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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/601

Metallurgical Examination of Sections from

Eighteen Rolled Homogeneous Armor Plates

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BY

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WATERTOWN ARSENAL LABORATORY

Memorandum Report No. WAL 710/601

Final Report on Problem B-4.25

20 March 1944

Metallurgical Examination of Sections from Eighteen Rolled Homogeneous Armor Plates

ABSTRACT

Metallurgical examination including Brinell hardnesses, fracture tests for steel soundness, fracture tests for response to heat treatment, macroetch tests, microscopic examination, V-notch Charpy impact tests on selected plates, chemical analysis and Jominy hardenability was conducted on eighteen plates submitted by Great Lakes Steel Corporation and tested at the Ordnance Research Center as a part of the effect of hardness program. There were six plates each of the three thicknesses 1-1/8, 1-1/4, and 1-1/2 inches. All plates were fairly satisfactorily heat treated. Three plates were of unsatisfactory quality with respect to steel soundness, (Numbers 173, 111, 112).

1. As requested by the Ordnance Research Center, A.P.G. 470.5/3549, Wtn 470.5/7747(r), metallurgical examination has been completed on sections from eighteen (18) plates tested at the Ordnance Research Center as a part of the program on the effect of hardness on ballistic properties. All plates were furnished by Great Lakes Steel Corporation and were rolled from the same heat of steel. Plates were of three thicknesses, six (6) each of 1-1/8, 1-1/4 and 1-1/2 inches. The plates in each series were of different hardnesses.

2. Metallurgical examination consisted of the following tests:

a. Brinell hardnesses on surface and through section.

b. Chemical analysis and Jominy hardenability.

c. Fracture test for steel soundness in both directions of rolling.

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Hardness readings across the section were of sufficient uniformity to indicate complete quench hardening followed by an adequate tempering cycle to produce a uniform hardness through the sections.

b. Chemical Analysis and Jominy Hardenability. A chemical analysis and Jominy hardenability determination were conducted on samples from plate 112. It is understood that all plates were produced from the same heat of steel, and, therefore, the results on this plate are indicative of the results to be expected on the other plates in the series. The chemical analysis follows:

Plate No.	C	Mn	Si	S	P	Ni	Cr	Mo	B	Al
112	.31	1.55	.30	.021	.022	Trace	.55	.20	.0035	.06

The hardenability of the steel is shown as Figure 4. Essentially full hardening is maintained at the slow cooled end of the Jominy bar, which indicates that, with respect to quench hardening or transformation to the high temperature transformation products ferrite and pearlite, the analysis should be satisfactory in thicknesses up to at least 4 inches upon water quenching. The great effect of the boron addition in increasing the hardenability is clearly indicated. The amount of boron reported is excessive for best results from the standpoint of toughness of the steel.

c. Fracture Tests for Steel Soundness and Response to Heat Treatment. Fracture tests for steel soundness in both directions and for response to heat treatment (fibre test) in one direction were made on samples from each plate. The samples for the steel soundness test were tempered prior to fracture to a hardness of 300 Brinell maximum. The results are given below:

		Steel Soundness Tests		Fibre Fracture Test	
Plate No.	Thickness	*Longitudinal	Transverse	Direction	Result
85	1-1/8"	B	B	Longitudinal	Mixed, (High hardness)
87	1-1/8"	B	B	Longitudinal	Mixed (high hardness)
89	1-1/8"	C	C	Longitudinal	Mixed (high hardness)
93	1-1/8"	B	B	Longitudinal	Mixed (high hardness)
95	1-1/8"	B	B	Longitudinal	Fibrous
173	1-1/8"	B	D	Longitudinal	Fibrous
99	1-1/4"	B	B	Longitudinal	Fibrous
105	1-1/4"	B	B	Longitudinal	Fibrous
107	1-1/4"	C	C	Longitudinal	Fibrous

Plate No.	Thickness	Steel Soundness Tests *Longitudinal	Steel Soundness Tests Transverse	Fibre Fracture Test Direction	Fibre Fracture Test Result
109	1-1/4"	B	B	Longitudinal	Fibrous
111	1-1/4"	D	D	Longitudinal	Fibrous
112	1-1/4"	D	D	Longitudinal	Fibrous
114	1-1/2"	B	B	Longitudinal	Fibrous
115	1-1/2"	C	B	Longitudinal	Fibrous
118	1-1/2"	B	B	Longitudinal	Fibrous
122	1-1/2"	B	B	Longitudinal	Fibrous
123	1-1/2"	B	B	Longitudinal	Fibrous
177	1-1/2"	B	B	Longitudinal	Fibrous

*Longitudinal - plane of fracture parallel to major rolling direction.

