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WAL 710/688

WATERTOWN ARSENAL LABORATORY

EXPERIMENTAL REPORT

NO. WAL 710/688

710/688

ARMOR—CAST

The Development of Chemical Compositions for 4½" Cast Armor Satisfying the Requirements of the Fibre Fracture Test after Heat Treatment

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BY
P. V. RIFFIN
Pvt., Ordnance Dept.

DATE 27 November 1944

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Watertown Arsenal Laboratory
Report No. WAL 710/688
Problem B-1.7

27 November 1944

ARMOR--CAST

The Development of Chemical Compositions for 4½" Cast Armor Satisfying the Requirements of the Fibre Fracture Test after Heat Treatment

OBJECT

To investigate chemical compositions for use in 4½" thick cast armor which will yield a fibrous fracture after a normal quench and temper heat treatment and to evaluate the metallurgical properties of these steels.

SUMMARY OF RESULTS

1. Four of the steels investigated fracture in a fibrous manner when water quenched in a 4½" thick plate and tempered to a fairly low hardness. The analyses of these steels and the hardnesses at which they were tested are as follows:

Plate No.	C	Mn	Ni	Cr	Mo	Other	Hardness BHN
8	.32	.82	.83	.81	.48	.002 B	229
11	.31	.97	1.32	1.07	.46	.10 V	229
15	.35	.65	.97	1.70	.48		229
16	.36	.90	1.01	1.71	.48		255

2. A composition containing 2% chromium and .5% molybdenum possessed insufficient hardenability for 4½" plate when water quenched. The use of at least 2.5% chromium is apparently required for 4½" thick armor in this type analysis.

[redacted]

3. Several of the higher alloy steels exhibited a tendency toward temper brittleness as manifested under Charpy impact tests conducted at -40°F. This reduction in notched bar toughness could be eliminated in $4\frac{1}{2}$" plate by water quenching from the tempering temperature.

4. It was possible to obtain fibrous fractures and fairly good notched bar impact properties in a steel tempered to a low hardness even though it contained as much as 80% nonmartensitic transformation constituents at the center of the section upon quenching. It was observed, however, that the nonmartensitic transformation constituent, which was most prominent, consisted of a very fine, randomly oriented carbide distribution having the appearance of tempered martensite upon tempering to a hardness of 250 Brinell or lower.

5. A fracture hardenability test was devised for making a preliminary evaluation of the toughness of the steel heat treated in heavy sections. In this test end-quenched bars were fractured after tempering to the desired hardness and their fractures rated. Results obtained from tests at -40°F. appear to be more informative than those obtained at room temperature..

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APPROVED:

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INTRODUCTION

Upon the introduction of the fibre fracture test as an acceptance test for cast armor, it was discovered that in many of the facilities considerable difficulty was encountered in making armor having satisfactory impact properties when treated in sections over 2 inches in thickness. For the most part, the 1.5% Mn, .5% Cr, .5% Mo type steel and the 1% Mn, .5% Ni, .5% Cr, .5% Mo type steel, which were used at the time the fracture test was introduced in the production of cast armor, did not possess sufficient hardenability for sections over 3" in thickness. Consequently, in the facilities making the heavier armor, the chromium, manganese, and nickel contents were raised as a means of increasing the hardenability. In the Mn-Cr-Mo type steel, the chromium and manganese were increased to 1.5% each. In another facility which used the Ni-Cr-Mo type steel, the manganese, nickel and chromium contents were raised to over 1% each. Results observed at both facilities showed that when the alloy content was on the high side of a nominal range, extremely brittle properties were obtained. This lack of toughness in metallurgical tests was reflected in poor ballistic shock properties of the ballistic test plates which were produced.

The poor metallurgical properties exhibited by these alloys when on the high side of the chemical range were believed to be associated with either (1) temper brittleness, (2) undesirable transformation products formed because the steel was not cooled to martensite transformation temperature before tempering, (3) transformation of retained austenite to undesirable products during tempering, or (4) a combination of these factors as indicated in a recent report[1].

An investigation[2] of 4" to 6" cast armor showed that there is a very good correlation between poor Charpy impact properties, crystalline fractures, and brittleness in the ballistic shock test. Other work[3,4] has been conducted at this arsenal showing that the fracture test results reveal the tendency of a steel to exhibit brittle properties in the ballistic shock test.

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1. Watertown Arsenal Laboratory Experimental Report No. WAL 710/678, "Cast Armor - The Development of Compositions and Heat Treatments to Yield Optimum Shock Properties in Cast Armor 1" to 6" Thick", 1 September 1944.

2. Watertown Arsenal Laboratory Experimental Report No. WAL 710/500, "Armor--Metallurgical Examination of Cast Gun Shield Armor Four to Six Inches in Thickness", 17 May 1943, by A. Hurlich.

3. Watertown Arsenal Laboratory Experimental Report No. WAL 710/534, "Armor Plate - Correlation of Metallurgical Properties with the Low Temperature Ballistic Shock Characteristics of 1" to 2" Low Alloy Cast Armor Tested at Camp Shilo", 16 August 1943, by P. V. Riffin.

4. Watertown Arsenal Laboratory Experimental Report No. WAL 710/532, "Armor--Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels upon Quenching", 1 August 1943, by A. Hurlich.

Work had been done previous to the above mentioned investigations by the British and by the U. S. Navy but very little information showing a correlation with ballistic tests is available. In any event the references mentioned contain the essential points showing the correlation between the fracture test, toughness under notched bar tests, and toughness under ballistic shock tests.

In general, it has been observed that the optimum toughness of quenched and tempered steel is obtained when it is completely transformed to martensite upon quenching. Consequently, in this investigation compositions were selected which would be expected to quench out in 4½" plate using a water quench. Also heats of lower alloy contents were studied to evaluate the properties obtained when the austenite was not completely transformed to martensite upon quenching. From this data it was possible to compare steels water quenched in a 4½" thick plate size, some of which were completely quenched out and others which were not completely transformed to martensite during the quench.

In view of the difficulties encountered by the facilities with the higher chromium-manganese combinations, the alloys selected for study were high in only one of these two elements. The effect of adding boron and also vanadium was observed in selected compositions.

EXPERIMENTAL DATA

1. Preparation of Plates

The sixteen (16) experimental heats studied in this investigation were melted in an induction furnace and cast into plates 4½" x 12" x 16" including a 6" deep hot top. Eight (8) of the heats were melted in an acid-lined furnace. Although no direct comparison could be made between heats melted in acid-lined and those made in basic-lined furnaces, both types were used in order to determine whether or not they could be employed to yield a product which would pass the fibre fracture test when heat treated as 4½" thick plates. Except for two heats deoxidized with vanadium, the heats were deoxidized with 1½ to 2 pounds of aluminum per ton. The effect of .002% boron was determined in one heat by adding ferroboron after the aluminum addition.

2. Heat Treatment of Plates

The castings were normalized at either 1850°F. or 1950°F. for 10 hours, the higher temperature being used for the heats containing over 1.5% chromium. In order to remove any excess scale which would lower the quenching efficiency, the plates were sand blasted after homogenization.

The 4½" thick plates were heat treated in the full section size of the casting (4½" x 12" x 16") according to the following schedule:

Heat-Treatment of 4½" Thick Plates

Plate No.	Austenitize		Coolant	Temper		
	Temp.	Time		Temp.	Time	Coolant
1-11	1650°F.	5 hrs.	agitated water until cold	1250°F.	8 hrs.	air*
12-16	1675°F.	5 hrs.	agitated water until cold	1250°F.	8 hrs.	water

*Plates 5, 6, 7, and 8 were water quenched from the temper.

3. Test Procedure

A chemical analysis was made from test coupons poured from each heat, and a check carbon analysis was obtained from a sample taken midway between the surface and center of the 4½" plates. The 4½" plates were heat treated and subjected to the following metallurgical tests:

a. Cross-Section Brinell Hardness Surveys

b. Fibre Fracture Tests. The plates were sectioned and then notched 1½" in from one face and 3/4" from the sides such that the fracture area was 3" x 3" square. The fracture bars were broken under the impact blow of a forge hammer.

c. V-Notched Charpy Impact Tests. Duplicate specimens from the center of selected plates were broken at 68°F. and -40°F. Tests were also conducted on sections heat treated in ½"x ½" square sections in order to determine the impact properties of the completely quench hardened material (disregarding the effect of any retained austenite which might be present after quenching). Two sets of specimens, one water quenched from the temper and the other furnace cooled, were broken at -40°F. in order to determine the susceptibility of these steels to temper brittleness.

d. Microscopic Examination of the cross section of each plate.

e. End Quench Hardenability Tests were conducted on each of the 16 heats using a heating cycle of 3 hours at either 1650°F. or 1675°F., the higher temperature being used for steels containing over 1.5% chromium.

f. Hardenability Test by Means of Fracture Test. A special fracture test was devised for evaluating the ability of steels to develop fibrous fractures in heavy sections. The details of this test are explained in Appendix A. The heating cycles employed on the fracture bars were similar to those employed on the heavy sections; namely 3 hour austenitize at the given temperature followed by an end quench. The specimens from all heats were tempered for 5 hours at 1250°F., and either water or furnace cooled from the temper. In those heats showing promise, specimens were tempered to hardnesses up to 300 Brinell in order to determine whether satisfactory fractures could be obtained at the higher hardnesses. The notch severity of this fracture test appeared to be roughly equivalent to that obtained in Charpy bars as evaluated from its effect upon the fracture, and consequently tests were conducted at -40°F. to obtain fractures whose results would predict those which are obtained on the heavy sections. Fractures were also made at room temperature to make the results more complete.

g. The susceptibility to temper brittleness in the heats was determined by using the commonly employed method of comparing the V-notch Charpy impact energy of bars water quenched from the temper with similarly treated bars furnace cooled from the temper. The heat treatment of the 3" x 3" x 3/4" bars used for this test was as follows:

	Austenitize			Temper		
Heat No.	Temp.	Time	Coolant	Temp.	Time	Coolant
1-3, 5-8, 12, 13	1650°F.	3 hrs.	water	1225°F.	5 hrs.	water or furnace
4, 9-11	1650°F.	3 hrs.	water	1250°F.	5 hrs.	water or furnace
14-16	1675°F.	3 hrs.	water	1250°F.	5 hrs.	water or furnace

The lower tempering temperature was used for several of the heats in order to obtain a hardness more appropriate for revealing any tendency toward brittleness resulting from slow cooling from the temper.

RESULTS

1. Compositions

In the selection of compositions to be studied, the carbon was held at approximately .30% because this is the maximum desired from a standpoint of weldability. Since carbon exerts considerable effect upon the hardenability (more than any of the other common elements) it was decided not to reduce it more than required. The molybdenum was added because of its potent effect upon the hardenability and its alleviation of temper brittleness, but it was held to .45% because carbides formed in higher molybdenum steels are difficult to dissolve at normal austenitizing temperatures. Combinations of up to 1.5% nickel, 2% chromium, and 1.5% manganese in the .30% carbon .45% molybdenum steel were investigated. Boron was added to a nickel-chromium-molybdenum analysis in order to determine the properties of a boron bearing steel in a 4½" thick plate. A comparison of a nickel-chromium-molybdenum steel with and without .1% vanadium was also made to determine whether worthwhile benefits could be obtained by using this alloying element in heavy armor. No heats containing both high manganese and high chromium were made in view of the production difficulties and inferior product encountered by many of the cast armor producers when using this combination.

