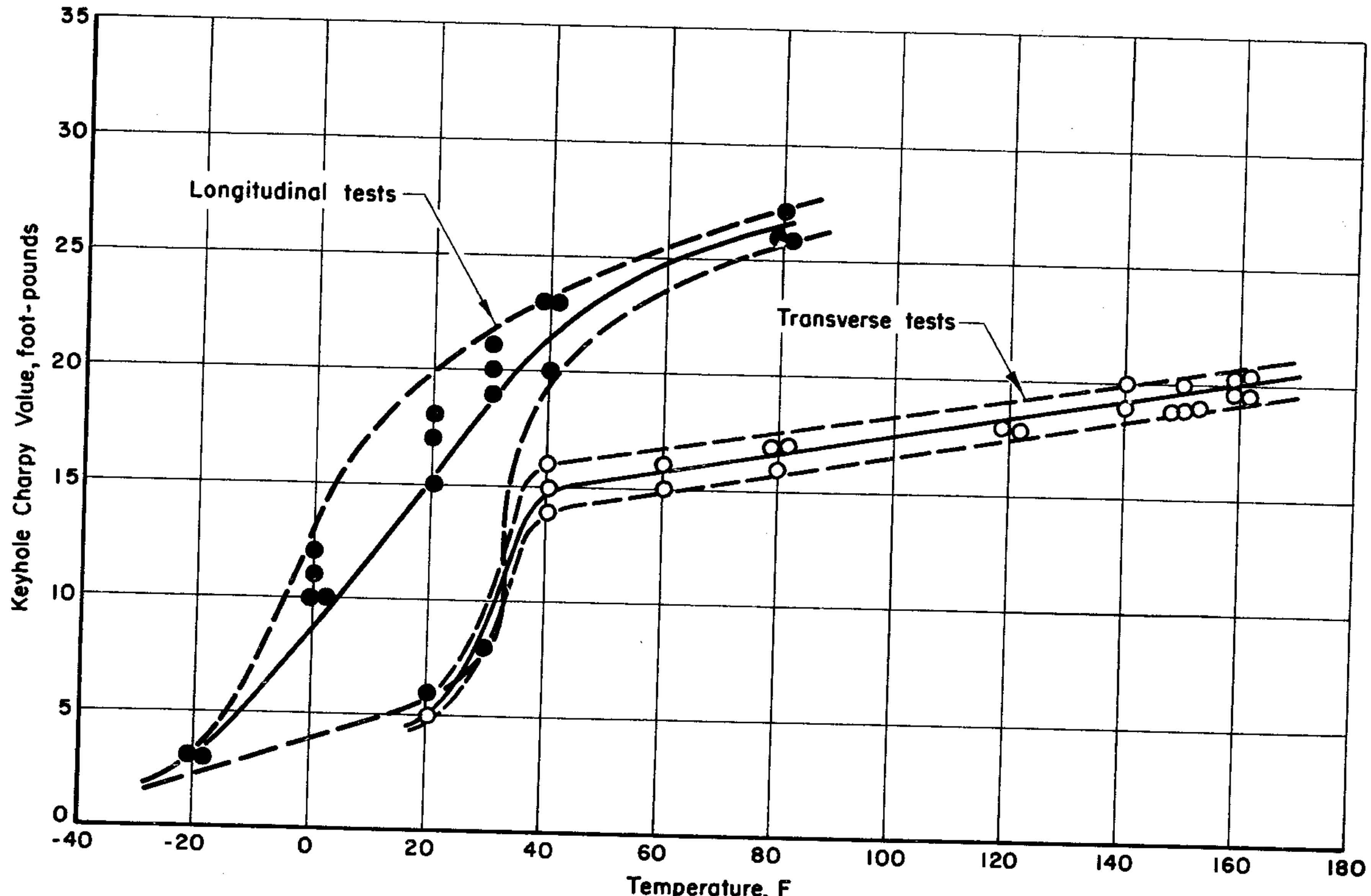


FIGURE 2. KEYHOLE CHARPY TRANSITION CURVES FOR LONGITUDINAL AND TRANSVERSE SPECIMENS FROM AS-ROLLED PROJECT STEEL "A"

A-6665

TABLE 1. SUMMARY OF TEAR-TEST RESULTS FROM AS-ROLLED PROJECT STEEL "A".

Group Number	Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds: To Start Fracture	Energy, foot-pounds: To Propagate Fracture	Average Per Cent Shear in Fracture	Number of Brittle Specimens
A	70	37,100	740	200	21	4
A	80	36,425	735	350	45	2
A	90	37,125	740	610	79	0
B	70	36,990	755	85	13	4
B	80	36,240	690	610	76	0
B	90	36,810	710	610	82	0
C	70	37,625	790	310	37	3
C	80	36,760	700	300	38	3
C	90	36,550	720	670	81	0
D	70	36,710	705	100	13	4
D	80	37,040	710	285	40	3
D	90	37,425	720	710	84	0
All	70	37,105	750	175	23	15
All	80	36,615	710	385	50	8
All	90	36,980	720	650	82	0

by specimens notched normal to the plate surface. The Charpy value of the transverse specimen is never as large as the value in the longitudinal direction. The transition temperature at the 20-foot-pound level is 34°F for the longitudinal specimens and approximately 160°F for the transverse direction. The 20-foot-pound value is in the flat portion of the transition curve for the transverse specimens and is not a good criterion to use for transition temperature.

Frequency distribution plots of Charpy values for steels of this type indicate that a minimum point in the frequency curve occurs at approximately the 12-foot-pound level[9]. At the 12-foot-pound level, the respective transition temperatures of longitudinal and transverse specimens are 10°F and 34°F. The temperature for the 12-foot-pound level will be used for comparisons in this report. Boodberg and others[6] reported the temperatures of the 20- and the 12-foot-pound levels as +20° and +8°F, respectively for longitudinal specimens. Tests made at Pennsylvania State College on plate from the same heat of steel showed the temperature for the two energy levels as +10° and -8°F[7] for longitudinal specimens.

HEAT TREATMENT

The heat treating was performed in a large electric furnace which had sufficient heating capacity to heat treat at least six 6- by 12 1/2-inch sections of 3/4-inch plate. The six plates were placed in a hot furnace on edge and separated by small sections of refractory brick splits. Since the two outer plates might have different heating and cooling rates, these plates were not used in the test program. One of the center plates contained a thermocouple for determining the heating and cooling rates that would be typical of the three remaining test plates. A typical heating curve is shown in Figure 3. Five austenitizing temperatures ranging from 1500° to 1900°F were used in this study. After the plates had been in the furnace for 1 1/2 hours, they were withdrawn and cooled by four different methods.

The 1 1/2-hour heating time was sufficient for all the plates to reach furnace temperature except those heated to 1500°F. Here the thermocouple showed a temperature of only 1480°F when 90 minutes had elapsed. The austenitic grain size resulting from the 90-minute treatments is shown by the photomicrographs in Figure 4. Since the plates treated at 1500°F for 1 1/2 hours did not reach furnace temperature, another group of plates was heat treated at 1500°F for 8 hours. The austenitic grain size, after such a treatment, was very similar to the one shown for the 1600°F treatment in Figure 4. This was a mixture of large and small grains.

The austenitic grain-coarsening temperature of this steel is about 1600°F. Both coarse and fine grains were found in the plate heated 1 1/2 hours at this temperature. Heating for

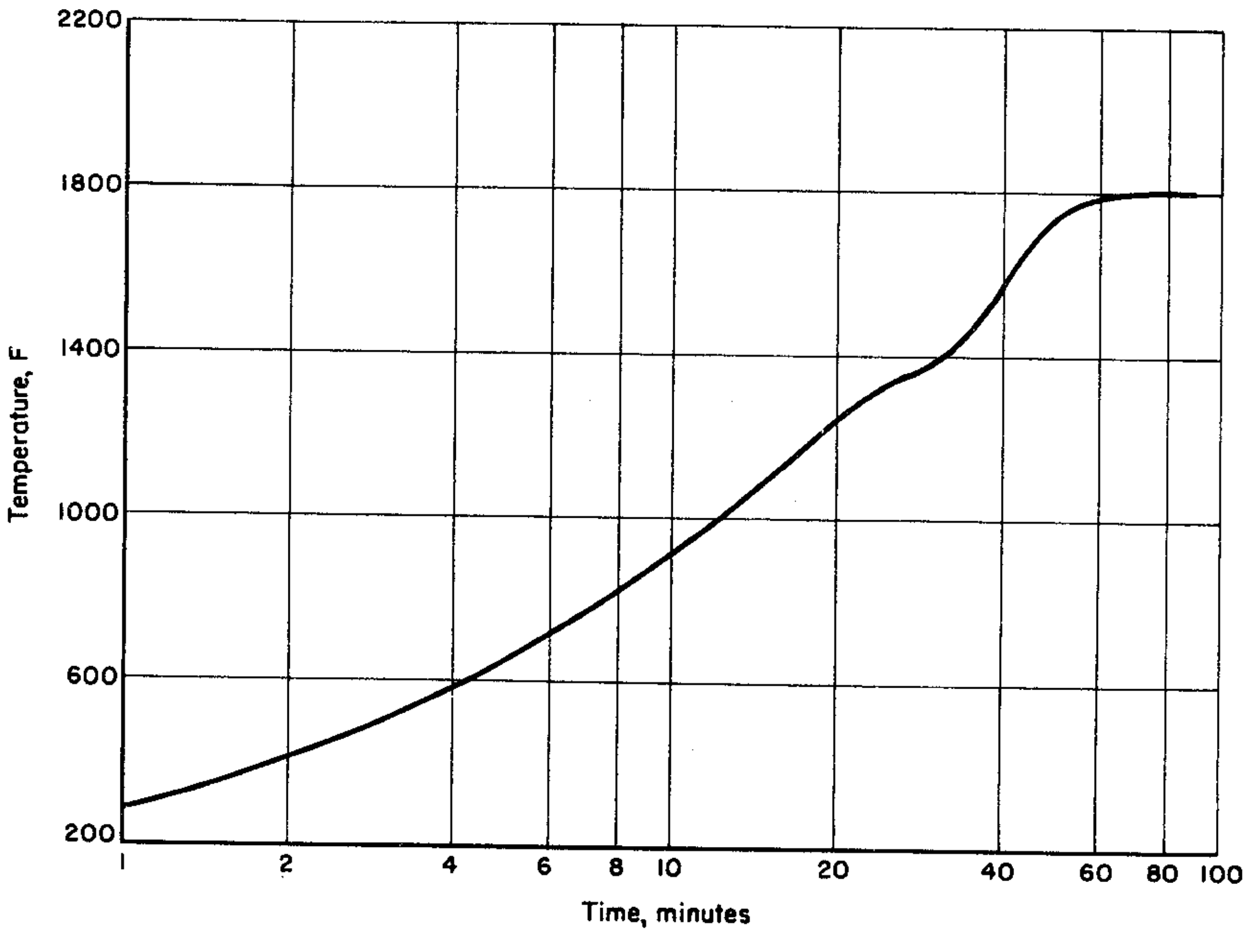
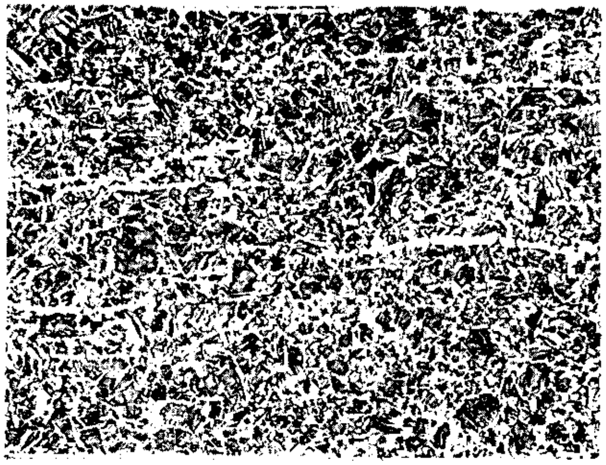
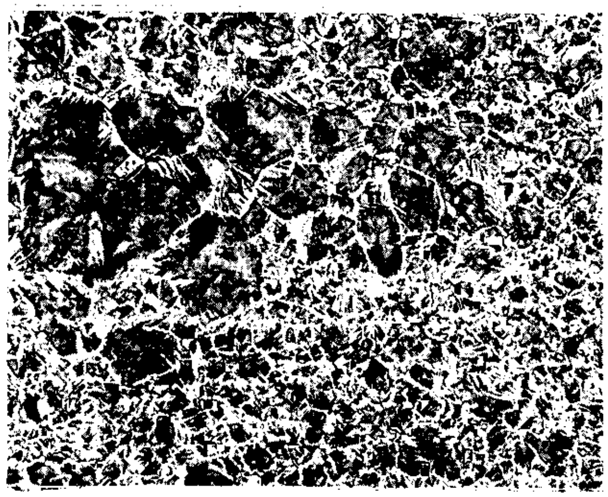