All plates developed fibrous fractures except four of the 1-1/8" plates at the higher hardnesses. This condition has been previously encountered and is to be expected in many of the type analyses now being employed in these thicknesses of plate and at hardnesses exceeding approximately 320 Brinell. It is not an effect which necessarily is caused by poor heat treatment or lack of hardenability. There has been no conclusive evidence to indicate that it should be considered a rejectable condition. This type of crystallinity occurring at high hardnesses can be distinguished from that caused by incomplete quench hardening. Plate 173 at 343 Brinell would probably also have shown crystallinity if the severe laminations in the center third of the section had not been present.

Plates 173, 111, and 112 were of unsatisfactory quality with respect to steel soundness. The poor fractures developed on these plates are probably influenced by factors other than nonmetallic inclusions since subsequent tests did not indicate a wide difference in nonmetallic content in these plates as compared to others which developed fractures devoid of serious laminations.

d. Macroetch Tests. Macroetch tests in the transverse direction were made on a sample from each plate. The results appear as Figures 1-3. It will be observed that plates 173, 111, and 112 which developed unsoundness in the fracture test show an ingot pattern effect to a greater degree than the balance of the plates.

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e. Microscopic Examination. Specimens for microscopic examination covering the cross section were prepared from each plate. Examination covered extent of decarburization, grain size, type and distribution of nonmetallic inclusions and microstructure. Decarburization was insignificant, amounting to less than .01 inch. Grain size was a uniform A.S.T.M. 6-7 in all plates. The results of the microscopic examination on each plate were as follows:

(1). Plate 85, 385 BHN. Steel adequately clean. Nonmetallic inclusions consist of small sulphides and silicates well distributed. (See Figure 5.) Microstructure consists of tempered martensite, tempered upper bainite, and possibly traces of ferrite and pearlite. (See Figure 6.)

(2). Plate 87, BHN 326. Nonmetallic distribution similar to plate 85 except for alumina type inclusion clusters near one face which caused short laminations on the fracture specimens. (See Figure 5.) Microstructure similar to that of plate 85 consisting of tempered martensite, tempered upper bainites and possibly traces of ferrite and pearlite. (See Figure 6.)

(3). Plate 89, 356 BHN. Transverse micro specimen shows well distributed nonmetallic inclusions. (See Figure 5.) Microstructure consists of tempered martensite, tempered upper bainite, with traces of ferrite and pearlite.

(4). Plate 93, 375 BHN. Clean steel except for alumina type inclusion clusters near plate surfaces promoting short, insignificant laminations. (See Figure 5.) Microstructure similar to that of plate 85, see Figure 6.

(5). Plate 95, 302 BHN. Nonmetallic inclusion distribution similar to that of plate 85, (See Figure 5.) Microstructure essentially tempered martensite and bainite with traces of ferrite and pearlite apparent. (See Figure 6.)

(6). Plate 173, 343 BHN. Considerable segregations of alumina inclusions near center of section. (See Figure 5.) Microstructure similar to that of plate 85, (See Figure 6), consisting of tempered bainite and martensite possibly with traces of ferrite and pearlite visible.

(7). Plate 99, 308 BHN. Fairly clean steel, containing small silicate inclusions somewhat more concentrated at center of section. Microstructure shows tempered martensite and upper bainite with apparent traces of ferrite and pearlite.

(8). Plate 105, 290 BHN. Fairly clean steel, similar to plate 89. (See Figure 5.) Microstructure essentially tempered with traces of pearlite apparent.