The compositions of the 16 heats investigated are shown in Table I. For ease in noting the important alloying elements they are underlined. The carbon content of the 2% chromium-molybdenum heat #13 was lower than desired, but by making up another heat (#14) of higher carbon it was possible to find the effect of a .1% change in carbon content upon the hardenability of this type composition. It should be noted that the carbon content reported is the value obtained midway between the surface and center of the plate. These values were between .01% and .04% higher than the values obtained on the coupons.

2. Hardenability

The term hardenability, according to Jominy[5], in a fairly inclusive sense, is considered as "the relationship between rates of cooling from above the critical range and the hardness and microstructure developed as a result". Grossman[6] has used the hardness of a structure containing 50% pearlite and 50% martensite as a basis for his hardenability studies. In armor plate, however, it is necessary to know the maximum section which can be heat treated to yield satisfactory impact properties. Data to date indicate that the optimum impact strength is obtained in a quenched and tempered steel when the austenite has been transformed to a homogeneous martensite upon quenching. Therefore, it is advisable to use a steel which will completely transform to martensite at the center of the section required. In heavier sections this condition becomes increasingly difficult to attain without resorting to high alloy steels which may be susceptible to welding and cracking difficulties. In this study, an attempt was made to discover what properties could be obtained in steels which were not completely transformed to martensite upon quenching.

The presence of high temperature transformation constituents (pearlite, ferrite, and upper bainite) have been associated with the tendency of a steel to exhibit brittleness under impact tests[4]. In many of the higher alloy steels, the decrease in cooling rates along the length of the Jominy bar result in the formation of considerable quantities of high temperature transformation constituents without an appreciable drop in hardness. Consequently the hardenability must be evaluated by means of a microscopic examination. The microstructure observed on the Jominy bar may be used to predict the transformation constituents formed in the plates after quenching. This circumstance is of considerable assistance in evaluating the microstructure in the plates, since sectioning plates in the as-quenched condition is a laborious undertaking.

The results of hardness surveys are shown in Figures 1-4. The microstructure at 1" and 2½" from the quenched end is shown in Figure 5. These locations are considered to have cooling rates equivalent to those obtained at the centers of 2½" and 4" plates respectively when water quenched[7].

The structure at the quenched end of the bars was a light etching acicular martensite. There may have been some retained austenite in the higher alloy heats, but its quantity was not sufficiently large to be visible microscopically. A short distance in from the quenched end a dark-etching acicular structure was observed which resembled either tempered martensite,

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[4] See footnote 4, page 3.

[5] W. E. Jominy, "Hardenability Tests", Page 66 of the Symposium on Hardenability of Alloy Steel, ASM 1939.

[6] M. A. Grossman, M. Assinow and S. F. Urban, "Hardenability and Its Relation to Quenching and Some Quantitative Data", Page 124 of the Symposium on Hardenability of Alloy Steel, ASM 1939.

[7] Hardenability Comparisons - a chart made by the Great Lakes Steel Corp., 1942.

low temperature bainite or high temperature martensite. This constituent did not contain any carbides or ferrite which were resolvable at a magnification of 1000X. It was not associated with a drop in hardness or impact strength and so it was not considered a nonmartensitic constituent in the evaluation of hardenability.

As the cooling rate was decreased along the length of the bar, a nonmartensitic constituent was observed which varied considerable in structure and quantity from heat to heat. In the lower alloy heats, this transformation structure appeared a few sixteenths of an inch before the hardness dropped a significant amount. Its structure was that of divorced carbides in ferrite, the relative amounts and distribution varying according to the alloy content. In the boron treated heat (#8), there was very little acicularity; the carbides were very small and ferrite was only present as a background for the carbides. In several of the other heats (1, 2, 3, 5, 6, and 7), the ferrite was the predominant nonmartensitic phase, and the carbides were large and scattered. In several cases, there was considerable orientation of these carbides. Most notable of this condition were heats 10 and 11, in which large acicular needles were observed.

As the air cooled end of the Jominy bars was approached a greater percentage of nonmartensitic transformation products were formed, and the structure varied from a bainite with 5% free ferrite in heat #8 to one containing 50% free ferrite in heat #2.

In the highest alloy heats studied (#15 and 16), a nonmartensitic constituent was formed which was similar in appearance to martensite except that it was dark etching and contained resolvable carbides.

3. Hardenability by Means of a Fracture Test

A preliminary evaluation of the tendency of a steel to fail in a brittle manner may be ascertained by fracturing end quench bars after tempering and notching them. This fracture test appears to be approximately as severe as the V-notched Charpy impact test, and consequently a low testing temperature (-40°F.) was required to reveal the tendency toward brittle fractures in all but the very low alloy plates. Crystalline fractures in the low alloy steels were observed in bars broken at room temperature (68°F.).

Except for a few of the lower alloy steels which were similar in hardenability to others which were tested, end quench bars were made from the steels, tempered to the hardnesses obtained in corresponding plates, and fractured. Those heats showing promise (fibrous throughout the length) were subjected to tests at higher hardnesses. The results are shown in Table II.

The results of this test indicate that only steels 8, 11, 15, and 16 are satisfactory for making 4" armor at a hardness of 240 to 260 Brinell. The remaining heats exhibit brittle fractures at -40°F. starting at various distances from the quenched end of the bar. The location at which the crystallinity starts corresponds roughly to the position on the as-quenched bar at which a marked decrease in hardness is observed. This position on the fracture bar can be used to predict the maximum plate thickness of steel which will yield a fibrous fracture.

In preliminary tests in which the steels were air cooled from the temper, some of the higher alloy steels were found to possess crystallinity over the complete length of the fracture. It was suspected that this might be caused by temper brittleness, and so subsequent bars were water quenched from the temper. Susceptibility to temper brittleness of the higher alloy steels was determined by furnace cooling companion bars from the temper, and it was found that of those tested, heats 4, 10, 11, 14, 15, and 16 were susceptible. To quantitatively evaluate this condition, the impact properties of the steels heat treated in small sections were compared and the results are discussed in the following section of the report.

4. Temper Brittleness

The susceptibility of a steel toward temper brittleness may be ascertained by comparing the properties of sections furnace cooled with those water quenched from a high tempering temperature. Small sections (3/4" x 3" x 3") were heat treated to 230-260 Brinell and either water quenched or furnace cooled from the temper, and the results of V-notched Charpy impact tests made at -40°F. were compared. (See Table III.)

Under the tests conducted none of the heats exhibited an extremely temper brittle condition, but the reduced impact strength accompanied by a partly crystalline fracture observed in several of the steels when furnace cooled from the temper as compared to specimens water quenched from the temper indicates that the toughness of these steels is impaired to some extent because of temper embrittlement.

The embrittlement was most prominent in heats 10, 11, and 16 which were among the highest alloy heats. Greaves and Jones[8] have observed that the higher alloy steels containing such elements as nickel, manganese and chromium are susceptible to temper brittleness under ordinary testing conditions. The embrittlement may be alleviated in these steels when used at hardnesses under 300 Brinell by water quenching from the temper.

Several of the other heats exhibited a slight tendency toward temper brittleness, although it was probably insufficient to impair the properties of these heats appreciably after normal heat treating cycles.

A comparison of the temper embrittlement encountered in the end quench bar fracture test and the V-notch Charpy bar test for temper brittleness used here shows that the Charpy test is somewhat more sensitive in revealing the tendency toward temper embrittlement than is the test using the end quench bars which, however, can be used to obtain results with greater rapidity and at a lower cost.

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[8] R. H. Greaves and J. A. Jones, "Temper Brittleness of Nickel Chromium Steels", The Journal of the Iron and Steel Institute, 102 No. II, Pages 171-222 (1920).

5. Properties of Heat Treated Sections

a. Hardness

The results of hardness surveys taken along a cross section of each of the sixteen (16) plates after heat treatment are given in Table IV. The hardness of the plates ranged from 200 to 260 Brinell depending upon the alloy content. The center of most of the low alloy plates was lower in hardness than at the surface. This condition is associated with the presence of high temperature transformation structures formed upon quenching.

b. Fibre Fracture Test

The fracture test has been developed to evaluate the toughness of armor. It has been shown, in preceding studies[3,4] that incomplete quenching or insufficient hardenability for a given section size will be reflected in a brittle or crystalline type fracture.

The results of fracture tests on the subject plates are given in Table VI. Examples of the best as well as of some of the poorer fractures are shown in Figures 6 and 7. The light appearing areas which are most prominent at the center of the fractures are crystalline. The darker gray, non-reflecting areas are fibrous.

Two types of crystallinity were observed. In heats in which the hardenability was insufficient and high temperature transformation constituents (ferrite and pearlite) were formed, the fracture consisted of a bright crystalline zone surrounded by a fibrous border. This fracture is indicated in the tables by the symbol Cbf. The fractures of the higher alloy steels (plates 3, 4, 9, 10, 11, and 14), which contained a large percentage of bainite, exhibited speckles of crystallinity in a fibrous matrix (Fc). Temper embrittlement is considered to be a contributing cause of brittleness in plate 11.

The three plates (#8, 15, and 16) possessed satisfactory fractures at their respective hardnesses and consequently would be expected to exhibit superior ballistic shock properties. Plate #11 was retempered to a hardness of 225 BHN and its Charpy impact properties were then comparable to those obtained in plate #8.

c. V-Notch Charpy Impact Properties

The results of the Charpy tests are shown graphically in Figure 8, and the complete data are summarized in Table V.

The impact strength of the steels may be evaluated by comparing the room temperature and low temperature values obtained on bars heat treated in small sections with the values obtained at the center of the $4\frac{1}{2}$" thick plates.

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[3] See footnote 3, page 3.
[4] See footnote 4, page 3.

The results of both the fracture test and Charpy impact tests show that plates 8, 15, and 16 possessed satisfactory toughness at the hardness level obtained with a 1250°F. temper. Plates 10 and 11, which were air cooled from the temper, developed temper brittleness, and, therefore, impact bar blanks from these plates were retempered at 1250°F. and water quenched in order to eliminate temper embrittlement. It has been observed by Greaves and Jones[8] that this type of treatment eliminates, for the most part, temper embrittlement introduced by slow cooling the steel from the tempering temperature. The impact results show that considerable improvement was obtained on steel #11 and it is indicated that the fracture and ballistic properties would be improved considerably by water quenching from the temper. The impact properties of plate #10 were improved somewhat although they could not be considered satisfactory. Consequently, it may be concluded that temper brittleness is not the only factor responsible for the inferior impact properties of this plate.

Test bars from plates 4, 9, 10 and 11 were retempered to a lower hardness level, with considerable improvement in Charpy impact strength. Only plate #11, however, was improved sufficiently to be considered satisfactory at the lower hardness.

The remaining plates possessed inferior low temperature impact values as a result of insufficient hardenability for the 4½" thick plates when water quenched. In general, it was observed that the room temperature impact values of specimens taken from the center of the 4½" thick plates were comparable to those obtained from bars heat treated in small sections. Plate #11, which was embrittled during tempering, exhibited poor room temperature values. In a previous examination of 4" to 6" armor, Hurlich[3] observed extremely poor room temperature values in heavy sections which were seriously underalloyed and insufficient in hardenability. These plates possessed microstructures containing large patches of ferrite and carbides. It is concluded that even the plates of lowest hardenability studied in this investigation exhibited an appreciable amount of toughness.

The toughness of the plates as indicated by the fibre fracture test correlates very well with the impact properties obtained in the Charpy test. (See Table VI.) It is seen that in the plates containing crystallinity in the fractures there is a corresponding decrease in impact strength between bars broken at room temperature and at -40°F.

Plate 8 which definitely contained a large percentage of bainite possessed satisfactory properties at a hardness of 229 Brinell. This condition would indicate that it is possible to achieve satisfactory impact properties at the lower hardness levels without complete transformation to martensite upon quenching. However, it is apparent that the type of transformation constituents formed has a marked influence upon the toughness obtained. Other plates with no greater quantity of intermediate and high temperature transformation products possessed considerably lower

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8. See Footnote 6, page 7.