FIGURE 3. HEATING RATE FOR CENTER OF $\frac{3}{4}$-INCH PLATE; FURNACE TEMPERATURE-1800 F

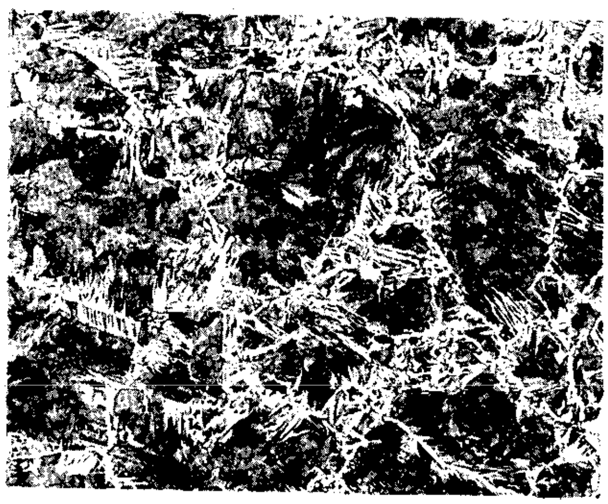
A-6666



100X Austenitized at 1500 F 79514



100X Austenitized at 1600 F 79523



100X Austenitized at 1700 F 79530

FIGURE 4. MICROSTRUCTURE AFTER WATER QUENCHING FROM VARIOUS AUSTENITIZING TEMPERATURES AFTER HEATING 1-1/2 HOURS; PICRAL ETCH

eight hours at 1600°F produced uniformly coarse austenite grains.

The four methods of cooling used to give different ferrite grain sizes and microstructures varied from air-blast cooling to furnace cooling. The air-blast cooling was done by placing the plates, still separated by the refractory-brick splits, in front of a large electric fan, thus cooling the plates in circulating air. Still-air cooling, done in a similar way but without the fan, produced a somewhat slower cooling rate. The third method consisted of burying the plates in vermiculite. This produced a faster cooling rate than that resulting from furnace cooling. The last and slowest cooling rate was produced by furnace cooling. Typical cooling curves are shown in Figure 5.

MICROSTRUCTURE

The ferrite grain sizes of the heat-treated steels were determined by counting the number of ferrite grains in a 4-square-inch area of a photomicrograph taken at 100 diameters and dividing by four. The counts of longitudinal and transverse direction were in good agreement, as shown in Table 2. In addition to changing the ferrite grain size, the heat treatments change the pearlite distribution and spacing. The pearlite distribution was measured by counting the patches of pearlite in the same areas used for the ferrite grain-size

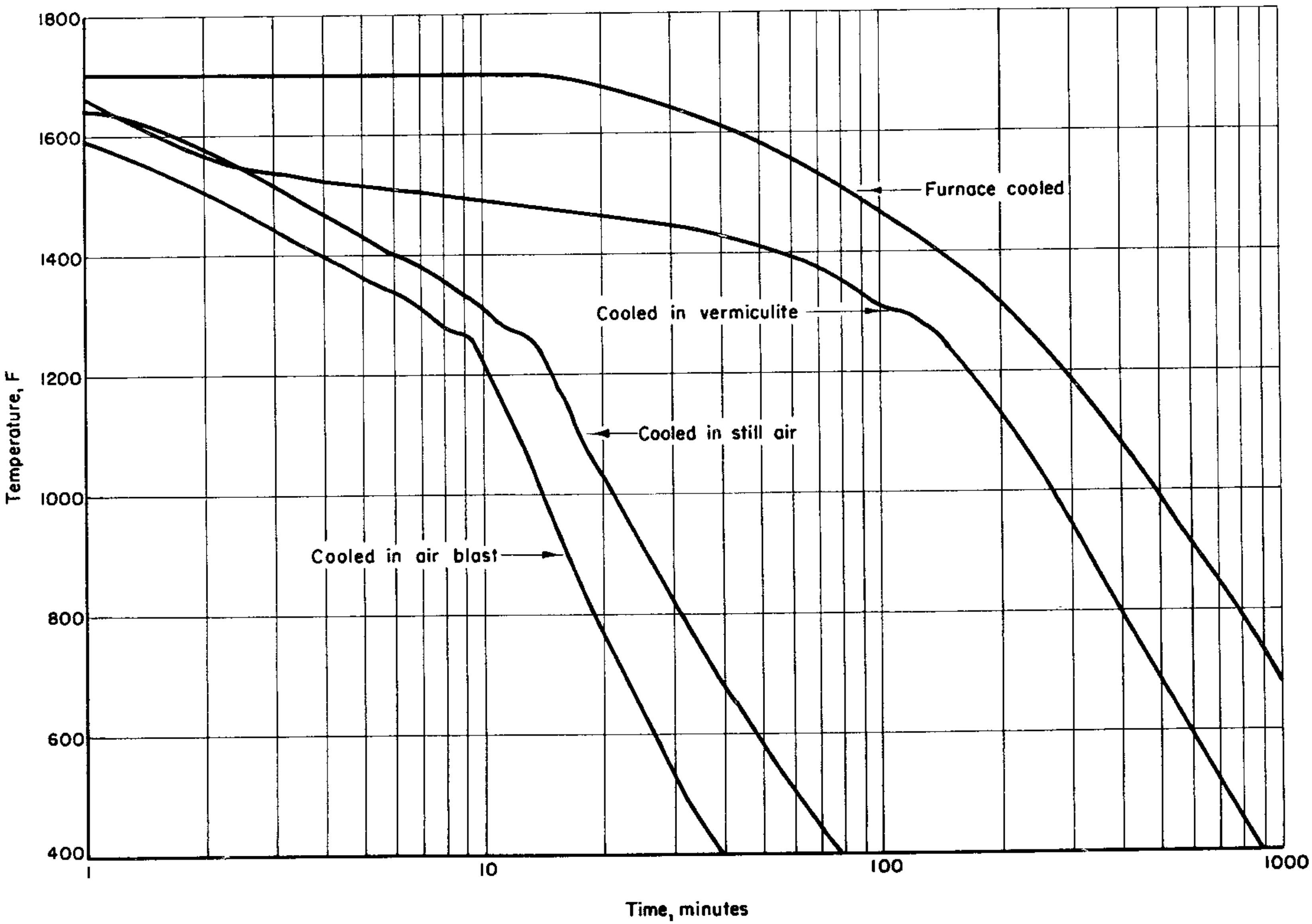


FIGURE 5. COOLING CURVES OF PLATE AUSTENITIZED AT 1700 F

A-6667

TABLE 2. FERRITE GRAIN SIZES OF SPECIMENS OF PROJECT STEEL "A" PLATE HEATED AT VARIOUS TEMPERATURES AND COOLED AT VARIOUS RATES TO ROOM TEMPERATURE

Austenitizing Temperature, F	Type of Cooling	Ferrite Grain Size, Grains per Square Inch at 100X		
		Longitudinal	Transverse	Average
		Furnace Time — 1-1/2 Hours		
1500	Air blast	90	96	93
1500	Still air	139	108	123
1500	Vermiculite	82	82	82
1500	Furnace	82	98	93
1600	Air blast	126	131	128
1600	Still air	98	100	99
1600	Vermiculite	57	48	51
1600	Furnace	56	62	59
1700	Air blast	114	139	126
1700	Still air	87	84	85
1700	Vermiculite	48	36	42
1700	Furnace	28	37	31
1800	Air blast	60	64	62
1800	Still air	51	46	48
1800	Vermiculite	21	23	22
1800	Furnace	18	20	19
1900	Air blast	52	61	56
1900	Still air	45	47	46
1900	Vermiculite	26	22	24
1900	Furnace	18	21	19
		Furnace Time — 8 Hours		
1500	Air blast	105	86	95
1500	Still air	86	77	81
1500	Vermiculite	64	64	64
1500	Furnace	41	44	42

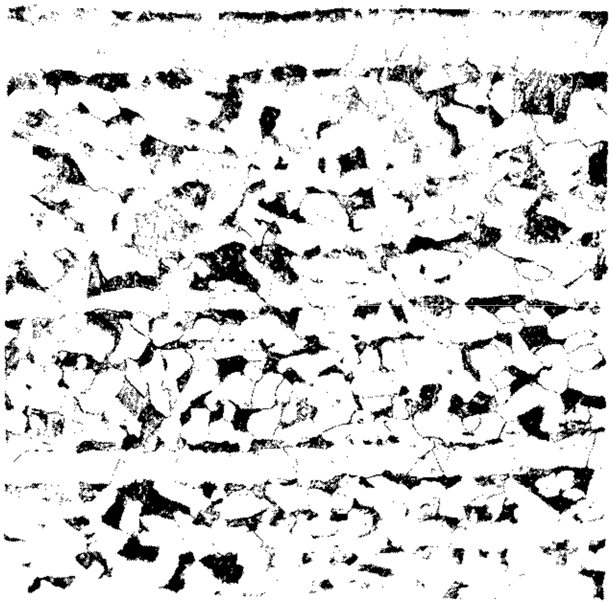
counts. This count was also divided by four to give pearlite areas per square inch at 100 diameters, as shown in Table 3. Pearlite spacing was not determined quantitatively, but microscopic examination of the specimens indicated a variation in spacing with the different cooling rates. The spacing was wider for slower cooling rates.