(9). Plate 107, 277 BHN. Steel contains fairly high concentrations of silicate and alumina inclusions along centerline. (See Figure 5.) Microstructure consists of essentially tempered martensite and tempered bainites. (See Figure 7.)

(10). Plate 109, 272 BHN. Fairly high concentration of small silicate inclusions, similar to plate 114. (See Figure 6.) Microstructure shows a uniform sorbitic structure.

(11). Plate 111, 308 BHN. Centerline segregations of alumina and silicate inclusions similar to plate 107. (See Figure 5.) Microstructure consists of tempered martensite and bainite with traces of pearlite visible.

(12). Plate 112, 291 BHN. Severe concentrations of silicate inclusions at center of section. (See Figure 6.) Microstructure essentially tempered martensite and bainites. (See Figure 7.)

(13). Plate 114, 283 BHN. Numerous small silicate inclusions well distributed. (See Figure 6.) Microstructure consists of desirable uniform distribution of spheroidal carbides, similar to plate 177. (See Figure 7.)

(14). Plate 115, 282 BHN. Nonmetallic inclusions and microstructure similar to plate 114.

(15). Plate 118, 271 BHN. Nonmetallic inclusions and microstructure similar to plate 114.

(16). Plate 122, 263 BHN. Nonmetallic inclusions consist of small silicate inclusions well distributed. Microstructure similar to that of plate 123. (See Figure 7.)

(17). Plate 123, 247 BHN. Scattered silicate and alumina inclusions. (See Figure 6.) Microstructure consists of a spheroidal carbide in ferrite with some evidence of banding of carbides. (See Figure 7.)

(18). Plate 177, 274 BHN. Nonmetallic condition similar to plate 114. Microstructure consists of desirable spheroidal carbide fairly well distributed. (See Figure 7.)

NOTE: Photomicrographic work conducted by M. Yoffa.

The steel in general, was fairly satisfactory with respect to nonmetallic inclusion content. In general, it appears that concentrations of the refractory alumina nonmetallic inclusions are responsible for the development of laminations in the fracture test. Silicate inclusions, unless extremely concentrated, apparently do not produce poor fractures. This observation confirms other evidence recently obtained. The microstructure in some cases reflect poor heat treating practice. The formation of bainites upon quenching is to be expected, but evidences of ferrite and pearlite indicate poor heat treatment practice in view of the high hardenability of the steel. The absence of any apparent ferrite and pearlite in the case of several plates indicates considerable variation in heat treatment practice.

f. V-Notch Charpy Impact Tests. Impact tests were taken from six (6) plates at equally spaced hardness levels covering the range 247 to 385 Brinell. Duplicate specimens were broken at room temperature (20°C) and -40°F (-40°C). The specimens were transverse bars the axes of which corresponded to a distance midway between surface and center of the plates. Bars were machined from plates of satisfactory soundness as indicated by fracture tests. Notches were cut perpendicular to plate surfaces to minimize the effect of nonmetallic inclusions. The results obtained were as follows:

		V-Notch Charpy Impact Values			
		20°C Tests		-40°C Tests	
Plate No.	BHN	Ft. Lbs.	Fracture	Ft. Lbs.	Fracture
85	385	19.7	Cbf	17.5	Cbf
		18.3	Cbf	14.2	Cbf
87	326	26.8	Fc	16.4	Cbf
		27.7	F	16.8	Cbf
89	356	23.3	Fc	13.2	Cbf
		21.6	Fc	12.7	Cbf
95	302	35.3	F	27.3	Fc
		35.3	F	24.2	Fc
118	271	56.4	F	52.8	F
		56.0	F	42.9	Fc
123	247	55.8	F	51.0	F
		55.5	F	45.3	Fc

Impact bar fractures were rated in accordance with a standard procedure, (See Figure 8.) which will henceforth be used in all cases wherein impact bar fracture ratings are reported.