3. See Footnote 3, page 3.

impact properties. Plates 10 and 14 are examples of plates which possessed inferior impact properties at -40°F. and yet they contained a smaller amount of nonmartensitic transformation products than plate #8.

d. Microscopic Examination

The microscopic examination of the plates in the tempered condition does not adequately evaluate the products formed during the quench. However, since the plates were difficult to section in the as-quenched condition, the microstructure observed at the air cooled end of the Jominy bars plus the information obtained by examining the bars after tempering were employed to evaluate the transformation constituents formed. The microstructure of the Jominy bars was discussed under hardenability. The microstructures at the center of the plates are shown in Figure 9 except for plates 1, 5, and 6 which were similar to plate #2, and plate #3 which was similar to plate #4. The presence of nonmartensitic transformation structures was difficult to discern except where free ferrite was observed or where the carbides tended to become oriented in a lamellar manner.

The lower alloy steels 1, 2, 3, 5, and 6 and the low carbon heat 13 contained a considerable quantity of free ferrite as well as a tendency toward lamellar carbides. This group of plates exhibited the poorest fractures and also the greatest loss of impact energy when the testing temperature was reduced from 68°F. to -40°F. Plates 4, 9, 10, and 12 exhibited inferior toughness yet these plates contained only a small amount of free ferrite at the center. There was, however, a definite tendency for the carbides to form in a lamellar or other oriented pattern. The remaining plates which possessed satisfactory impact properties contained very little or no free ferrite or oriented carbide distributions. Nevertheless in this group was plate #8 which contained about 80% nonmartensitic transformation products, consisting mainly of nonlamellar carbides in a ferrite background(bainite). The carbide distribution was very uniform and after tempering at a high temperature the structure was difficult to distinguish from tempered martensite.

It is apparent that there may be a close correlation between the impact properties and the microstructure or more accurately the constituents formed during the quench which give rise to the size, shape, and distribution of carbides after tempering.

DISCUSSION

In order to make a comparison of all the metallurgical factors of the heats, the results have been summarized in Table VI.

It may be seen that plates 8, 15, and 16, and plate 11 (after lowering the hardness and water quenching from the temper) exhibited the greatest toughness of the plates studied. These plates would be expected to exhibit satisfactory ballistic properties when heat treated as 4½" armor. A distinct tendency toward brittleness was observed in plates 11 and 16 when slow cooled from the temper. This temper embrittlement may be prevented in 4½" plates tempered at temperatures above 1100°F. by water quenching from the temper.

The remaining plates possessed insufficient hardenability for the section size involved. The 2% chromium, .5% molybdenum heats 13 and 14 possessed insufficient hardenability for a 4½" plate thus indicating the necessity for maintaining the chromium content at the 2.5% level in the 4" to 6" armor being currently produced. Heat #13 having a carbon content on the low side (.24%), was markedly inferior in hardenability and toughness to the higher carbon plate #14. Heat #14 would be expected to quench out in a 3" to 4" section for it possessed only a slight deficiency in hardenability.

Heats 10 and 11 possess a borderline hardenability for 4½" plate; the slightly lower manganese content of heat #10 makes it unsatisfactory whereas heat #11 does exhibit satisfactory properties at a low hardness.

It was observed that satisfactory toughness could be obtained in steels not completely transformed to martensite upon quenching when tempered to a low hardness (230 Brinell). The boron treated plate #8 possessed about 80% bainite but very little ferrite. The bainitic structure did not contain appreciable oriented carbide distributions which are believed to be associated with the tendency to exhibit brittle properties. Heats 10 and 11, on the other hand, possessed rather pronounced striated carbide formations which probably are responsible for the reduced impact strength of these steels when heat treated in heavy sections. In the lower hardenability steels, the presence of high temperature transformation products (as indicated by the presence of ferrite) was responsible for the poor impact properties observed

As it was stated in the introduction, these plates were tempered to a rather low hardness for testing, a condition which would minimize the tendency toward brittleness resulting from incomplete quench hardening. The hardnesses of plates 11 and 16 were greater than that currently in use for heavy armor. Plates 8 and 15 at 230-240 Brinell were at the hardness presently being used. However, increased ballistic efficiency, which is at present desired, can only be accomplished by increasing the hardness without impairing the shock resistance (toughness). It is felt that steels of type 15 and 16 show the most promise of successful application at higher hardnesses.

In the higher alloy steels, susceptibility to temper brittleness appears to be a very important factor. Heats 10, 11, and 16 are all sufficiently influenced by temper brittleness that they must be water quenched from the temper if inferior toughness is to be avoided. A more complete discussion of this phenomenon and its presence in armor compositions is included in a recent report[1].

It was observed that satisfactory room temperature notched bar impact values were obtained on several of the steels which were not completely quench hardened, whereas the low temperature values as well as the fracture results revealed the relatively inferior toughness. Thus it is indicated that the room temperature Charpy test is not always a satisfactory criterion of the toughness of armor steels. On the other hand, it should be stated

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1. See footnote 1, page 3.

that the high room temperature values show that these plates are far superior to armor which has been made in the past possessing very poor impact values even at room temperature.

The use of a fracture hardenability test is advantageous for evaluating the ability of steel to yield fibrous fractures in section sizes from about 2" to 4". The test shows how far the fibrous condition extends along the fracture Jominy bar. This distance may be converted to a plate thickness which would be expected to quench harden in such a manner as to yield a fibrous fracture when tempered to the same hardness. In the present study, a fairly good correlation was obtained between the results of this test and the results on the $4\frac{1}{2}$" plates.

TABLE I

Chemical Analyses

Heat No.	Type Furnace*	C	Mn	Si	S	P	Ni	Cr	Mo	Residual Al	
1	B	.28	1.52	.27	.023	.010	—	.62	.48	.07	
2	B	.26	1.51	.29	.021	.012	—	.89	.47	.09	
3	B	.28	1.52	.28	.023	.011	.77	.65	.47	.07	
4	A	.30	1.21	.37	.025	.012	.79	.88	.46	.08	
5	A	.33	.71	.33	.021	.014	.88	.98	.46	.05	
6	A	.29	.56	.32	.020	.019	.87	1.20	.44	.02	
7	A	.29	.68	.32	.019	.019	.91	1.02	.46	.05	
8	A	.32	.82	.28	.022	.011	.83	.81	.48	.06	B .002
9	A	.31	.63	.31	.025	.012	1.65	1.15	.46	.10	
10	A	.31	.79	.31	.027	.012	1.56	1.14	.46	—	V .10
11	A	.31	.97	.36	.026	.012	1.32	1.07	.46	—	.10
12	B	.31	.79	.23	.023	.008	—	1.71	.46	.08	
13	B	.24	.76	.21	.021	.010	—	2.02	.46	.08	
14	B	.34	.72	.32	.023	.009	—	2.01	.46	.07	
15	B	.35	.65	.06	.020	.009	.97	1.70	.48	.08	
16	B	.36	.90	.34	.021	.016	1.01	1.71	.48	.08	

*Legend: B – basic-lined induction furnace.

A – acid-lined induction furnace.

TABLE II

End Quench Fracture Bar Results on Tempered Bars

	Hardness				Distance to Crystallinity Bars Water Quenched from Temper		Distance to Crystallinity* Bars Furnace Cooled from Temper	
	1/16" From Quenched End		40/16" From Quenched End					
Heat No.	Rc	BHN Converted	Rc	BHN Converted	Fractured at 68°F.	Fractured at -40°F.	Fractured at 68°F.	Fractured at -40 °F.
2	25	255	23	241	No C	1/16"	—	—
3	17	217	15	212	No C	18/16"	—	—
4	18	220	16	215	No C	30/16"	—	4/16" (Fc 1/8)
7	20	229	17.5	218	No C	10/16"	—	—
7	26	262	20	229	No C	9/16"	—	—
7	33	321	30	293	12/16"	2/16"	—	—
8	20	229	19	223	No C	No C	—	—
8	27	269	24	248	No C	No C	—	—
8	33	321	31	302	No C	1/16" (Fc 1/4)	—	—
9	20	229	18	220	No C	23/16"	No C	23/16"
10	20	229	19	223	No C	No C	No C	—
10	23	241	22	237	—	No C	—	1/16" (Cbf 3/4)
11	19	223	18	220	No C	—	No C	—
11	21	235	20	229	—	No C	—	1/16" (Cbf 3/4)
12	19	223	15	212	No C	14/16"	—	—
13	14	207	10	189	No C	1/16"	—	—
14	23	241	21	235	No C	No C	No C	1/16" (Fc 1/8)
15	23	241	23	241	No C	No C	No C	1/16" (Fc 1/8)
15	28	277	25	255	No C	No C	—	—
16	24	248	24	248	No C	No C	No C	1/16" (Fc 1/2)
16	30	293	29	285	No C	No C	—	—

*Legend: Fc – Fibrous background with scattered crystallinity.

Cbf – Bright crystalline zone surrounded by fibrous border.

No C – No crystallinity over length of fracture bar.

Fractions refer to approximate fractional area of crystallinity.

TABLE III

Temper Brittleness Susceptibility Test

V-Notch Charpy Test at -40°F

	Bars Water Quenched from Temper			Bars Furnace Cooled from Temper		
Heat No.	Ft. Lbs.	Fracture	Hardness Rc	Ft. Lbs.	Fracture	Hardness Rc
1	46.0	F	24	49.0	Fc 1/8	18
	49.0	F	24	49.0	Fc 1/8	18
2	51.0	F	24	48.5	Cbf 1/8	15
	50.5	F	25	46.0	Cbf 1/4	16
3	49.0	F	24	42.0	F	21
	45.0	F	24	39.5	Fc 1/8	20
4	54.5	F	21	48.0	Fc tr	19
	54.0	F	20	44.5	Fc tr	19
5	49.0	F	27	53.5	F	21
	46.5	F	27	53.5	F	20
6	49.0	F	25	51.5	F	19
	46.0	F	25	52.0	F	21
7	46.5	F	24	50.0	F	23
	49.0	F	23	49.0	F	22
8	49.0	F	23	46.0	F	21
	49.0	F	23	44.5	F	22
9	47.5	F	21	50.0	F	20
	47.0	F	22	39.0	F	20
10	48.0	F	24	36.5	Cbf 1/2	25
	44.0	F	24	46.0	Fc tr	25
11	55.5	F	25	42.5	Cbf 1/4	23
	58.0	F	25	57.0	Fc tr	23
12	51.0	F	24	53.0	Cbf 1/8	22
	58.0	F	24	53.0	F	22
13	64.5	F	20	58.0	Cbf 1/4	16
	58.5	F	21	69.0	F	16
14	57.0	F	20	54.5	F	19
	55.5	F	20	57	F	20
15	46.0	F	22	43.5	F	22
	41.0	F	20	48.5	F	22
16	50.0	F	22	41.0	Fc 1/8	22
	48.5	F	22	44.5	Fc 1/8	21

TABLE IV

Hardness Surveys on 4-1/2" Sections

Plate No.	Surface BHN	Midway between Surface and Center BHN	Center BHN
1	229	212	207
2	229	217	207
3	229	207	201
4	255	248	235
5	241	229	229
6	241	235	223
7	235	212	207
8	241	241	229
9	241	229	217
10	255	255	241
11	269	269	269
12	223	217	217
13	217	212	197
14	269	255	248
15	248	235	229
16	262	255	255