The variations in ferrite grain size and pearlite distribution are shown by the photomicrographs in Figure 6. These are longitudinal sections austenitized at 1700°F for 1 1/2 hours. The space between the lamellae in the pearlite increased with slower cooling rates. The size of the ferrite grains increased with decreases in cooling rate. These samples were etched to show the ferrite grain boundaries and pearlite distribution, but do not show the lamellae of the pearlite plainly.

The effects of austenitizing temperature and various cooling rates on ferrite grain size and pearlite distribution are shown in Figures 7 and 8, respectively. Of course, many other changes in microstructure occur when steels are cooled from various temperatures and at various rates. One of the most noticeable changes is the distance between bands of pearlite; the slower the cooling rate, the wider the bands. This change is accompanied by a variation in the size of the pearlite areas; therefore, one characteristic is related to the other. For the purpose of this study, the ferrite grain size and the number of pearlitic areas were used as parameters.

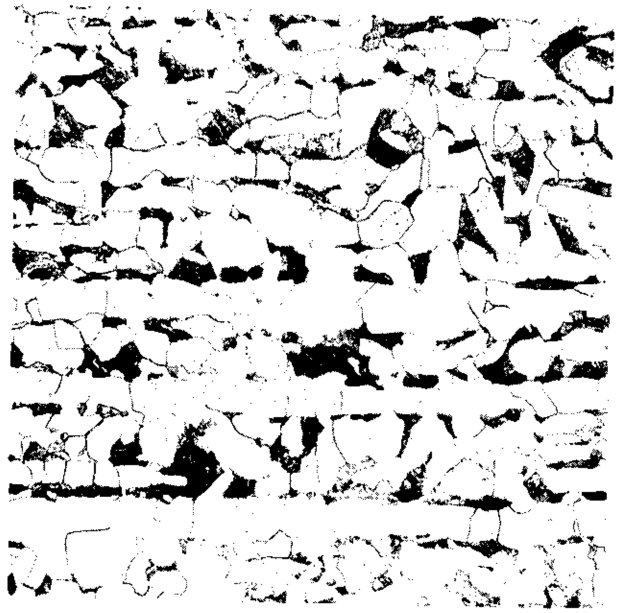
TABLE 3. PEARLITE DISTRIBUTION IN SPECIMENS OF PROJECT STEEL "A" PLATE AFTER HEAT TREATMENT

Austenitizing Temperature, F	Number of Pearlite Areas per Square Inch at 100X			
	Cooled in Air Blast	Cooled in Still Air	Cooled in Vermiculite	Furnace Cooled
		Furnace Time — 1-1/2 Hours		
1500	80	64	29	35
1600	46	41	21	25
1700	49	41	18	12
1800	29	25	8	9
1900	27	24	11	8
		Furnace Time — 8 Hours		
1500	48	41	28	18



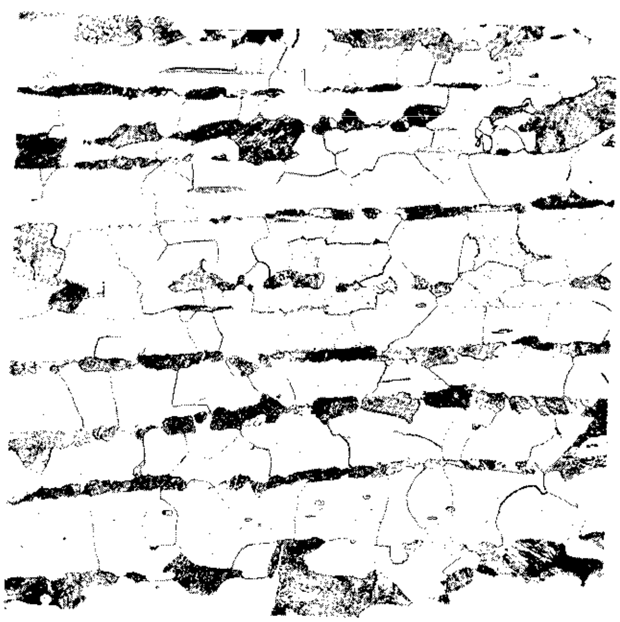
180X 96260

Cooled in Air Blast



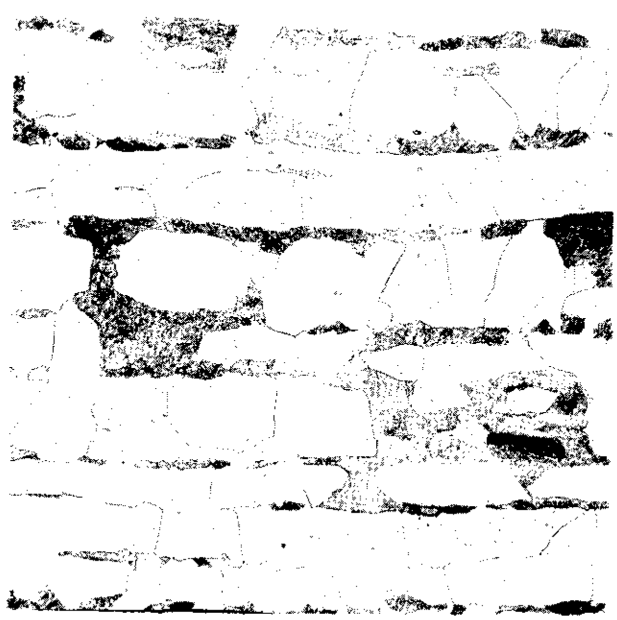
180X 96258

Cooled in Still Air



180X 96256

Cooled in Vermiculite



180X 96254

Furnace Cooled

FIGURE 6. MICROSTRUCTURE OF 3/4-INCH PLATES COOLED BY VARIOUS METHODS FROM AN AUSTENITIZING TEMPERATURE OF 1700 F; NITAL ETCH