The impact values as a function of hardness and temperature have been plotted as Figure 9. Also superimposed upon the curve are the zones of hardness within which fibrous and crystalline fractures were obtained on the standard fibre test specimens. It will be noted that the sharp decrease in impact value with increasing hardness occurs somewhere between 270 and 300 Brinell whereas the transition from fibrous to crystalline fractures occurs at some hardness between 300 and 326 Brinell. It will be noted that in the case of the steels which developed crystalline fractures in the fibre test, the percentage change in impact properties as a function of the lower testing temperature is considerably higher. Furthermore, as compared to impact values previously obtained and reported[1] on rolled armor, the values obtained on the plates at 300 Brinell and higher hardnesses are somewhat below the expected values.

Crystallinity occurring in the subject steel at hardnesses above 320 Brinell is, of course, a function of both chemistry and heat treatment. It has been indicated that in certain type chemistries utilized for a given plate thickness, this tendency cannot be eliminated by normal adjustments in heat treatment. Other chemistries of lesser hardenability than the subject steel will produce fibrous fractures in 1 inch plate thickness at hardnesses of 375 and 388 Brinell. In the case of these plates, a peculiarity of the steel coupled with evidence of inferior heat treatment is undoubtedly responsible. Factors which may be involved are (1) the temperature at which bainite forms on continuous cooling, (2) the effect of boron, and (3) the possibility of the retention of austenite upon quenching which may subsequently transform upon tempering to yield poor properties.

4. In general, the soundness of the plates was satisfactory. In addition to poor steel soundness characteristics noted in the fracture test of three plates, the ingot pattern effect noted on the macroetch tests of sections from additional plates may contribute to inferior ballistic performance under obliquity attack. The crystallinity observed at high hardnesses is believed to be a function both of type analysis and heat treatment practice. Fibrous fractures can be obtained in these thicknesses at hardnesses up to 388 Brinell using other type analyses with normal heat treatments. It is assured that the material which produces the fibrous fracture will exhibit superior ballistic performance provided other factors such as hardness and steel quality are equal.

N. A. Matthews

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Major, Ordnance Dept.