TABLE V

V-Notch Charpy Impact Results

	Tests at 68°F (20°C)						Tests at -40°F (-40°C)			
	4-1/2" Sections			1/2" Sections			4-1/2" Sections		1/2" Sections	
Heat No.	Energy Ft. Lbs.	Fracture**	Hardness BHN	Energy Ft. Lbs.	Fracture	Hardness BHN	Energy Ft. Lbs.	Fracture	Energy Ft. Lbs.	Fracture
2	63.5	Fc tr	207	61.5	F	229	10.5	Cbf 7/8	53.0	F
	64.0	"	207	57.0	F	223	23.5	"	57.0	F
3	50.0	Cbf 1/8	229	58.0	F	223	26.5	Cbf 3/4	57.0	F
	37.5	"	229	57.5	F	212	27.0	"	49.5	F
4	48.0	Fc tr	239	56.0	F	229	33.5	Cbf 1/2	51.5	F
	49.0	"	239	57.0	F	229	26.0	"	55.5	F
4 Retempered & W.Q.*	65.5	F	212	--	--	--	53.5	Fc tr	--	--
	--	--	--	--	--	--	50.0	"	--	--
7	56.5	Cbf 1/8	207	44.5	F	248	40.5	Cbf 1/2	54.5	F
	68.5	Fc tr	207	54.0	F	229	31.0	Cbf 3/4	53.5	F
8	60.0	F	220	54.0	F	223	59.5	F	54.5	F
	53.5	F	217	58.0	F	220	56.0	Fc tr	49.0	F
9	50.0	Fc tr	229	41.5	F	245	29.5	Cbf 1/2	43.0	F
	47.5	Fc tr	229	40.5	F	248	36.5	"	39.0	F
9 Retempered & W.Q.	53.0	F	217	--	--	--	43.5	Fc 1/4	--	--
	--	--	--	--	--	--	39.0	Fc 1/4	--	--
10	37.5	Fc 1/8	255	40.5	F	272	22.0	Fc 3/4	45.0	F
	45.0	"	255	--	--	--	26.5	Fc 3/4	--	--
10 Retempered & W.Q.	47.5	Fc 1/8	255	--	--	--	34.5	Fc 1/2	--	--
	51.0	F	255	--	--	--	30.5	Fc 1/2	--	--

TABLE V (CONT'D)

	Tests at 68°F (20°C)						Tests at -40°F (-40°C)			
	4-1/2" Sections			1/2" Sections			4-1/2" Sections		1/2" Sections	
Heat No.	Energy Ft. Lbs.	Fracture**	Hardness BHN	Energy Ft. Lbs.	Fracture	Hardness BHN	Energy Ft. Lbs.	Fracture	Energy Ft. Lbs.	Fracture
10 Retempered @ 1280°F W.Q.	59.0	F	217	—	—	—	46.5	Fc 1/4	—	—
	60.5	F	220	—	—	—	42.5	Fc 1/4	—	—
11	32.5	Fc 1/8	269	48.0	F	262	16.0	Fc 7/8	52.5	F
	31.0	"	272	53.5	F	269	20.5	Fc 7/8	47.5	F
11 Retempered & W.Q.*	45.5	F	265	—	—	—	48.5	Fc 1/4	—	—
	62.0	F	260	—	—	—	44.0	Fc 1/4	—	—
11 Retempered @ 1280°F W.Q.	65.0	F	229	—	—	—	61.0	Fc tr	—	—
	64.5	F	223	—	—	—	60.0	Fc tr	—	—
12	68.5	F	217	64.5	F	217	29.0	Cbf 3/4	55.5	F
	69.5	F	217	58.0	F	235	30.5	Cbf 3/4	50.5	F
13	62.0	Fc tr	207	62.5	F	217	34.0	Cbf 7/8	67.0	F
	—	—	207	74.0	F	207	32.0	Cbf 7/8	71.5	F
14	54.5	F	239	56.0	F	248	30.5	Cbf 1/2	49.0	F
	53.0	F	239	60.0	F	235	38.5	Cbf 1/2	55.0	F
15	40.0	F	235	36.0	F	248	36.5	F	37.5	F
	39.5	F	235	37.5	F	248	39.5	Fc tr	—	—
16	39.0	Fc 1/8	245	46.5	F	255	34.0	Fc tr	50.5	F
	40.5	Fc 1/8	255	45.0	F	262	35.5	Fc tr	51.0	F

*W.Q. – water quenched from temper.

**Symbols for fracture ratings same as in Table II.

TABLE VI.

SUMMARY OF THE COMPOSITION, HARDENABILITY AND IMPACT PROPERTIES OF THE EXPERIMENTAL HEATS.

CHEMICAL COMPOSITION							HARDENABILITY							PROPERTIES OF 4½" SECTIONS AFTER 1250° F. TEMPER					PROPERTIES OF SMALL SECTIONS AFTER 1250° F. TEMPER			SUSCEPTIBILITY TO TEMPER BRITTLENESS	USE IN 4½ INCH SECTION
HEAT NO.	C	Mn	Ni	Cr	Mo	Other	1/16" from Q.E. Hardness	1" from Q.E. Hardness	1" from Q.E. Micro*	2½" from Q.E. Hardness	2½" from Q.E. Micro*	Distance to Rc 43	ø - Distance to Cryst.	Hardness	Fracture	V-notch Charpy		Micro at Center *	Hardness	V-notch Charpy			
							Rc	Rc		Rc		Inches	Inches	BHN	‡	68°F	-40°F		BHN	68°F	-40°F		
1	.28	1.52	-	.62	.48		48.5	37		30		9/16		229/207	Cbf 3/4			C 40 F				slight	Unsatisfactory
2	.26	1.51	-	.89	.47		47	35	Bfc	27	Fc	8/16	1/16	229/207	Cbf 3/4	64	18	C 40 F	226	59	55	slight	Unsatisfactory
3	.28	1.52	.77	.65	.47		51	47	Mb	40	Bfm	32/16	18/16	229/201	Fc 1/2	43	27	C 20 F	217	58	54	slight	Unsatisfactory
4	.30	1.21	.79	.88	.46		49.5	46	Mb	40	Bfm	23/16	30/16	255/235	Fc 1/4	49	30	C 20 F	229	57	53	slight	Unsatisfactory
5	.33	.71	.88	.98	.46		50	42		34		13/16		241/229	Cbf 3/4			C 30 F				none	Unsatisfactory
6	.29	.56	.87	1.20	.44		50	39		33		11/16		241/223	Cbf 3/4			C 50 F				none	Unsatisfactory
7	.29	.68	.91	1.02	.46		49	40	MB	32	BFc	12/16	10/16	235/207	Cbf 3/4	62	36	C 50 F	235	49	53	none	Unsatisfactory
8	.32	.82	.83	.81	.48	B.002	49	46	Mb	40	Bf	24/16	None	241/229	F	57	58	C 5 F	222	56	52	none	Satisfactory
9	.31	.63	1.65	1.15	.46		51	49	Mb	42	MBf	32/16	23/16	241/217	Fc 1/2	49	33	C 10 F	247	41	41	none	Unsatisfactory
10	.31	.79	1.56	1.14	.46	V .10	50	48	Mb	41	MB	32/16	None	255/241	Fc 3/4	42	24	BC 10 F	272	40	45	moderate	Unsatisfactory
11	.31	.97	1.32	1.07	.46	V .10	49	48	Mb	46	MB	Beyond end of bar.	None	269/269	Fc 1/2	31	18	BC 10 F	267	51	50	moderate	Borderline
12	.31	.79	-	1.71	.46		48	42	MB	38	Bfm	14/16	14/16	223/217	Cbf 3/4	69	30	BC 30 F	225	61	53	slight	Unsatisfactory
13	.24	.76	-	2.02	.46		46	40	MB	35	CF	10/16	1/16	217/197	Cbf 3/4	62	33	C 40 F	212	69	69	none	Unsatisfactory
14	.34	.72	-	2.01	.46		54	51	Mb	45	MB	Beyond end of bar	None	269/248	Fc 1/8	54	34	C 10 F	242	58	52	slight	Borderline
15	.35	.65	.97	1.70	.48		53	50	Mb	45	MB	"	None	248/229	Fc Tr	40	38	C 5 F	248	37	37	slight	Satisfactory
16	.36	.90	1.01	1.71	.48		55	51	Mb	50	Mb	"	None	262/255	Fc Tr	40	35	C 5 F	258	45	51	moderate	Satisfactory

ø — Fracture end quench bar after 1250° F. temper, broken at -40° F.
‡ — See Table VII for standard fracture rating systems.
* — Micro Symbols:

F — Large	amount of ferrite
f — Small	" " "
M — Large	" " martensite
m — Small	" " "
B — Large	" " bainite
b — Small	" " "
C — Large	" " carbides
Number —	Percent ferrite

WTN. 639-7096

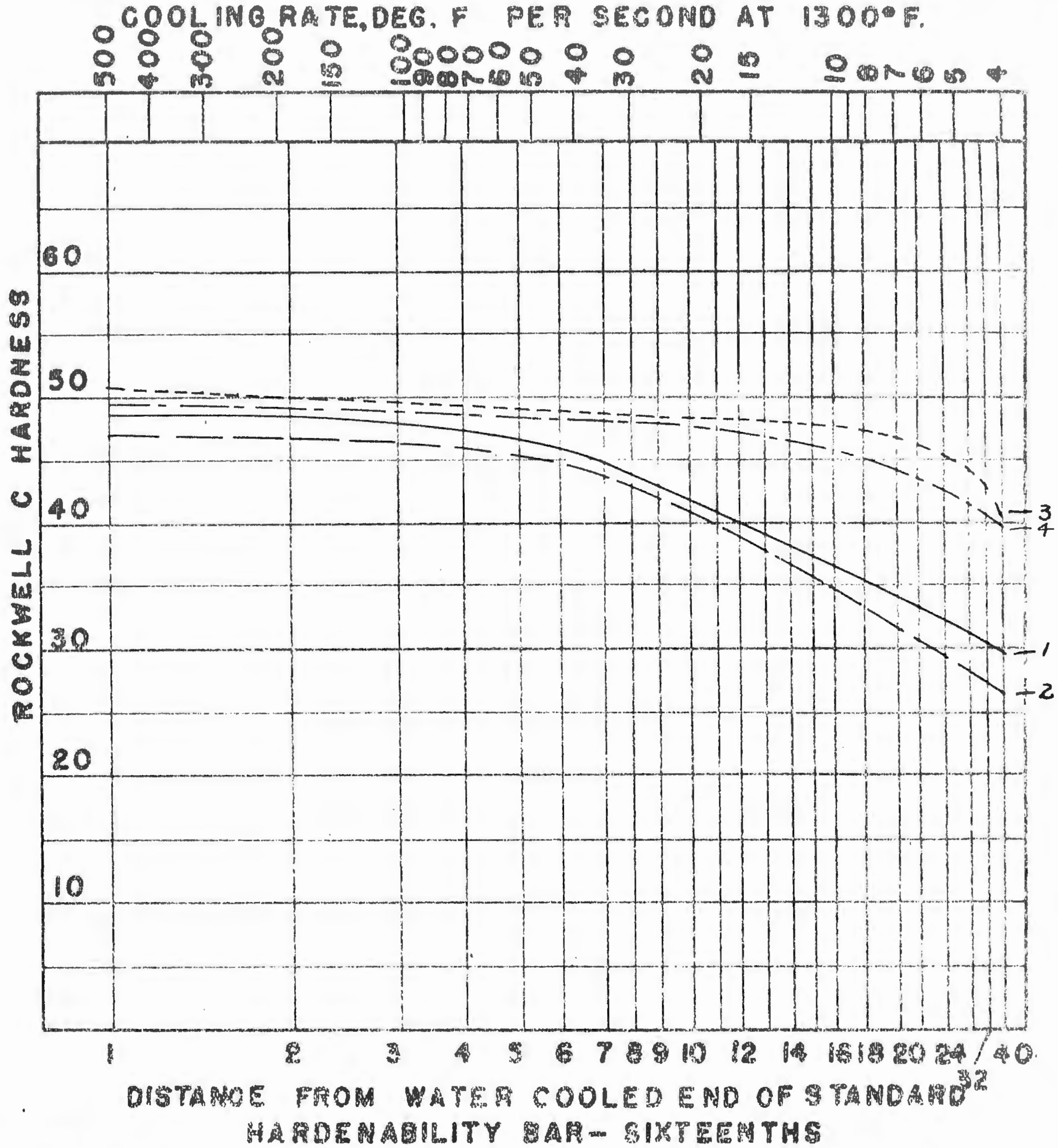


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	AL		QUENCH TEMP.	QUENCH TIME	G.S.
———	1	.28	1.52	.27	.023	.010	—	.62	.48	.07		1650°F	3 Hrs	
— —	2	.26	1.51	.29	.021	.012	—	.89	.47	.09		"	"	
- - - -	3	.28	1.52	.28	.023	.011	.77	.65	.47	.07		"	"	
— - —	4	.30	1.21	.37	.025	.012	.79	.88	.46	.08		"	"	