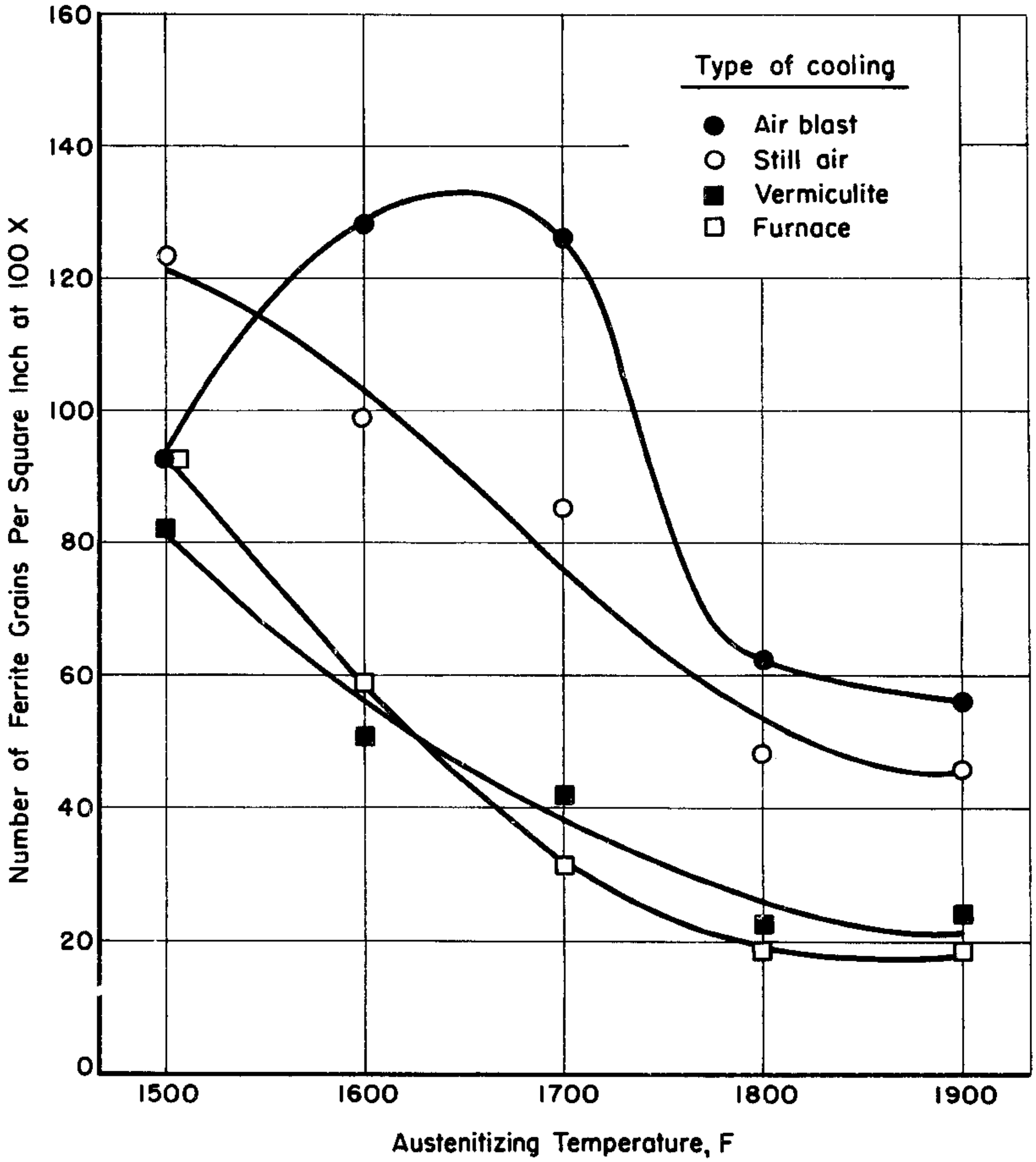


FIGURE 7. EFFECT OF AUSTENITIZING TEMPERATURE AND COOLING RATE ON FERRITE GRAIN SIZE

A-6668

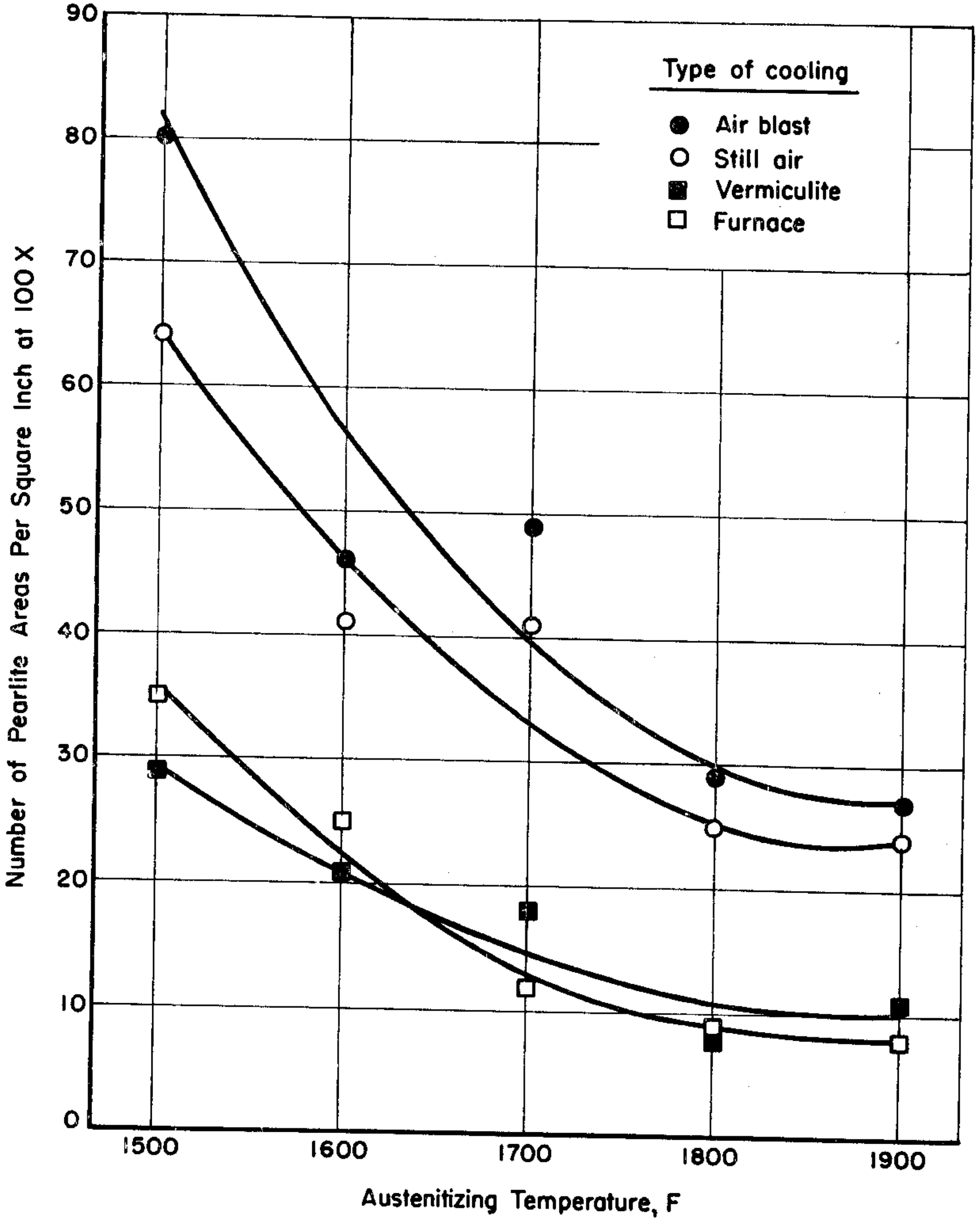


FIGURE 8. EFFECT OF AUSTENITIZING TEMPERATURE AND COOLING RATE ON DISTRIBUTION OF PEARLITIC AREAS

A-6669

INFLUENCE OF HEAT TREATMENT ON TEAR-TEST PROPERTIES

Sufficient material was heat treated to prepare twelve tear-test specimens representing each condition. In a few cases, unfortunately, some of the specimens were lost in their preparation. The remaining ones were broken at various temperatures to determine transition temperatures. The transition temperature was defined, in this case, as the highest temperature where 25 per cent or more of the specimens are brittle. This is the method recommended by Kahn[8] and was used because of the limited number of specimens from the heat-treated plates available for this study. Additional work in progress at Battelle suggests there are some advantages in defining tear-test transition temperatures on the basis of 50 per cent probability of cleavage fracture.

The results of each test are shown in Tables A-3 through A-8 of the Appendix. A summary of the transition temperatures for the plates heated 1 1/2 hours is shown in Table 4. For the plates heated 8 hours at 1500°F, the transition temperatures are listed in Table 5. The transition temperatures for the plates cooled at a faster rate appear to have been lowered by the increase in heating time; the furnace-cooled plates indicate the opposite effect. Figure 9 shows the influence of austenitizing temperature on the tear-test transition temperature of the heat-treated steel.

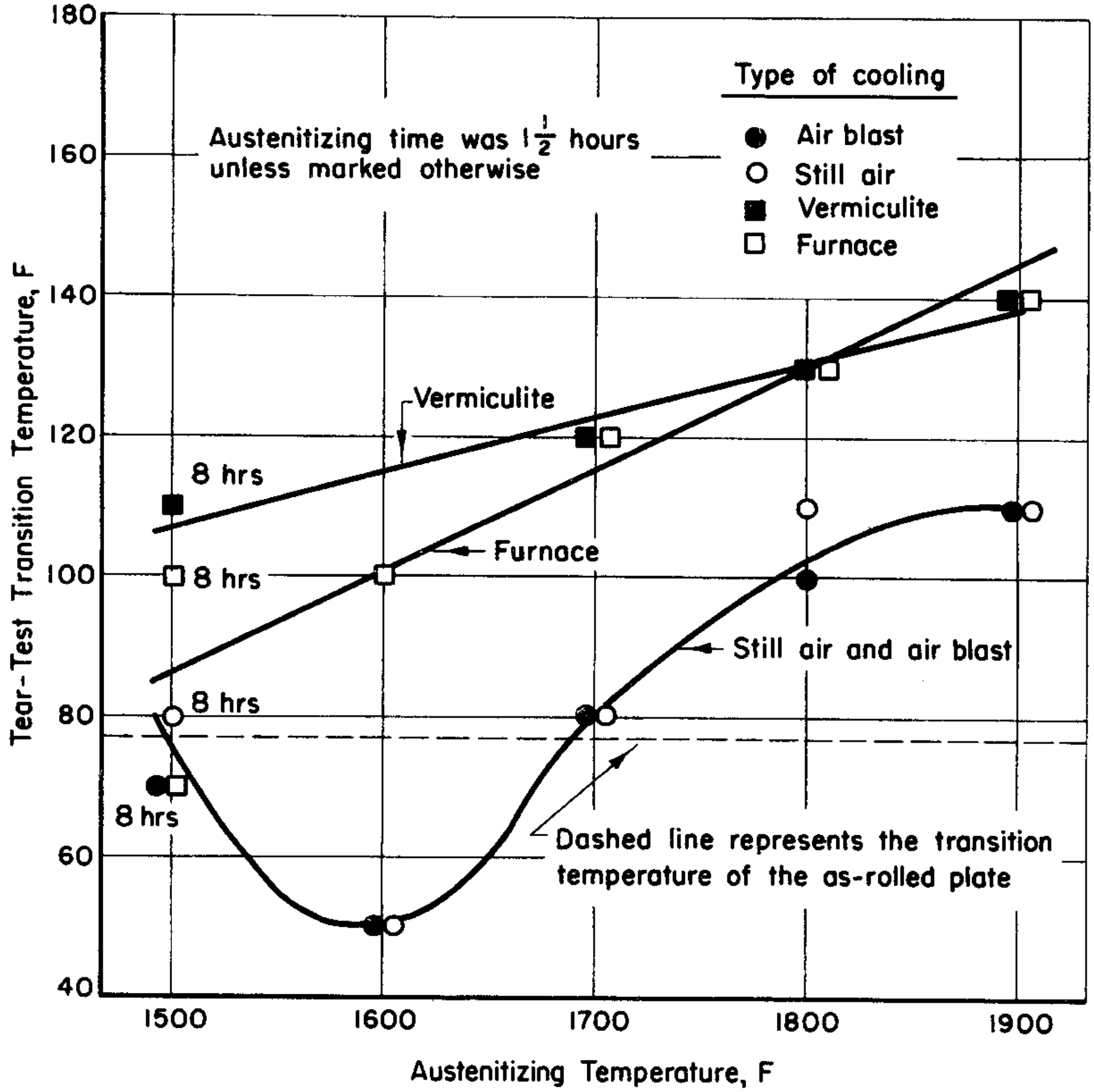


FIGURE 9. EFFECT OF AUSTENITIZING TEMPERATURE AND COOLING RATE ON TEAR TEST TRANSITION TEMPERATURE OF PROJECT STEEL "A"

A-6670

TABLE 4. SUMMARY OF TEAR-TEST TRANSITION TEMPERATURES OF PROJECT STEEL "A" PLATES HEAT TREATED IN VARIOUS WAYS

Type of Cooling	Tear-Test Transition Temperature, F(1) — Austenitizing Temperature, F: 1500	1600	1700	1800	1900
Air blast	100(2)	50	80	100	110
Still air	90(2)	50	80	110	110
Vermiculite	110(2)	60(2)	120	130	140
Furnace	70	100	120	130	140

(1) The tear-test transition temperature is defined as being the highest temperature where one or more of four specimens breaks with less than 50 per cent of the fracture area exhibiting a dull or fibrous texture.

(2) Transition temperatures are based on limited data. Only one to three ductile specimens were tested at temperatures 10 degrees higher than the transition temperature reported. These temperatures will not be used in the study.

TABLE 5. SUMMARY OF TEAR-TEST TRANSITION TEMPERATURES OF PROJECT STEEL "A" PLATES AUSTENITIZED AT 1500 F FOR 8 HOURS

Type of Cooling	Tear-Test Transition(1) Temperature, F
Air blast	70
Still air	80
Vermiculite	110
Furnace	100

(1) The tear-test transition temperature is defined as being the highest temperature where one or more of four specimens breaks with less than 50 per cent of the fractured area exhibiting a dull or fibrous texture.

When the ferrite grain size of the steels is considered, it appears that the steels with the coarser grains have the highest transition temperature, as shown in Figure 10. The transition temperature decreases 10°F for an increase of 12 grains per 0.01-inch-square area.

Heat treatment also affected the maximum load necessary to break the test specimen, the energy absorbed by the specimen before maximum load, and the energy absorbed after the maximum load was reached. Table 6 is a summary of these properties. The maximum load was decreased by an increase in austenitizing temperature and slower cooling rates. Since this load is a crude measurement of the ultimate strength and ductility, it is difficult to decide which property was affected most by the heat treatment. A general tendency exists for the amount of energy required to initiate and propagate the fracture to decrease with an increase in austenitizing temperature and slower cooling rate. These properties are dependent on the maximum load, so therefore should follow the same pattern as maximum load.