1. Memorandum Report No. WAL 710/567, 10 December 1943.

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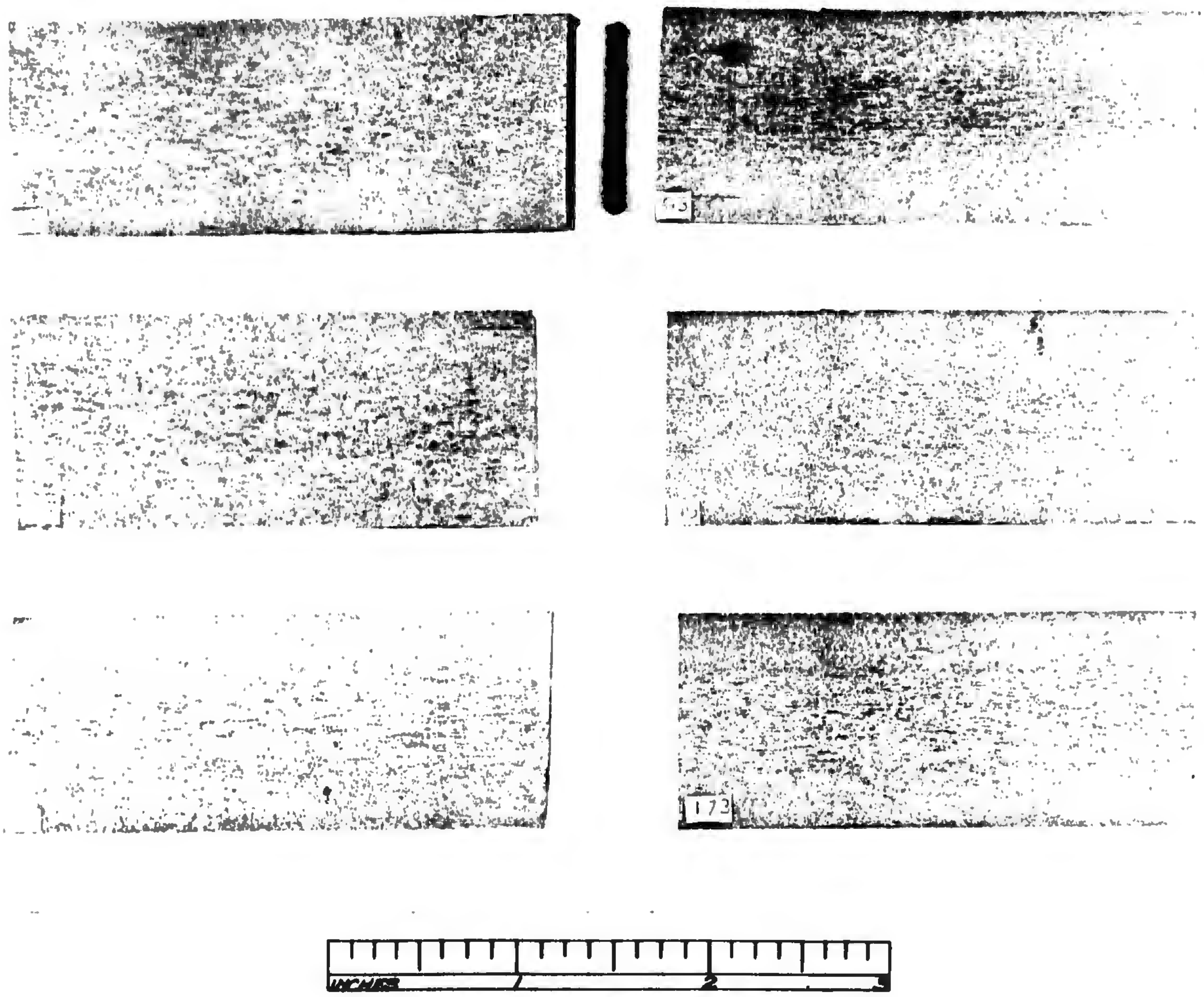
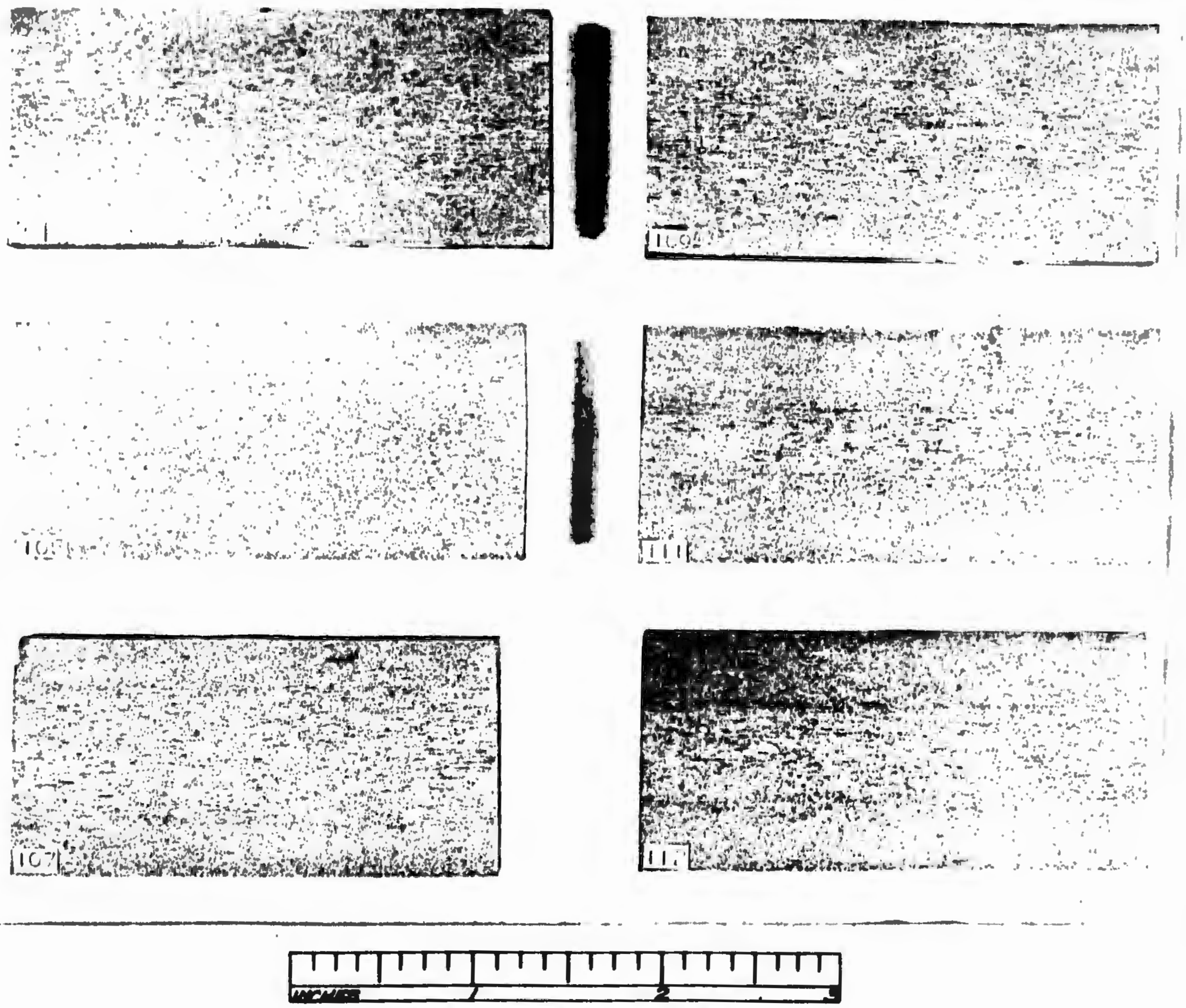