FIGURE 1

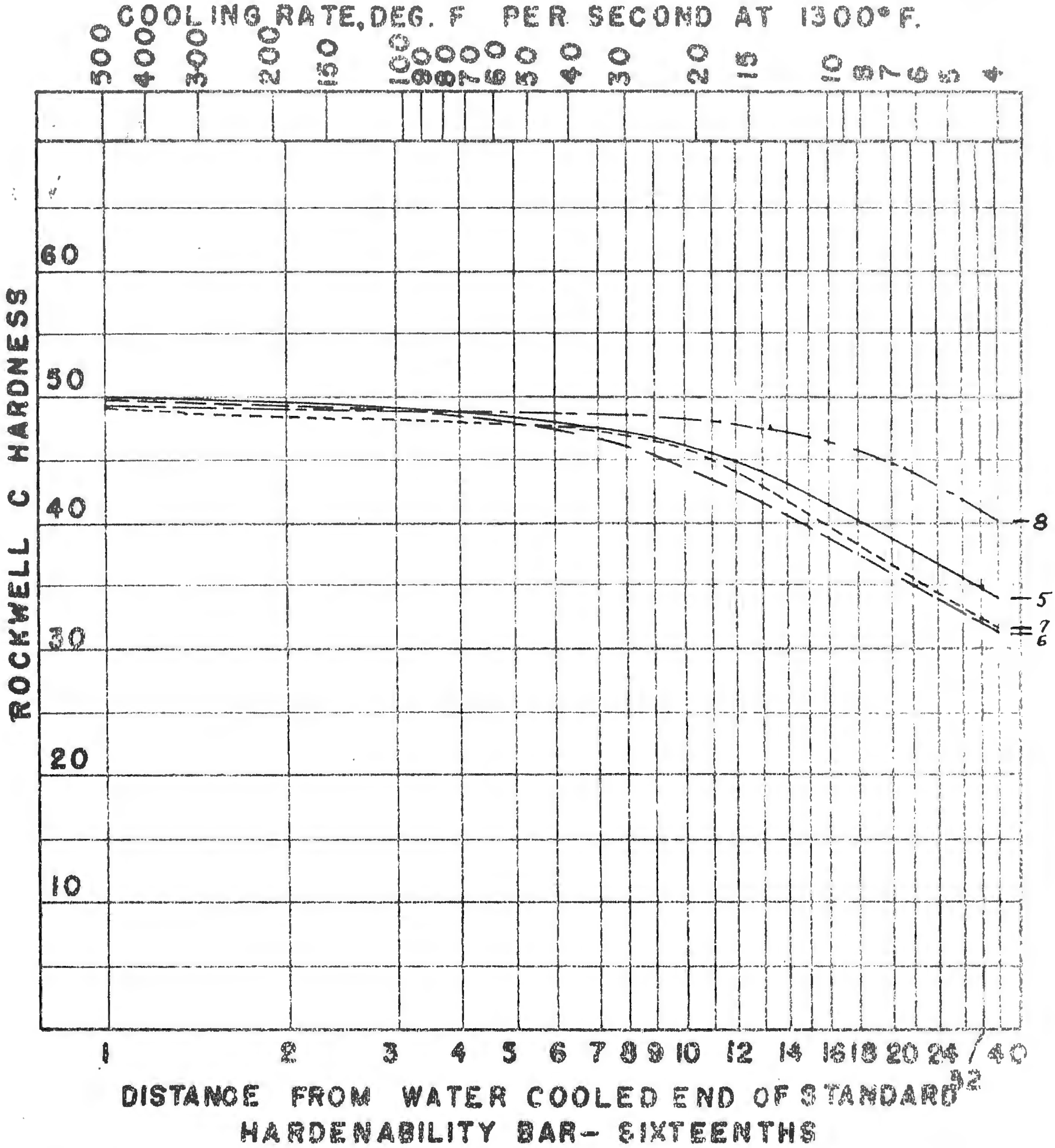


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	AL	B	QUENCH TEMP	TIME	G.S.
———	5	.33	.71	.33	.021	.014	.88	.98	.46	.05		1650°F	3 Hrs.	
—— ——	6	.29	.56	.32	.020	.019	.87	1.20	.44	.02		"	"	
- - - - -	7	.29	.68	.32	.019	.019	.91	1.02	.46	.05		"	"	
—— - - -	8	.32	.82	.28	.022	.011	.83	.81	.48	.06	.002	"	"	

FIGURE 2

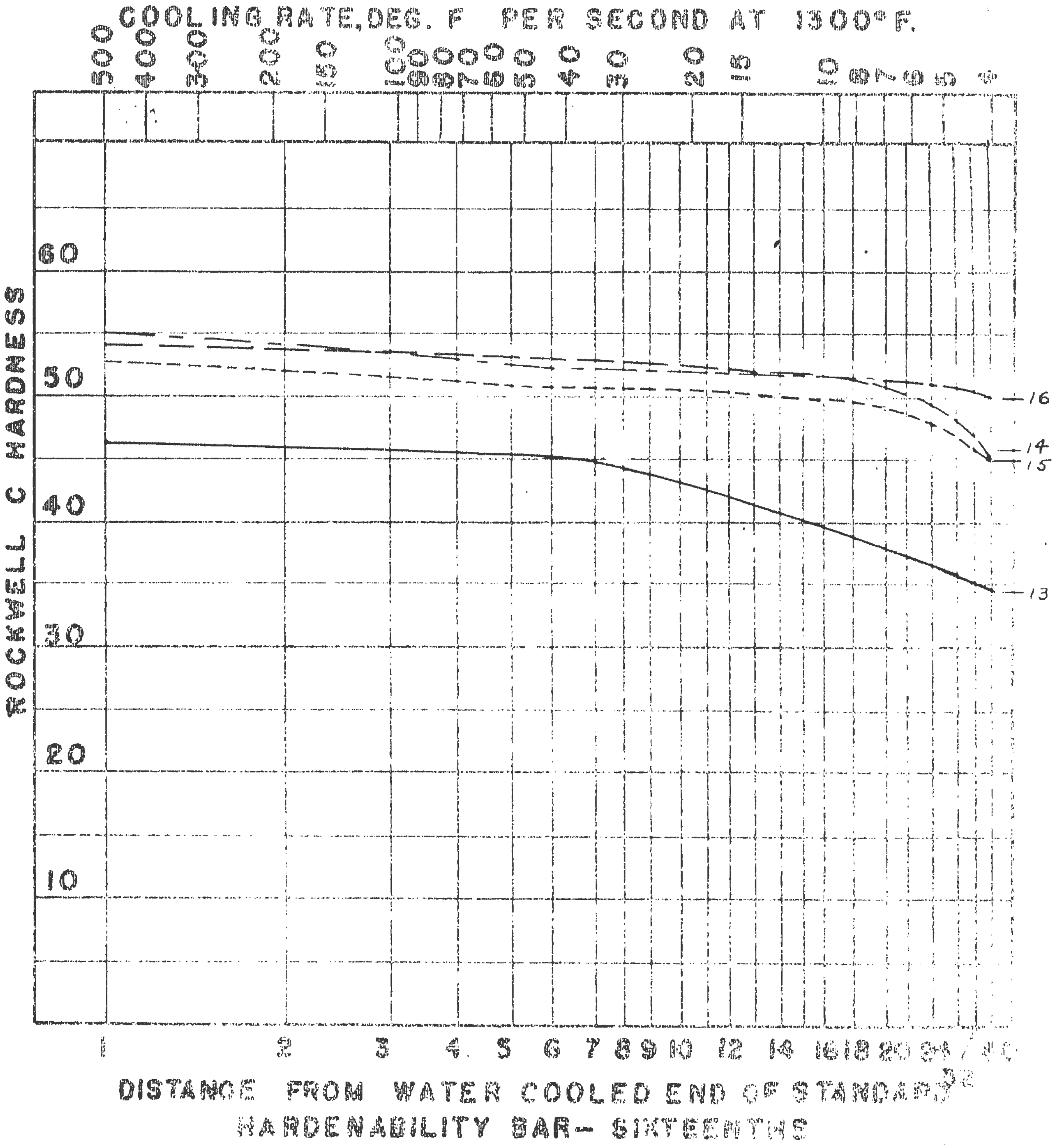


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	AL		QUENCH TEMP	QUENCH TIME	G.S.
———	13	.24	.76	.21	.021	.010	—	2.02	.46	.08		1575°F	3Hrs.	
— —	14	.34	.72	.32	.023	.009	—	2.01	.46	.07		"	"	
- - - -	15	.35	.65	.06	.020	.009	97	1.70	.48	.08		"	"	
— - —	16	.36	.90	.34	.021	.016	1.01	1.71	.48	.08		"	"	