INFLUENCE ON KEYHOLE CHARPY PROPERTIES

Four keyhole Charpy specimens representing each heat treatment were broken at each 10°F temperature interval throughout the transition range. The specimens were parallel to the direction of rolling and were notched perpendicular to

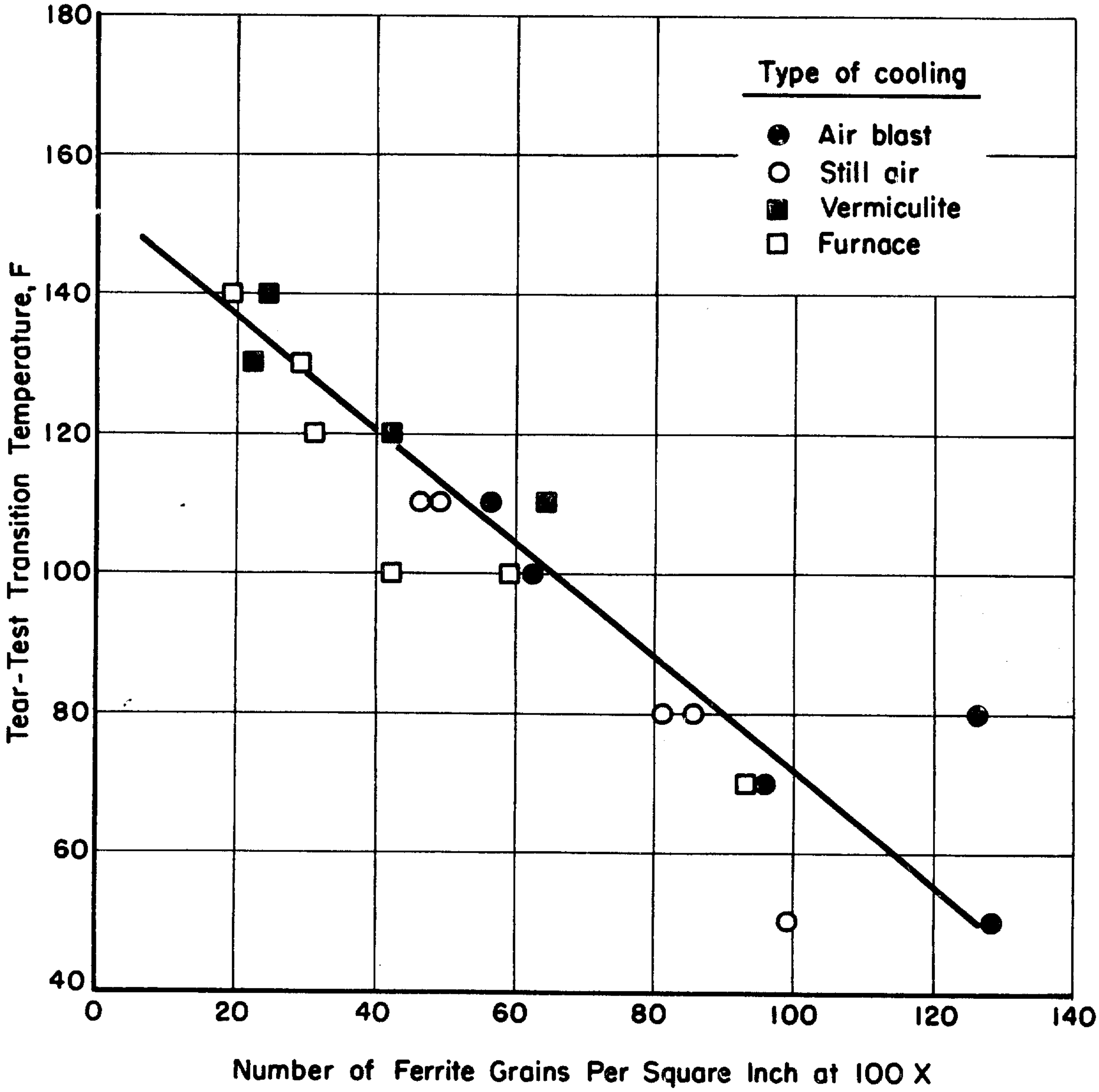


FIGURE 10. EFFECT OF FERRITE GRAIN SIZE ON TEAR-TEST TRANSITION TEMPERATURE

A-6671

TABLE 6. TEAR-TEST PROPERTIES OF PROJECT STEEL "A" AFTER HEAT TREATMENT

Austenitizing Temperature, F	Type of Cooling	Maximum Load, pounds	Energy to Initiate Fracture, foot-pounds(1)	Energy to Propagate Fracture, foot-pounds(1)
1500	Air blast	37,480	580(2)	630(2)
1500	Still air	36,610	720(2)	630(2)
1500	Vermiculite	33,480	730(2)	700(2)
1500	Furnace	33,580	690	530
1600	Air blast	37,290	810	650
1600	Still air	36,350	745	550
1600	Vermiculite	32,990	770(2)	510(2)
1600	Furnace	31,472	620	560
1700	Air blast	36,025	780	660
1700	Still air	35,235	700	580
1700	Vermiculite	31,390	580	490
1700	Furnace	31,430	600	500
1800	Air blast	33,870	730	645
1800	Still air	31,180	725	660
1800	Vermiculite	31,350	600	490
1800	Furnace	30,580	590	485
1900	Air blast	35,640	690	645
1900	Still air	34,900	770	640
1900	Vermiculite	30,410	540	490
1900	Furnace	29,960	535	470

(1) Average of the results from the four ductile specimens broken 10 F above the transition temperature.
(2) Average, based on limited number of tests.

the plate surface. As shown by Figure 2, the Charpy value at room temperature is well above 25 foot-pounds for the as-rolled plate in the longitudinal direction. However, many of the heat treatments reduced the values to approximately 20 foot-pounds, far above the transition temperature; therefore, a 12-foot-pound transition value was used. Table 7 is a summary of the transition temperatures for the 10-, 12-, 15-, and 20-foot-pound criteria. The Charpy value at 80°F is also shown for comparison. Results of individual tests are reported in Tables A-9 through A-14 in the Appendix.

The effect of austenitizing temperature on the 12-foot-pound transition temperature is shown in Figure 11. Lowering the temperature from 1900°F to 1800°F had no significant effect. The major change in transition temperature, with austenitizing temperature, occurred between 1800° and 1600°F. In most cases, the longer austenitizing time at 1500°F gave a lower transition temperature. The effect of cooling rate appeared to be far more important than austenitizing temperature. It must be remembered from Figure 5 that the major change in cooling rate was between the plates cooled in still air and those cooled in vermiculite. This is also reflected in Figure 11 where the major change in transition temperature occurred between the same two types of cooling.

The relationships between ferrite grain size and Charpy transition temperature are shown in Figure 12. For plates

TABLE 7. SUMMARY OF KEYHOLE CHARPY PROPERTIES OF PROJECT STEEL "A" PLATES AFTER VARIOUS HEAT TREATMENTS

Austenitizing Temperature, F	Type of Cooling	Charpy Value at 80 F	Transition Temperature, F			
			10-ft-lb Level	12-ft-lb Level	15-ft-lb Level	20-ft-lb Level
	As-Rolled	26.3	4	10	19	34
		Furnace Time — 1-1/2 Hours				
1500	Air blast	22.8	33	37	43	54
1500	Still air	23.0	24	29	35	51
1500	Vermiculite	13.8	65	71	79	93
1500	Furnace	16.3	63	69	79	95
1600	Air blast	26.5	2	7	12	22
1600	Still air	27.0	2	6	13	29
1600	Vermiculite	16.5	58	64	72	92
1600	Furnace	12.8	69	75	84	102
1700	Air blast	28.5	2	8	15	28
1700	Still air	25.0	19	25	33	47
1700	Vermiculite	15.3	69	76	86	105
1700	Furnace	8.8	77	83	92	106
1800	Air blast	20.0	34	42	54	75
1800	Still air	20.5	39	43	49	72
1800	Vermiculite	7.8	83	88	97	117
1800	Furnace	8.0	87	93	103	122
1900	Air blast	24.5	35	40	48	60
1900	Still air	24.5	33	35	39	55
1900	Vermiculite	9.3	82	87	95	113
1900	Furnace	8.5	87	95	105	126
		Furnace Time — 8 Hours				
1500	Air blast	26.0	10	15	21	32
1500	Still air	26.0	8	12	19	34
1500	Vermiculite	19.8	53	57	65	82
1500	Furnace	11.8	67	74	84	99

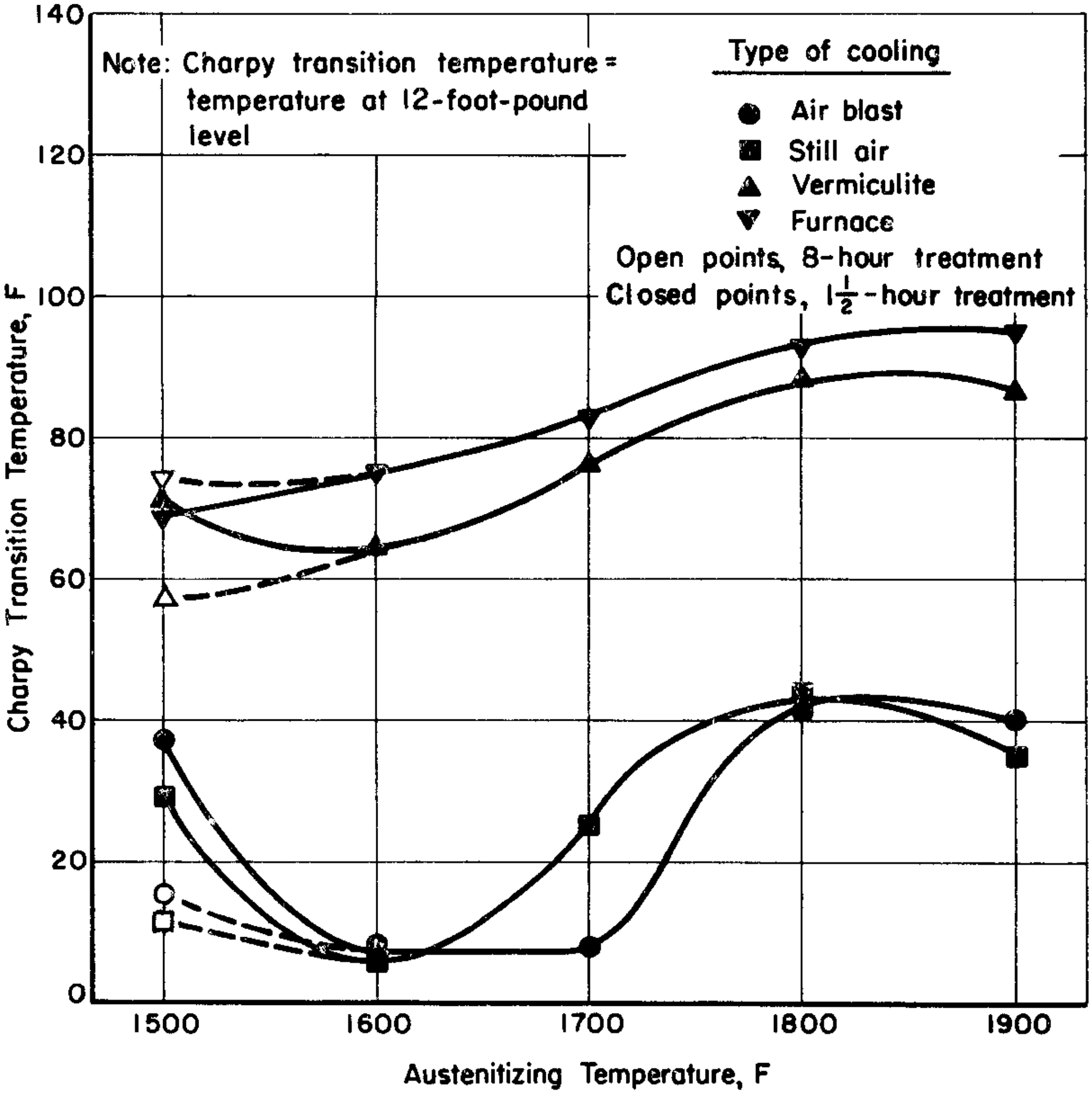


FIGURE 11. EFFECT OF AUSTENITIZING TEMPERATURE AND COOLING RATE ON CHARPY TRANSITION TEMPERATURE OF STEELS COOLED BY VARIOUS METHODS