GREAT LAKES STEEL CORPORATION 1 1/8" PLATES
10 FEB 1944 WTN.710-2274

FIGURE 1

REPRODUCED AT GOVERNMENT EXPENSE

MACROETCH TESTS



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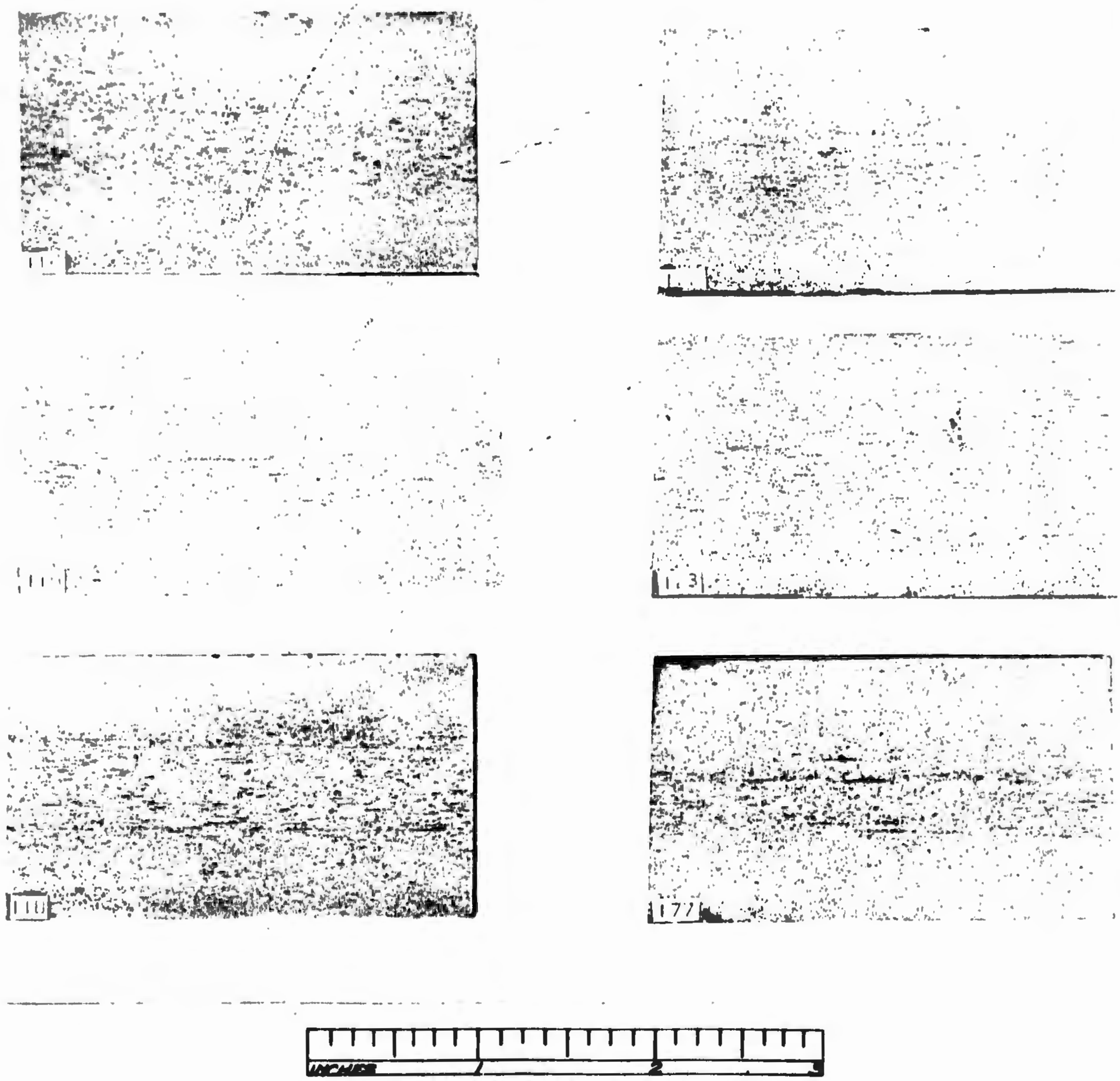
GREAT LAKES STEEL CORPORATION 1 1/4" PLATES
10 FEB 1944 WTN.710-2276