FIGURE 4

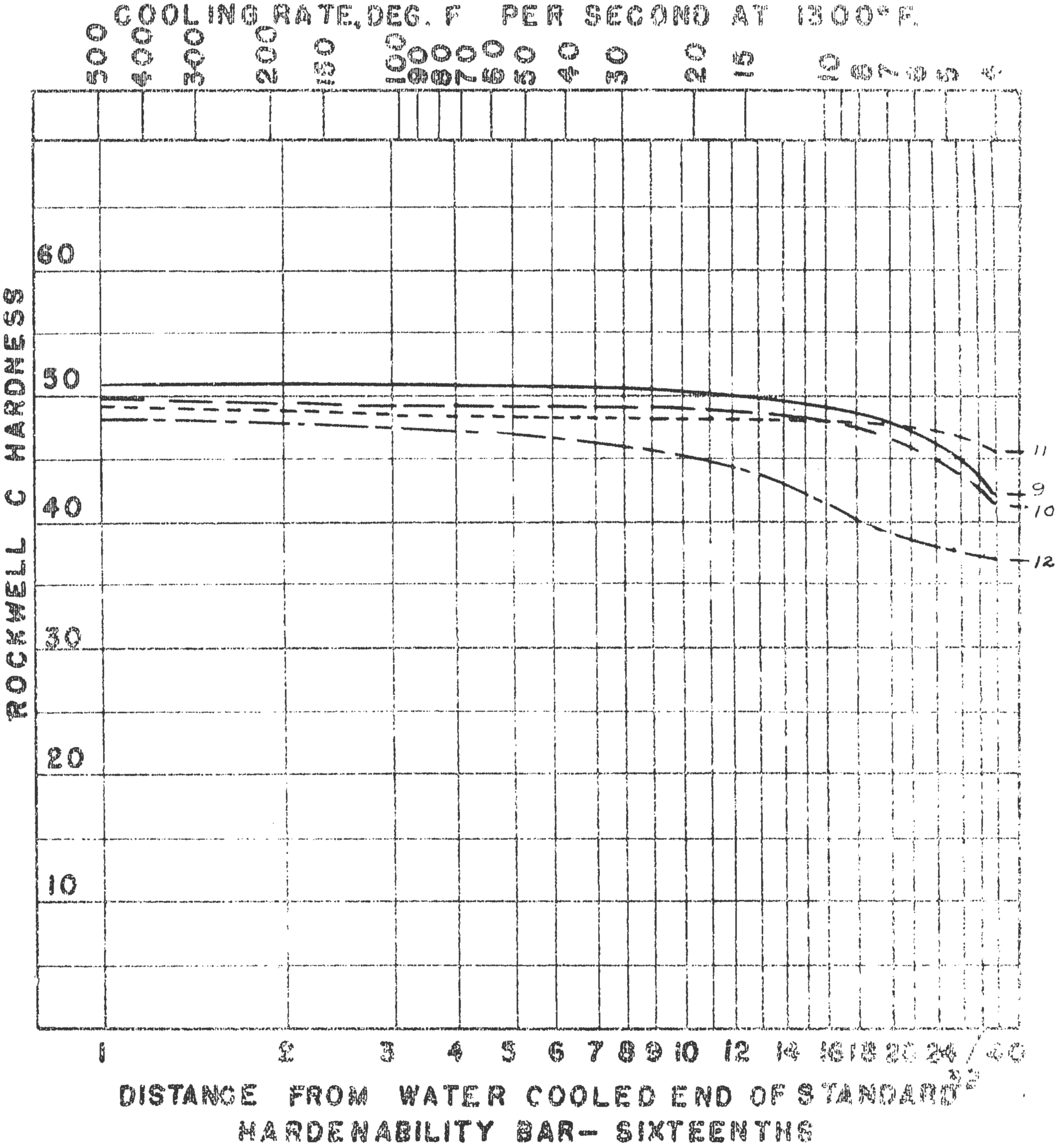
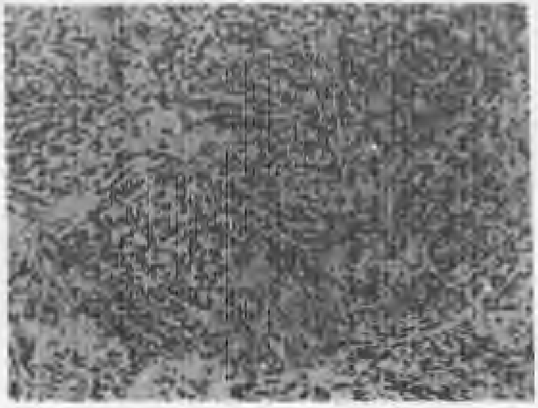


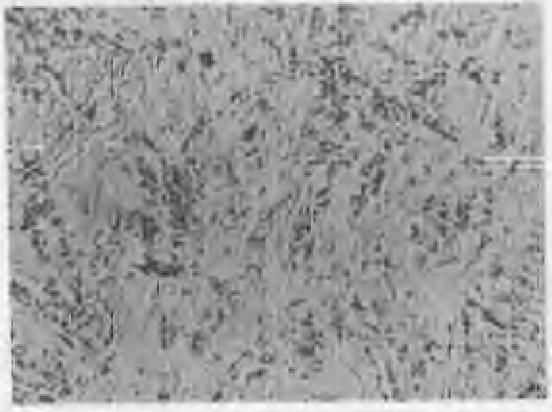
PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	AL	V	QUENCH TEMP	QUENCH TIME	G.S.
———	9	.31	.63	.31	.025	.012	1.65	1.15	.46	.10		1650°F	3 Hrs.	
— —	10	.31	.79	.31	.027	.012	1.56	1.14	.46		.10	"	"	
- - - -	11	.31	.97	.36	.026	.012	1.32	1.07	.46		.10	"	"	
— - —	12	.31	79	.23	.023	.008	—	1.71	.46	.08		1675°F	"	

FIGURE 3

Microstructure of Hardenability Bars

1" from quenched end — 2½" from quenched end

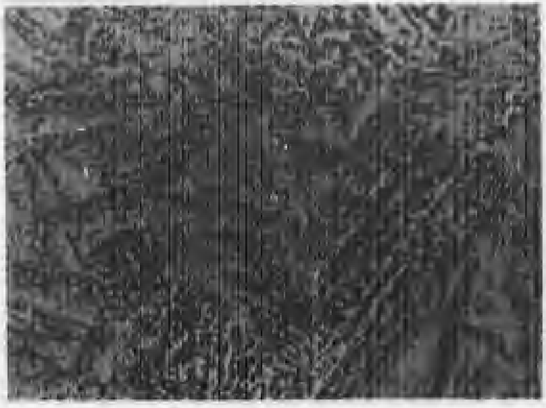


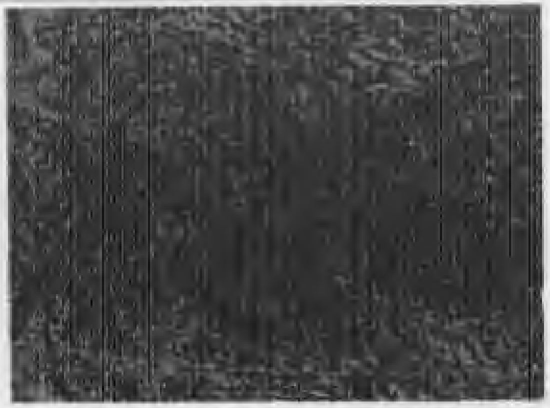


Heat 2

A
Bainite, ferrite and carbides. Rc 35.

B
Ferrite and carbides. Rc 27.

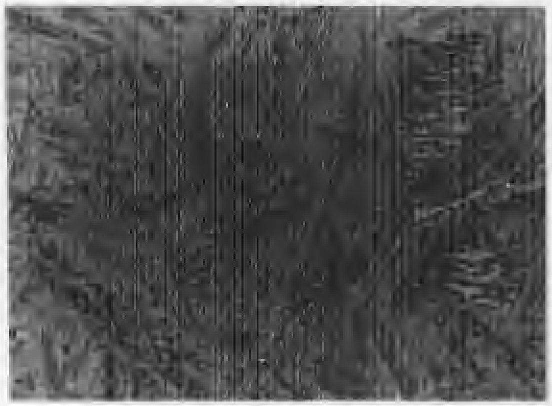


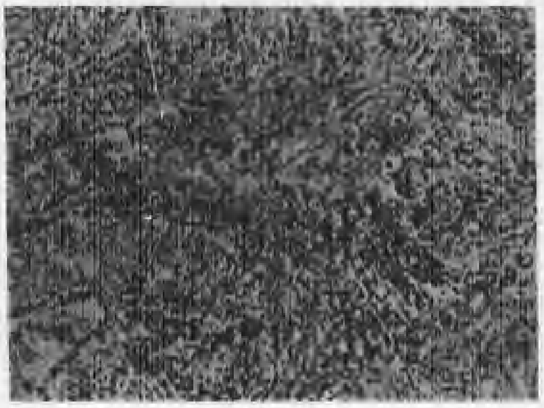


Heat 3

C
Martensite and resolvable acicular bainite. Rc 48.

D
Bainite and ferrite with some martensite. Rc 41.





Heat 4

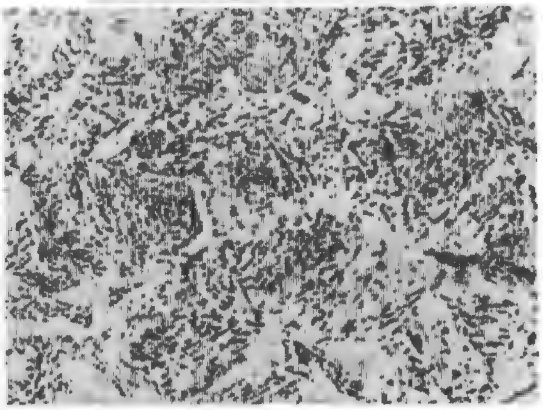
E
Martensite and resolvable acicular bainite. Rc 46.

F
Bainite and ferrite with some martensite. Rc 40.

WTN.529-723

1" from quenched end

2½" from quenched end



Heat 7

G
Martensite and resolvable acicular bainite. Rc 40.

H
Bainite and ferrite. Rc 32.

Heat 8

I
Martensite and resolvable bainite. Rc 47.

J
Bainite and a small amount of ferrite. Rc 40.

Heat 9

K
Martensite and resolvable bainite. Rc 49.

L
Martensite, resolvable bainite and ferrite. Rc 42.

WTN. 639-7232

1" from quenched end

2½" from quenched end

Heat 11

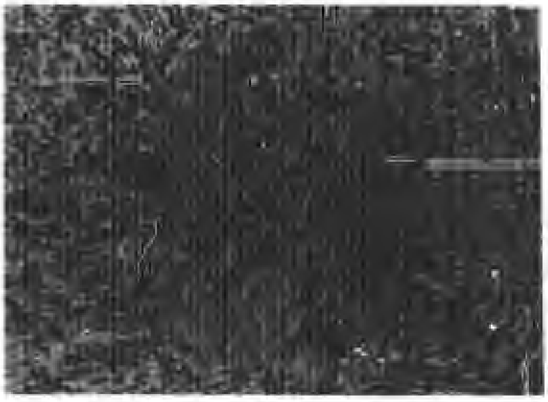
M
Martensite and a small amount of resolvable bainite. Rc 48.

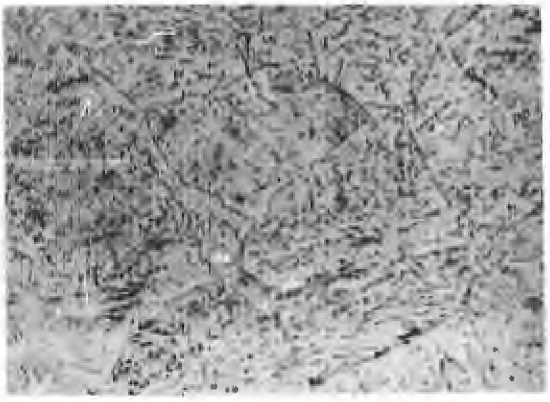
N
Martensite and coarse acicular bainite. Rc 46.

Heat 12

O
Martensite, bainite and ferrite. Rc 42.

P
Bainite and ferrite with some martensite. Rc 38.





Heat 13

Q
Martensite and bainite. Rc 40.

R
Ferrite and carbides. Rc 35.

Microstructure of Hardenability Bars

1" from quenched end

2½" from quenched end

Heat 14

S

Martensite and a small amount of resolvable bainite. Rc 52.

T

Martensite and resolvable bainite. Rc 45.

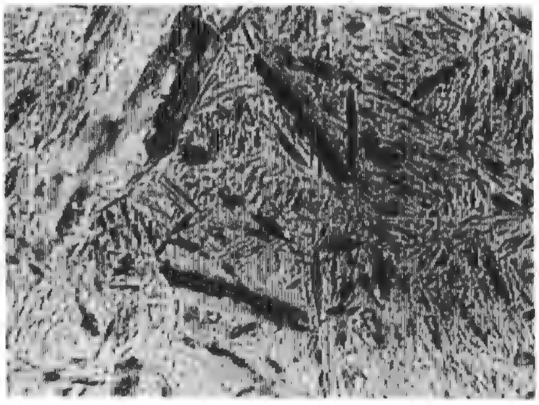
Heat 15

U

Martensite with traces of bainite. Rc 50.