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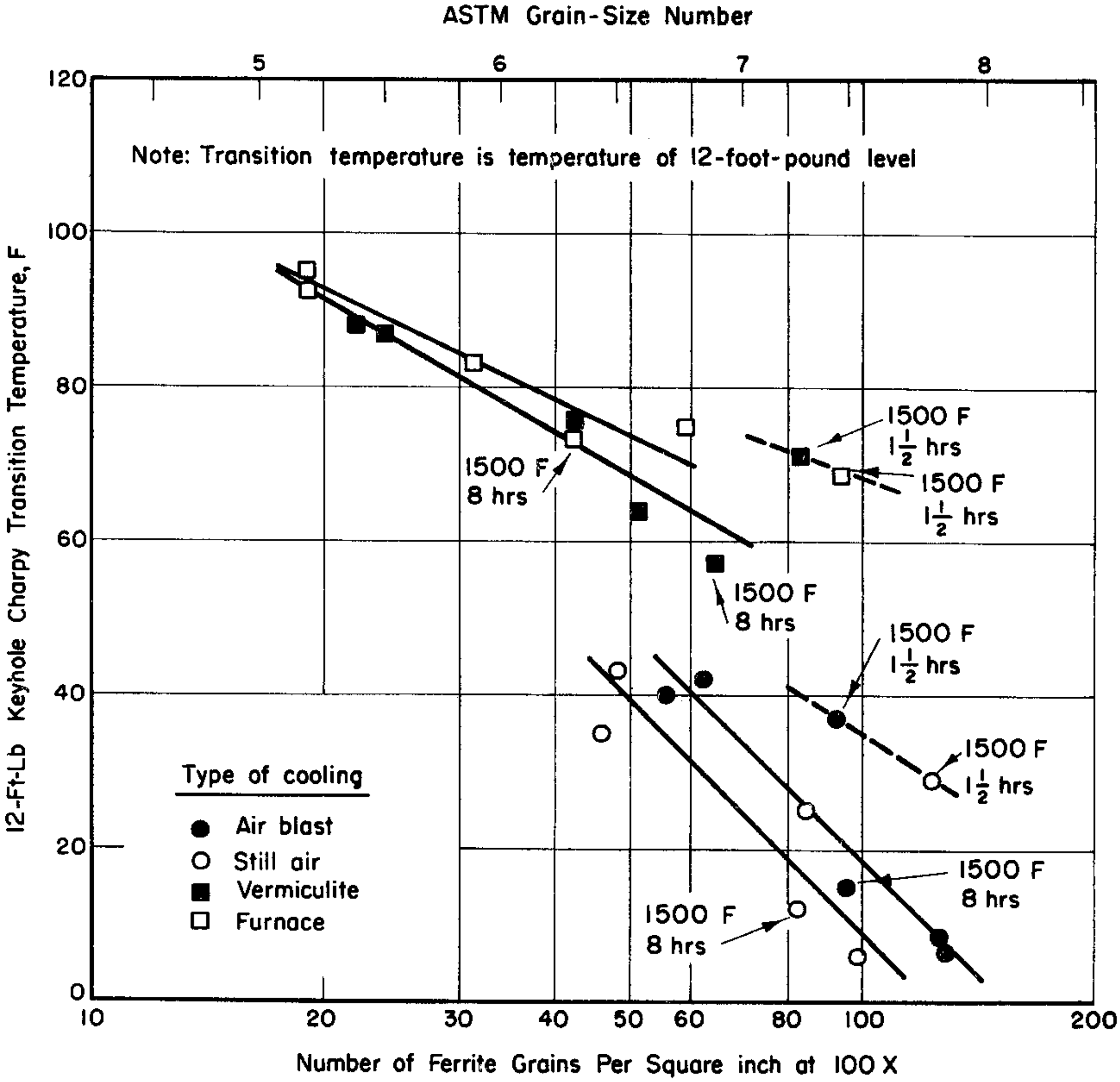

FIGURE 12. EFFECT OF FERRITE GRAIN SIZE ON KEYHOLE CHARPY TRANSITION TEMPERATURE OF PROJECT STEEL "A" COOLED AT DIFFERENT RATES. The variation in grain size was obtained by using different austenitizing temperatures and cooling rates.

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cooled at equal rates, the transition temperature decreased regularly with grain size. As in the previous discussion, the plates can be considered representative of two significantly different cooling rates. The steels cooled fairly rapidly, in still air or by an air blast, showed the same influence of grain size. The Charpy transition temperature decreased about 30°F for an increase of one ASTM number. This value agrees with data reported by previous investigators[4,5].

The plates cooled slowly in vermiculite or in the furnace behaved approximately alike. The effect of ferrite grain size on the Charpy transition temperature of these steels is less pronounced than for the other group. The transition temperature decreased only 13°F for each ASTM number in the case of the materials cooled fairly slowly from the austenitizing temperature.

For ferrite grain sizes approximating ASTM No. 6 1/2, the Charpy transition temperature is about 30°F higher for the plates cooled at the slower rate.

The four points for the plates heated to 1500°F for 1 1/2 hours do not fit the curves for steels containing coarser austenite grains. The fine austenite grain size in this case appears to be detrimental to transition temperature.

COMPARISON BETWEEN TEAR TEST AND KEYHOLE CHARPY TRANSITION TEMPERATURES

It seems natural to expect a correlation between transition temperatures established by different kinds of notched-bar tests. At least, several investigators have suggested formulas for estimating Charpy Keyhole transition temperatures from data obtained with other notch types or at other energy levels. Conversions of this kind can be misleading. Earlier experiments on this project showed that a particular change in nitrogen or manganese content does not have the same effect on the transition temperature in Keyhole Charpy tests as it does in tear tests. That is, the difference between the two transition temperatures is influenced by chemical composition. The present study shows that the relationship between the transition temperatures of a particular steel in the Charpy and in the tear test is also influenced by microstructure. This conclusion is illustrated by Figure 13.

Figure 13 compares the transition temperatures determined in the tear test with those set by the 12-foot-pound Charpy level. It shows that specimens cooled relatively rapidly fit a trend line different from that for the plates cooled quite slowly from the same austenitizing temperatures. The graph indicates that changing the rate of cooling can cause a variation of about 35°F in Charpy transition temperature between plates of this steel having the same transition

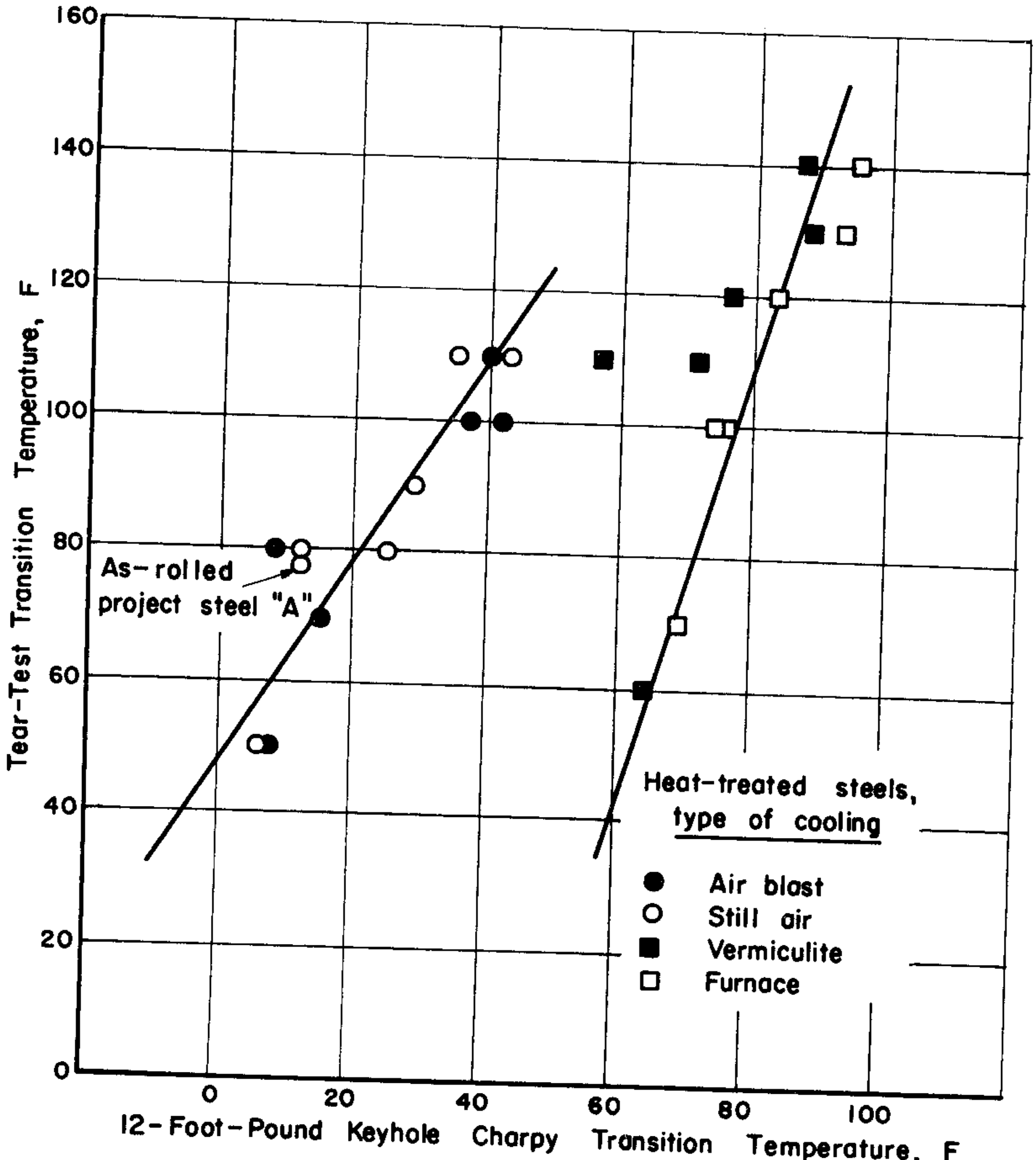

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FIGURE 13. COMPARISON BETWEEN TEAR-TEST TRANSITION TEMPERATURES AND 12-FOOT-POUND KEYHOLE CHARPY TRANSITION TEMPERATURES OF A HEAT-TREATED SHIP PLATE STEEL

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temperature in tear tests. Similarly, two plates having 12 foot-pound Charpy values at the same temperature could perform quite differently in tear tests.

If the slight differences in slopes of the trend lines in Figure 13 are neglected, it appears that the principal effect of slow cooling is to raise the Charpy transition temperature. As discussed previously, slow cooling increased the size of the pearlite patches and the distance between pearlite bands. Therefore, the data show that the Charpy test is more sensitive than the tear test to these variations in microstructure. The results for this steel in the heat-treated conditions emphasize the dangers of converting transition temperatures for different types of tests.

SUMMARY

The results of this work may be summarized as follows:

1. The average ferrite grain size was found to be dependent on the cooling rate as well as the austenitizing temperature.

2. The number of pearlite areas was also found to be dependent on both the cooling rate and austenitizing temperature.

3. The tear-test transition temperature was found to depend entirely on ferrite grain size, regardless of the pearlite distribution or other variations resulting from different types of cooling. An increase of 12 ferrite grains per square inch of image at 100X means an increase of 1 degree F in transition temperature. The maximum load and the energy required to start or to propagate fracture were decreased by increases in austenitizing temperature and by decrease in cooling rate.

4. The keyhole Charpy transition temperature is dependent upon the ferrite grain size, whether changed by the austenitizing temperature or the cooling rate. There is also a reflection of the austenite grain size in the transition temperature. The ferrite grain size has the greatest effect on transition temperature when the steels are air cooled. Here, the change is approximately 30°F for each ASTM grain-size number.

5. The relationship between tear-test transition temperature and keyhole Charpy transition temperature is good only when there is no major change in microstructure, as is the case when the cooling rate has been greatly changed. Other factors such as composition may also change this relationship.

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A P P E N D I X

TABLE A-1. TEAR-TEST DATA FOR PROJECT STEEL "A" IN THE AS-ROLLED CONDITION

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
70	37,350	810	80	11
70	36,700	680	230	22
70	37,350	820	90	10
70	37,000	650	410	42
70	37,050	770	90	13
70	37,450	780	90	8
70	36,550	670	50	14
70	36,900	800	110	15
70	37,300	820	220	24
70	38,150	820	120	11
70	37,350	730	330	36
70	37,700	800	580	76
70	35,800	680	80	13
70	37,250	790	80	10
70	36,900	680	170	20
70	36,900	670	60	10
80	36,100	640	630	85
80	36,050	720	110	11
80	37,300	940	580	70
80	36,250	630	70	15
80	36,100	660	480	56
80	36,800	770	690	85
80	35,850	650	670	85
80	36,200	680	600	78
80	36,550	690	380	40
80	36,300	610	340	48
80	37,150	800	430	51
80	37,050	690	50	12
80	36,800	670	350	40
80	36,300	610	80	11
80	38,150	880	150	30
80	36,900	680	560	79

TABLE A-1. (Continued)

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
90	36,000	660	630	82
90	37,200	800	630	77
90	37,250	700	610	76
90	37,050	790	570	82
90	35,700	610	630	85
90	36,800	680	600	80
90	37,050	780	600	81
90	37,700	780	620	80
90	36,500	800	630	84
90	36,600	660	630	84
90	36,850	780	790	82
90	36,250	630	630	74
90	36,400	720	680	77
90	37,400	790	570	83
90	39,950	730	930	89
90	35,950	640	670	85

TABLE A-2. KEYHOLE CHARPY IMPACT DATA FOR PROJECT STEEL "A" IN THE AS-ROLLED CONDITION

Testing Temperature, F	Charpy Value, foot-pounds				
	Specimen Number				
	1	2	3	4	Average
	Transverse Direction				
20	6	5	--	--	5.5
40	14	16	15	--	15.0
60	16	15	--	--	15.5
80	17	16	17	--	16.7
120	18	18	--	--	18.0
140	19	20	--	--	19.5
150	19	19	20	19	19.3
160	20	20	20	20	20.0
	Longitudinal Direction				
-20	3	3	--	--	3.0
0	10	11	10	12	10.8
20	15	18	6	17	14.0
30	20	19	8	21	17.0
40	23	23	20	--	21.5
80	27	26	26	--	26.3

TABLE A-3. TEAR-TEST DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1500 F FOR 1-1/2 HOURS

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds: To Start Fracture	Energy, foot-pounds: To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Air Blast		
30	38,400	780	60	2
40	37,600	690	60	1
50	37,400	730	190	10
60	37,650	760	620	75
60	38,000	870	60	3
60	37,350	820	530	65
70	37,600	780	70	5
80	36,600	720	50	5
90	37,900	--	--	80
90	37,000	740	600	62
90	36,800	780	70	12
100	36,000	580	630	75
		Cooled in Still Air		
20	36,150	780	50	1
30	35,650	780	110	2
40	36,750	680	110	1
50	37,000	700	70	1
60	37,350	790	70	1
70	36,600	670	60	2
80	37,050	730	660	80
80	37,200	690	40	2
90	37,300	840	80	12

TABLE A-3. (Continued)

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Still Air		
100	34,900	690	580	80
100	36,100	720	680	85
100	36,250	740	620	75
		Cooled in Vermiculite		
60	34,950	730	40	2
70	34,150	750	40	2
70	34,850	740	40	3
80	34,350	750	560	70
80	35,650	850	540	72
80	34,000	870	50	2
90	33,200	730	50	2
90	32,250	720	360	62
100	32,750	860	200	35
110	31,350	720	30	2
120	31,800	640	800	75
120	32,500	820	600	75
		Furnace Cooled		
60	35,650	890	50	3
70	35,050	780	70	3
70	33,750	830	100	3
70	33,250	720	50	2
70	31,750	580	40	1
80	33,850	720	490	63
80	33,100	700	540	65
80	32,900	660	550	60
80	32,900	680	540	69

TABLE A-4. TEAR-TEST DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1600 F FOR 1-1/2 HOURS

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds: To Start Fracture	Energy, foot-pounds: To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Air Blast		
40	37,200	770	380	29
50	38,150	710	650	75
50	37,800	940	70	5
50	36,950	840	630	75
50	37,000	830	130	5
60	37,700	780	640	80
60	36,250	730	600	72
60	37,200	870	750	82
60	37,400	850	600	75
		Cooled in Still Air		
30	37,000	820	110	3
40	36,900	780	550	70
40	36,700	710	180	10
50	37,050	790	660	77
50	35,650	730	80	2
60	35,600	710	630	80
60	36,350	770	420	72
60	36,000	740	530	55
60	36,000	760	630	75
70	36,200	750	600	85
		Cooled in Vermiculite		
50	33,500	720	70	2
60	34,000	800	490	65
60	32,750	560	80	2
70	32,650	750	530	65
70	32,850	750	510	76
70	33,700	810	500	84

TABLE A-4. (Continued)

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Vermiculite		
80	32,400	590	430	62
90	32,050	520	520	73
		Furnace Cooled		
90	31,800	590	50	12
100	31,600	590	510	72
100	31,050	560	550	75
100	31,600	580	530	70
100	31,350	580	80	5
110	31,200	570	490	75
110	31,500	630	560	77
110	31,400	620	620	75
110	31,750	670	580	75

TABLE A-5. TEAR-TEST DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1700 F FOR 1-1/2 HOURS

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds: To Start Fracture	Energy, foot-pounds: To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Air Blast		
60	36,900	930	90	4
70	36,300	740	560	70
70	36,500	830	540	80
70	36,200	860	70	3
80	35,300	730	580	80
80	36,000	790	80	3
90	35,950	670	650	90
90	36,150	830	680	86
90	35,350	830	590	76
90	35,650	800	730	70
		Cooled in Still Air		
70	34,600	820	40	5
70	35,400	890	60	7
80	34,500	610	60	10
80	34,800	650	290	25
80	35,050	640	640	80
80	35,550	660	210	13
90	36,450	850	490	70
90	35,500	690	620	77
90	34,900	600	640	80
90	35,600	660	590	80
		Cooled in Vermiculite		
90	30,550	510	40	1
120	31,300	500	180	10
130	30,950	590	510	80
130	32,000	610	540	80
130	31,450	550	420	80
130	32,100	590	500	80

TABLE A-5. (Continued)

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Furnace Cooled		
90	32,500	480	50	2
100	29,900	430	50	10
110	32,200	560	150	16
120	30,300	520	470	79
120	30,550	530	270	38
130	31,250	580	510	80
130	31,300	520	520	80
130	33,350	720	490	74
130	31,500	580	480	70

TABLE A-6. TEAT-TEST DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1800 F FOR 1-1/2 HOURS

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Air Blast		
90	30,650	430	340	85
100	35,200	730	70	15
100	34,350	720	120	15
100	30,200	420	390	99
100	34,500	750	80	13
110	34,600	780	560	80
110	35,350	720	660	70
110	35,200	790	730	80
110	34,800	630	630	70
		Cooled in Still Air		
90	34,650	820	90	14
100	35,150	880	520	75
100	35,100	830	170	14
110	34,300	790	580	65
110	34,400	700	100	20
110	33,400	680	450	35
120	34,400	700	700	90
120	34,200	690	700	85
120	34,900	680	620	80
120	35,700	830	630	72
		Cooled in Vermiculite		
120	31,200	570	250	15
130	31,050	560	340	43
140	32,300	640	460	79
140	31,050	540	500	87
140	31,400	640	530	86
140	31,100	580	480	82

TABLE A-6. (Continued)

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Furnace Cooled		
120	30,950	560	180	8
130	30,200	550	190	15
140	30,550	560	510	80
140	29,500	510	480	70
140	31,100	620	520	81
140	31,200	660	430	70

TABLE A-7. TEAR-TEST DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1900 F FOR 1-1/2 HOURS