V

Martensite and acicular bainite. Rc 45.



Heat 16

W

Martensite with traces of bainite. Rc 52.

X

Martensite and a small amount of acicular bainite. Rc 50.

WTN.639-7234

All Photomicrographs 1000X - Picral Etch

FIGURE 5

DESCRIPTION OF FRACTURES

Plate 5 - Mixed fracture characterized by a crystalline zone surrounded by a fibrous edge extending in about 3/4" from the surface of the plate.

Plate 7 - Mixed fracture similar to that of plate 5.

Plate 4 - Mixed fracture characterized by a fibrous matrix containing scattered spots of crystallinity confined, for the most part, to the central third of the casting.

Plate 11 - Mixed fracture characterized by a fibrous matrix containing spots of crystallinity covering about one-half of the fracture area.

FIGURE 6

FRACTURE BLOCKS

PLATE 5

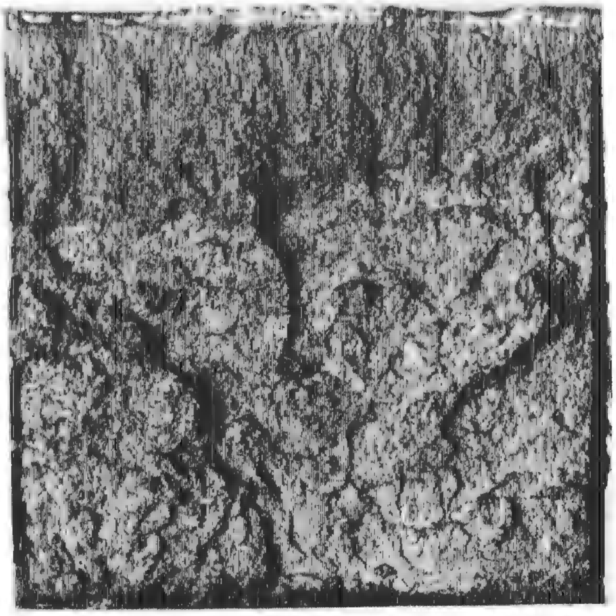


PLATE 7

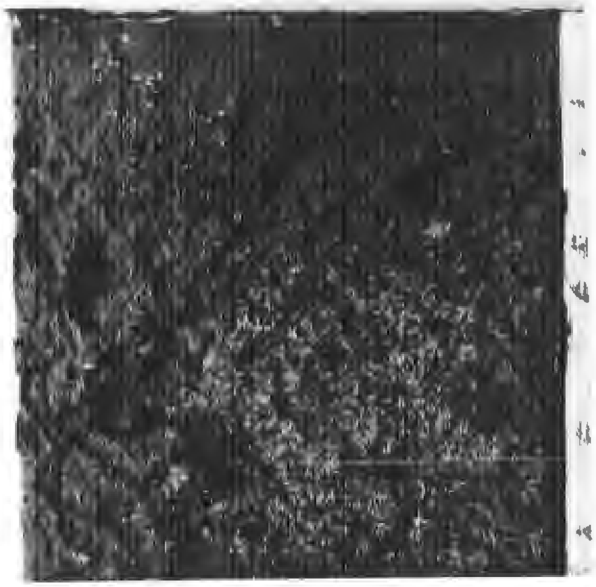


PLATE 4

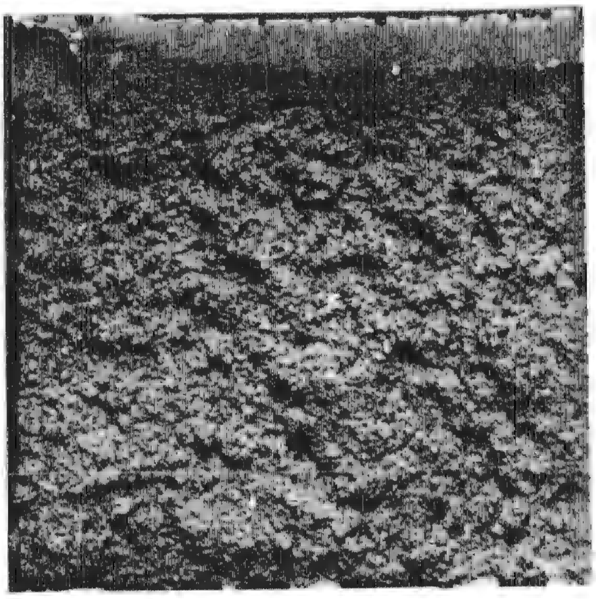


PLATE 11

FIGURE 6

DESCRIPTION OF FRACTURES

Plate 8 - Fibrous fracture characterized by a dull gray non-reflecting surface containing no bright facets.

Plate 14 - Mixed fracture characterized by a fibrous matrix containing scattered spots of crystallinity covering about one-eighth of the fracture area.

Plate 15 - Fibrous fracture containing a few spots of crystallinity.

Plate 16 - Fibrous fracture containing a few spots of crystallinity similar to fracture of plate 15.