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds: To Start Fracture	Energy, foot-pounds: To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Air Blast		
100	36,500	800	100	15
110	35,100	650	600	75
110	35,600	630	170	24
110	36,500	660	620	75
120	36,050	680	640	80
120	35,700	750	700	85
120	35,100	660	630	76
120	35,750	680	610	89
130	34,450	650	680	85
		Cooled in Still Air		
100	35,400	780	450	60
110	33,700	650	230	35
110	33,150	600	570	70
110	34,500	730	260	20
110	35,250	790	170	25
120	34,650	810	680	91
120	36,500	870	630	80
120	34,400	670	630	81
120	35,500	740	630	87
130	35,950	850	730	82
		Cooled in Vermiculite		
130	30,550	530	410	70
140	30,150	530	480	85
140	30,400	490	530	80
140	30,400	520	430	65
140	30,000	500	450	40

TABLE A-7. (Continued)

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Vermiculite		
150	30,400	550	490	77
150	30,050	520	480	85
150	30,400	550	530	84
150	30,250	550	470	86
160	31,500	610	480	94
		Furnace Cooled		
130	29,800	490	420	70
140	29,600	500	480	80
140	29,900	470	470	73
140	29,500	470	230	40
140	30,100	520	380	70
150	30,350	520	480	75
150	29,800	480	460	80
150	30,350	610	480	81
150	29,900	530	460	75
160	30,300	520	480	79

TABLE A-8. TEAR-TEST DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1500 F FOR 8 HOURS

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Air Blast		
60	36,200	730	70	3
70	37,600	790	180	12
80	36,450	660	560	88
80	36,550	720	630	82
80	37,350	770	580	83
80	36,350	700	580	77
		Cooled in Still Air		
50	35,600	910	50	1
60	36,950	820	530	62
60	36,050	750	80	7
70	36,750	820	140	13
80	36,500	730	570	70
80	35,900	680	20	12
90	35,750	750	590	74
90	35,450	730	530	70
90	35,700	630	500	74
90	35,600	670	570	80
		Cooled in Vermiculite		
60	32,000	590	30	1
80	32,650	680	70	4
100	31,950	620	60	7
110	31,150	570	480	74
110	31,750	640	50	20
110	30,400	580	540	80

TABLE A-8. (Continued)

Testing Temperature, F	Maximum Load, pounds	Energy, foot-pounds To Start Fracture	Energy, foot-pounds To Propagate Fracture	Per Cent Shear in Fracture
		Cooled in Vermiculite		
120	32,450	670	510	80
120	31,750	700	540	75
120	32,500	780	550	77
120	31,850	590	580	90
		Furnace Cooled		
60	31,450	480	10	1
80	31,100	490	20	1
90	32,250	700	460	70
90	32,950	730	560	73
90	33,000	690	60	5
100	31,700	630	520	78
100	31,900	660	50	8
100	31,850	642	70	7
110	30,650	570	430	80
110	31,350	590	490	78
110	32,250	690	480	75
110	30,850	580	380	65

TABLE A-9. KEYHOLE CHARPY IMPACT DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1500 F FOR 1-1/2 HOURS

Testing Temperature, F	Charpy Value, foot-pounds				
	Specimen Number				
	1	2	3	4	Average
	Cooled in Air Blast				
20	15	4	5	5	7.3
30	5	5	6	6	5.3
40	13	15	14	10	13.0
50	19	20	24	21	21.0
60	21	15	22	25	20.8
70	25	24	25	24	24.5
80	27	16	26	22	22.8
90	25	25	30	25	26.3
	Cooled in Still Air				
10	4	3	4	4	3.8
20	4	5	5	17	7.8
30	19	17	15	16	16.8
40	22	6	5	20	13.3
50	21	19	21	21	20.5
60	19	21	24	22	21.5
70	22	20	22	23	21.8
80	24	21	25	22	23.0
	Cooled in Vermiculite				
50	5	4	5	5	4.8
60	7	6	15	6	8.5
80	15	17	12	11	13.8
90	21	21	21	21	21.0
100	21	22	21	21	21.3
120	25	23	--	--	24
	Furnace Cooled				
50	5	5	4	5	4.8
60	6	11	6	6	7.3
70	8	19	15	13	13.8
80	12	15	19	19	16.3
90	17	20	20	15	18.0
100	20	22	22	21	21.3
120	25	27	--	--	26.0

TABLE A-10. KEYHOLE CHARPY IMPACT DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1600 F FOR 1-1/2 HOURS

Testing Temperature, F	Charpy Value, foot-pounds				
	Specimen Number				
	1	2	3	4	Average
			Cooled in Air Blast		
-20	4	5	6	4	4.8
-10	5	14	4	5	7.0
0	5	4	17	5	7.8
10	19	18	15	20	18.0
20	21	6	21	21	17.3
30	23	22	24	22	22.8
40	25	28	24	27	26.0
80	25	28	--	--	26.5
			Cooled in Still Air		
-10	6	3	3	4	4.0
0	11	19	14	4	12.0
10	4	4	16	20	11.0
20	17	16	21	18	18.0
30	23	21	21	21	21.5
40	24	21	22	22	22.3
80	28	26	--	--	27.0
			Cooled in Vermiculite		
50	4	4	4	5	4.3
60	7	16	12	17	13.0
70	18	15	7	15	13.8
80	12	18	18	18	16.5
90	17	23	19	21	20.0
100	21	23	21	21	21.5
120	23	22	--	--	22.5
			Furnace Cooled		
60	5	5	6	5	5.3
70	13	6	13	14	11.5
80	13	11	8	19	12.8
90	16	17	12	18	15.8
100	21	21	19	18	19.8
110	21	23	21	22	21.8
120	21	22	21	23	21.8

TABLE A-11. KEYHOLE CHARPY IMPACT DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1700 F FOR 1-1/2 HOURS

Testing Temperature, F	Charpy Value, foot-pounds				
	Specimen Number				
	1	2	3	4	Average
		Cooled in Air Blast			
-10	5	5	4	4	4.5
0	11	4	8	14	9.3
10	17	10	18	11	14.0
20	17	15	5	21	14.5
30	21	21	22	20	21.0
40	21	25	26	24	24.0
80	28	29	--	--	28.5
		Cooled in Still Air			
0	3	5	--	--	4.0
10	6	10	6	6	7.0
20	12	5	11	5	8.3
30	17	18	8	16	14.8
40	21	19	19	20	19.8
50	23	20	19	17	19.8
60	23	20	21	23	21.8
70	24	23	22	--	23.0
80	24	26	--	--	25.0
		Cooled in Vermiculite			
50	5	5	5	6	5.3
60	7	6	6	5	6.0
70	12	13	9	17	12.8
80	13	18	18	12	15.3
90	13	12	12	17	13.5
100	20	20	19	18	19.3
110	21	19	21	20	20.3
120	23	20	21	21	21.3
		Furnace Cooled			
60	6	11	7	6	7.5
70	7	15	8	8	9.5
80	6	8	9	12	8.8
90	11	16	20	19	16.5
100	20	21	18	21	20.0
110	21	25	17	21	21.0
120	21	24	20	24	22.3
140	30	--	--	--	30.0

TABLE A-12. KEYHOLE CHARPY IMPACT DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1800 F FOR 1-1/2 HOURS

Testing Temperature, F	Charpy Value, foot-pounds				
	Specimen Number				
	1	2	3	4	Average
			Cooled in Air Blast		
30	6	5	18	6	8.8
40	8	16	7	15	11.5
50	21	8	9	13	12.8
60	22	16	24	15	19.3
70	14	22	20	17	18.3
80	25	16	22	17	20.0
			Cooled in Still Air		
30	7	8	5	6	6.5
40	6	8	11	11	9.0
50	23	19	9	18	17.3
60	24	17	15	18	18.5
70	20	20	21	20	20.3
80	16	22	21	23	20.5
90	29	25	24	25	25.3
100	30	27	--	--	28.5
			Cooled in Vermiculite		
70	7	7	6	7	6.8
80	10	7	7	7	7.8
90	12	13	13	9	11.8
100	18	15	13	19	16.3
110	18	21	19	18	19.0
120	19	20	19	21	19.8
130	23	23	21	22	22.3
			Furnace Cooled		
80	6	9	8	9	8.0
90	12	12	8	7	9.8
100	17	12	13	16	14.5
110	15	11	14	18	14.5
120	21	21	21	25	22.0
140	23	21	24	21	22.3

TABLE A-13. KEYHOLE CHARPY IMPACT DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1900 F FOR 1-1/2 HOURS

Testing Temperature, F	Charpy Value, foot-pounds				
	Specimen Number				
	1	2	3	4	Average
		Cooled in Air Blast			
20	5	5	--	--	5.0
30	7	6	12	13	9.5
40	14	15	13	12	13.5
50	13	15	7	13	12.0
60	19	22	22	20	20.8
70	24	23	19	22	22.0
80	24	25	--	--	24.5
		Cooled in Still Air			
20	6	4	5	5	5.0
30	6	5	5	9	6.3
40	24	18	22	6	17.5
50	19	18	13	18	17.0
60	24	17	24	17	20.5
70	21	21	--	--	21.0
80	27	22	--	--	24.5
		Cooled in Vermiculite			
70	6	6	7	7	6.5
80	7	9	13	8	9.3
90	13	14	12	13	13.0
100	17	16	19	15	16.8
110	19	20	19	21	19.8
120	22	22	19	20	20.8
130	20	21	22	21	21.0
		Furnace Cooled			
70	8	5	7	6	6.5
80	7	10	12	--	9.7
90	7	8	7	12	8.5
100	11	13	16	14	13.5
110	20	19	19	21	19.8
120	14	16	21	19	17.3
130	19	19	21	21	20.0
140	20	21	21	21	20.8

TABLE A-14. KEYHOLE CHARPY IMPACT DATA FOR PROJECT STEEL "A" HEAT TREATED AT 1500 F FOR 8 HOURS

Testing Temperature, F	Charpy Value, foot-pounds				
	Specimen Number				
	1	2	3	4	Average
		Cooled in Air Blast			
-10	5	3	3	6	4.3
0	5	8	4	7	6.0
10	5	18	15	18	14.0
20	10	17	11	6	11.0
30	22	22	24	21	22.3
40	23	21	22	20	21.5
80	25	27	--	--	26.0
		Cooled in Still Air			
-10	4	3	3	3	3.3
0	4	12	4	6	6.5
10	15	16	8	12	12.8
20	17	18	5	19	14.8
30	17	19	20	20	19.0
40	19	21	26	20	21.5
80	26	26	--	--	26.0
		Cooled in Vermiculite			
50	14	13	14	11	13.0
60	11	9	9	7	9.0
70	14	19	20	18	17.8
80	19	18	21	21	19.8
90	21	20	24	20	21.3
		Furnace Cooled			
50	6	5	8	6	6.3
60	15	6	6	12	9.8
70	6	16	16	8	11.5
80	19	9	10	9	11.8
90	19	21	14	21	18.8
100	21	18	21	21	20.3
110	21	21	23	--	21.7
120	25	26	26	27	26.0
160	26	27	--	--	26.5