FIGURE 7

FRACTURE BLOCKS

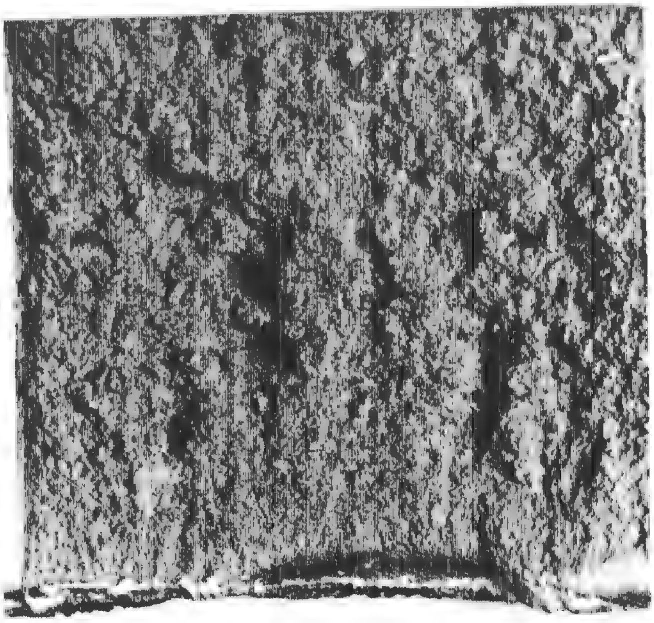


PLATE 8


PLATE 14

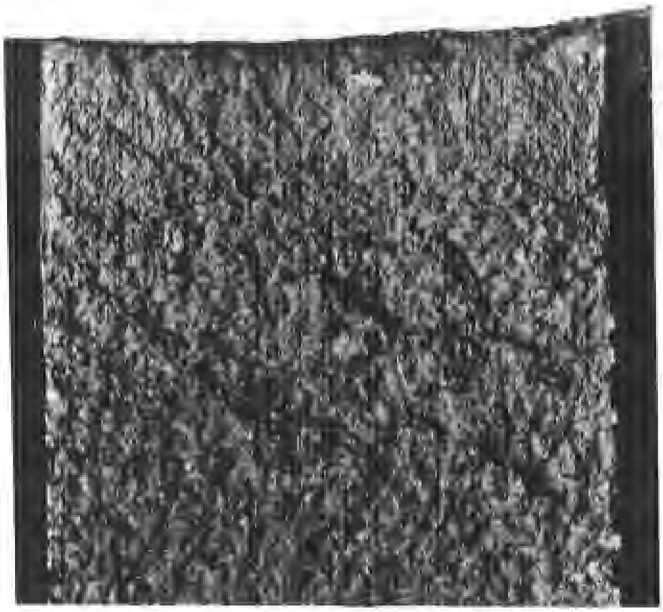


PLATE 15

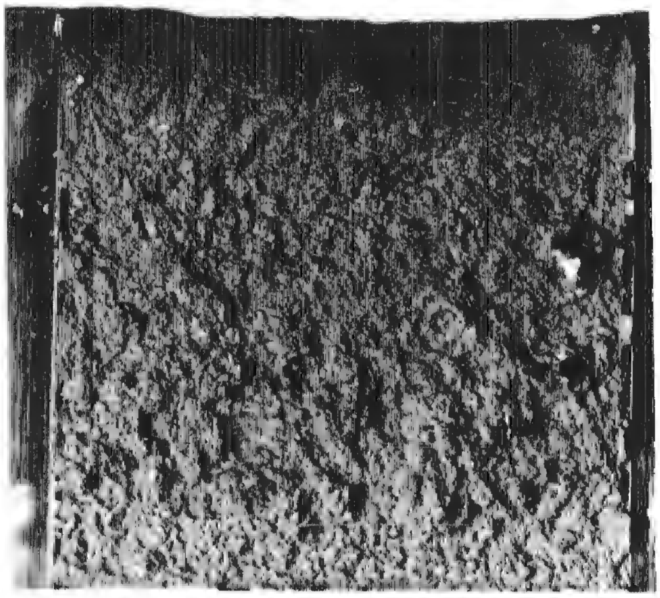


PLATE 16

FIGURE 7

V-NOTCHED CHARPY IMPACT VALUES OF EXPERIMENTAL HEATS HEAT TREATED IN LARGE AND SMALL SECTIONS

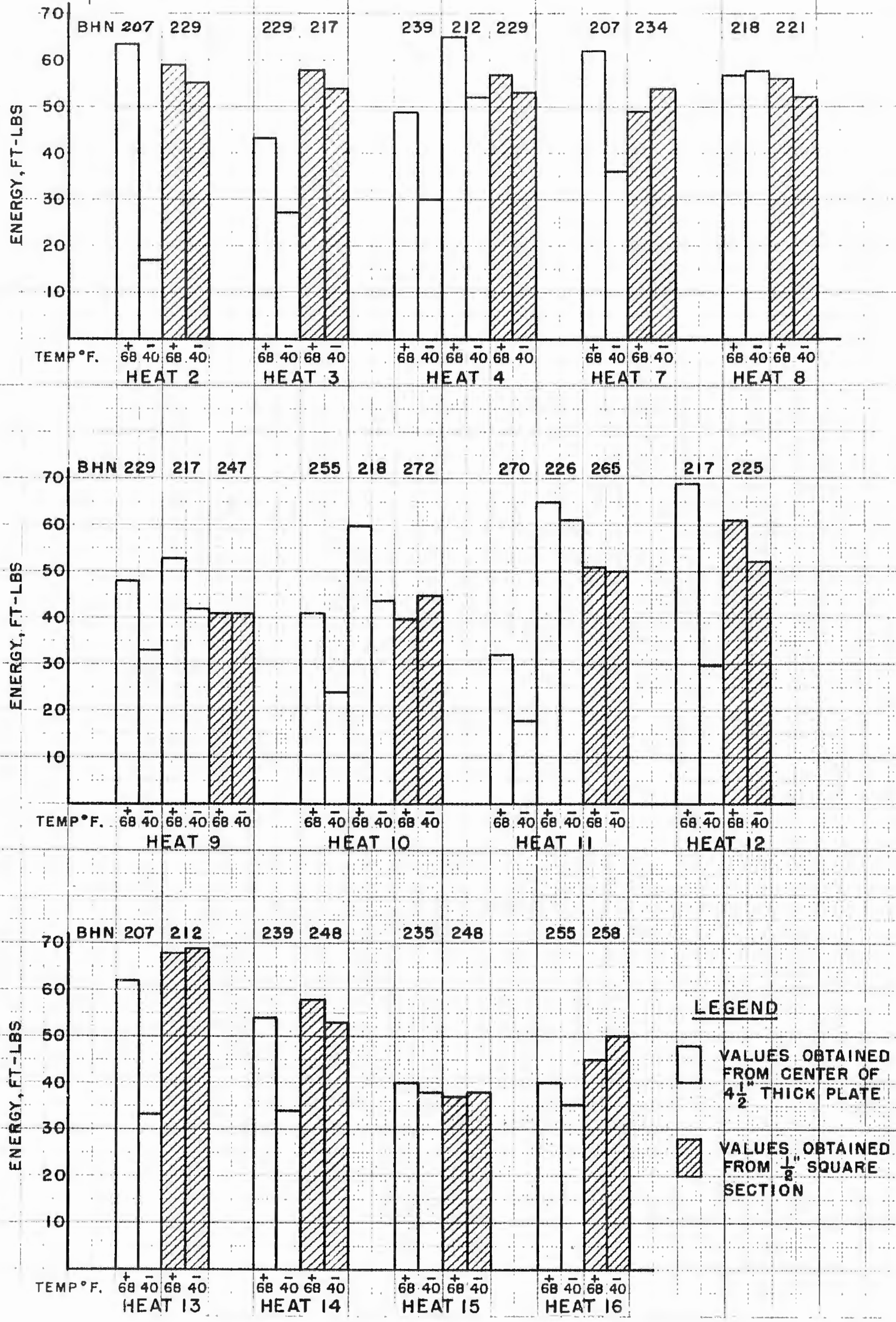


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FIGURE 8

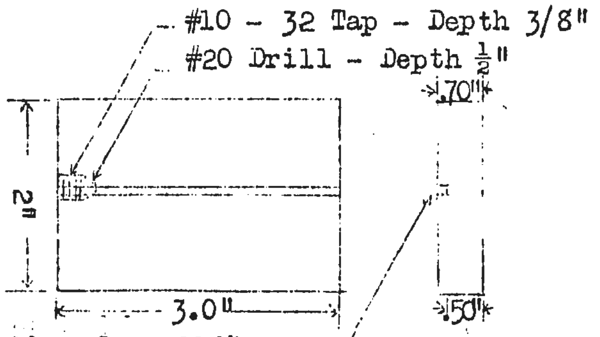
APPENDIX A

Method of Making the Fracture Type Hardenability Test

The fracture test as applied to armor reveals in a qualitative manner the toughness of steel after a given heat treatment[1]. In steels of insufficient hardenability, the fracture contains a crystalline zone in the center of the plate. In some steels, generally those of higher hardenability, mixed fractures are characterized by facets of crystallinity in a fibrous matrix. It appeared that the crystallinity in the first type of fracture mentioned may be associated to some extent with the poorly heat treated area at the center of the plate. The second type is fairly uniformly distributed over the fracture, and may be associated with a uniform reduction in toughness such as in temper embrittled steels.

A test which would reveal the ability of a steel to form the two types of fractures and the cooling rates involved would be advantageous in evaluating new alloy steels. It was decided that fracturing Jominy bars would yield just such information, i.e., determine the maximum section in which a steel could be heat treated and still maintain a fibrous fracture.

The Jominy bar as originally designed is not completely satisfactory for making a fracture test along the length of the bar for the limited width of the bar makes it difficult to support the specimen for fracturing. Therefore, a bar was designed in the form of a flat plate having a cooling rate at the air cooled end approximately the same as that obtained at this location on the one-inch round bar. The bar is dimensioned in the following drawing:



Notched by 1/16" Rubber Cut-off Wheel

Bar Used in Fracture Type End Quench Hardenability Test

A comparison of the hardness gradient on the flat bar with that of the standard round bar was obtained for several low and high alloy steels so that the difference in cooling rates between the two types of bars could be determined. In general, there was fairly good agreement although, in some cases, slightly lower hardnesses were obtained at the air cooled end of the flat bar than was observed on the standard bar. This may have been due to casting segregations in the steel or a slight difference in the cooling rate at this end. If the test is applied very extensively, it will be desirable to measure the cooling rates on this type of bar accurately.

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[1] For details of the test, See the W.A. Manual entitled: "The Fibre Fracture Test as a Control of the Toughness of Cast and Rolled Homogeneous Armor", dated 25 April 1944.

Since the bars are fairly thin, it was necessary to use a 1/4" diameter nozzle instead of the usual 1/2" nozzle, and this may be responsible, to some extent, for the lower hardnesses (lower cooling rates) obtained on the flat bars.

The bars are heat treated by using the same austenitizing treatment as the standard bar receives followed by a tempering cycle to obtain the desired hardness. Rockwell C hardness surveys are obtained along the length of the bar. Then the bars are notched lengthwise and broken by the impact blow obtained on the drop weight machine. The steel may be rated by measuring the distance to which the bar maintains a fibrous appearance.

From the tests already completed, it is apparent that this fracture is approximately as severe as the V-notched Charpy test or considerably less severe than the standard practice test which is approximately as severe as the Charpy test at -40°F. The tests to date of bars broken at the lower hardness levels indicate that the end quench fracture bar results at -40°F. are approximately equivalent to room temperature tests using the standard full section fracture coupon. The end quench fracture test is less severe because the severity of notch in this $\frac{1}{2}$" x 3" fracture area is considerably less than in the usual fracture bar with a square cross section.

Microstructure of Selected 4½" Plates in the Heat Treated Condition

Plate 2 A
Tempered martensite and bainite with a moderate amount of ferrite.

Plate 4 B
Tempered martensite and bainite with small amount of ferrite.

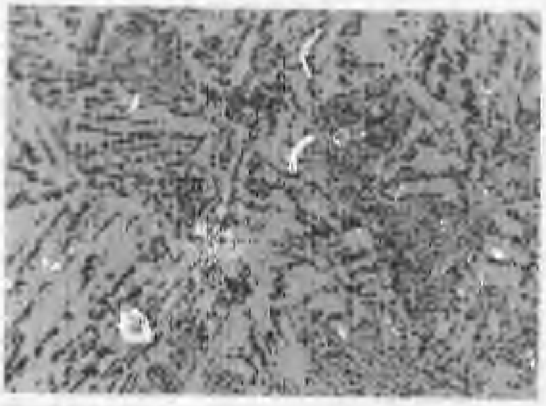

Plate 7 C
Tempered bainite and large amount of ferrite.

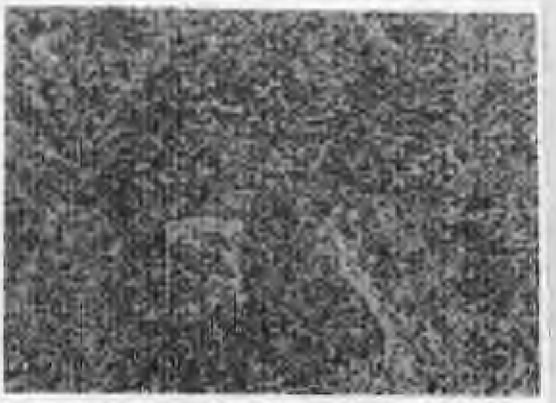

Plate 8 D
Tempered martensite and bainite and a very small amount of ferrite.

Plate 9 E
Tempered martensite and bainite with small amount of ferrite.

Plate 10 F
Tempered martensite and bainite with small amount of ferrite.

WTN.639-7070

All Photomicrographs 1000X - Picral Etch

Plate 11 G
Tempered martensite and bainite with small amount of ferrite.

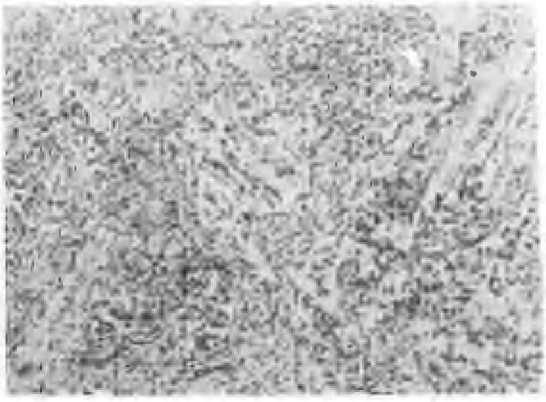

Plate 12 H
Tempered martensite and bainite with a moderate amount of ferrite.

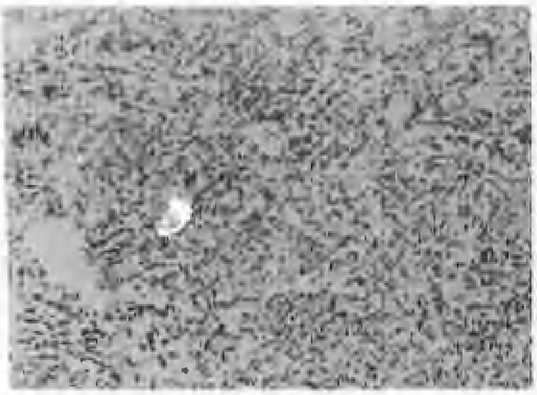

Plate 13 I
Tempered martensite and bainite with moderate amount of ferrite.

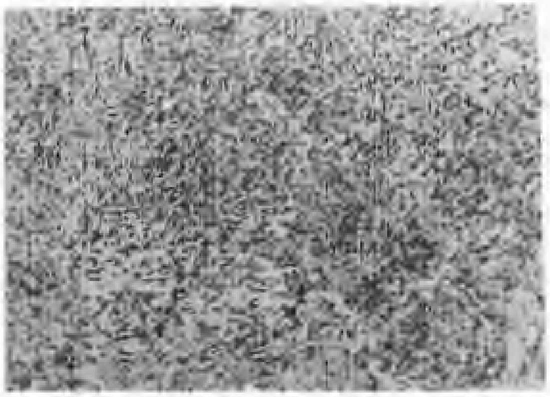

Plate 14 J
Tempered martensite and bainite with small amount of ferrite.

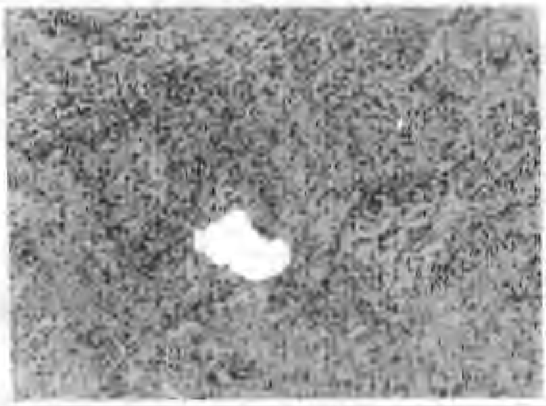

Plate 15 K
Tempered martensite and bainite with very small amount of ferrite.

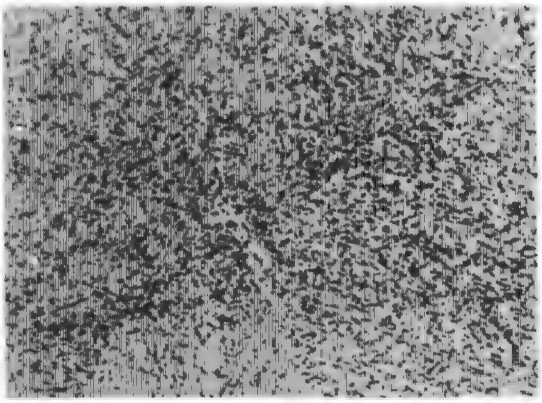

Plate 16 L
Tempered martensite and bainite.

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FIGURE 9.