FIGURE 2

REPRODUCED AT GOVERNMENT EXPENSE

MACROETCH TESTS



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GREAT LAKES STEEL CORPORATION 1 1/2" PLATES
10 FEB 1944 WTN.710-2275

FIGURE 3

REPRODUCED AT GOVERNMENT EXPENSE

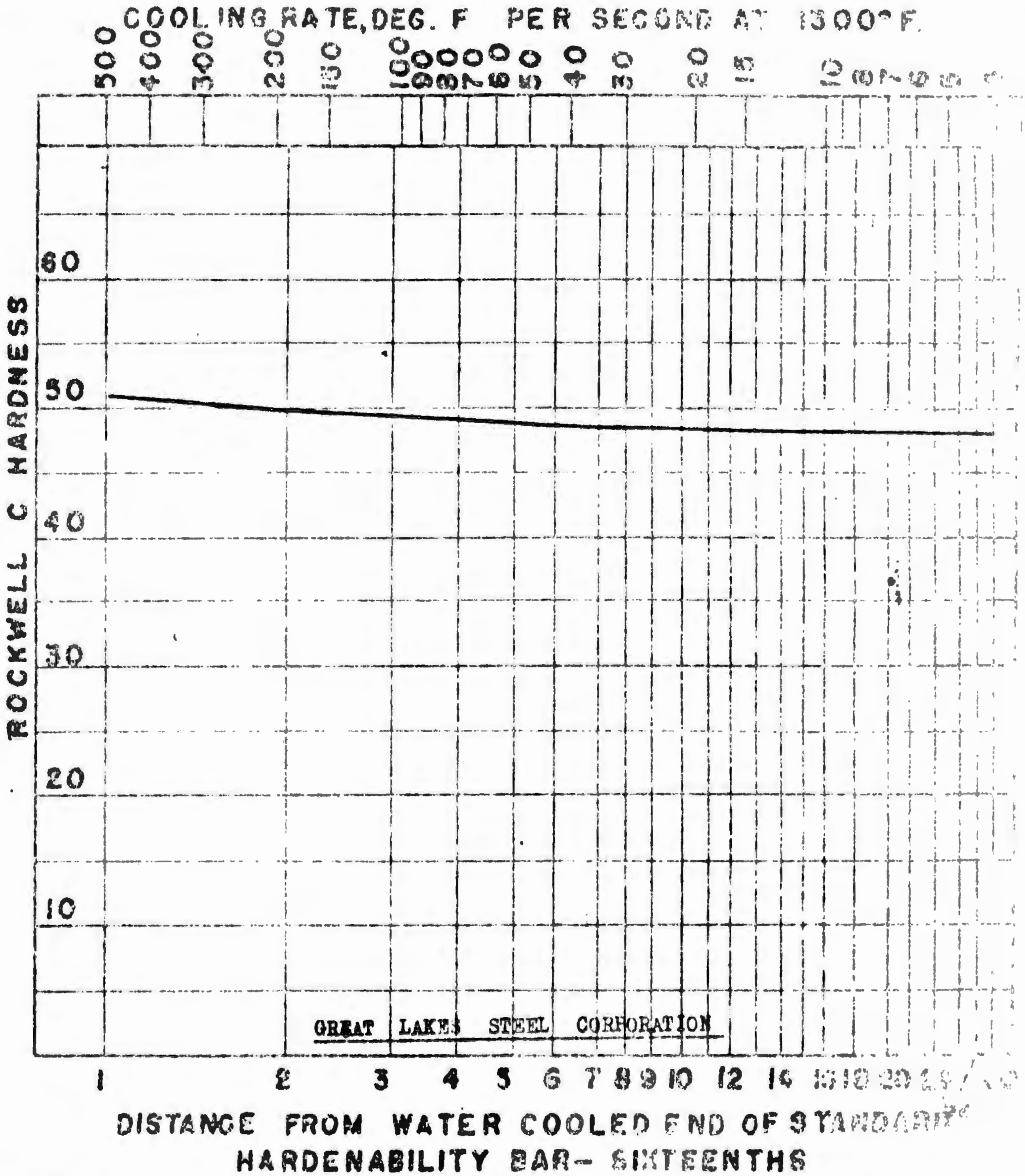

PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	B	QUENCH TEMP	TIME	[illegible]
112		.31	1.55	.30	.021	.022	Tr.	.55	.20	.13	.06	.0035	1600	2 h.	

Figure 4.

REPRODUCED AT GOVERNMENT EXPENSE

Great Lakes Steel Corporation Armor
Typical Nonmetallic Inclusion Types and Distribution
Unetched - X100.

Plate 85. Well distributed small sulphide and silicate inclusions.

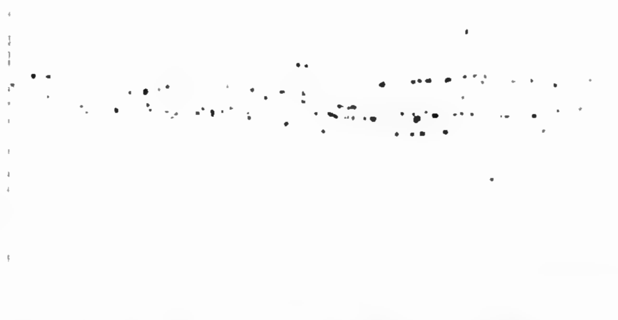

Plate 87. Clusters of alumina inclusions occurring near face of plate.

Plate 89. Transverse specimen. Well distributed nonmetallic inclusions.

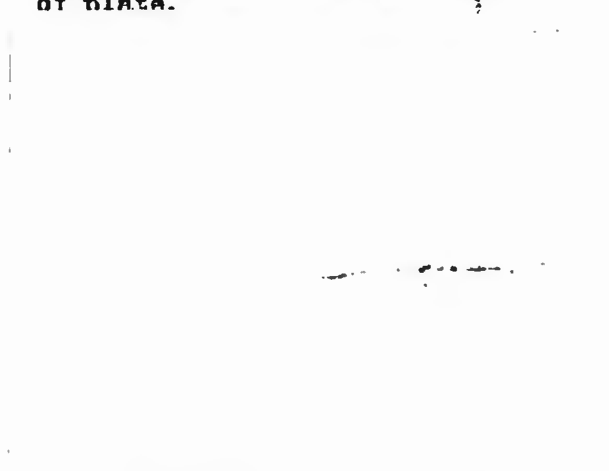

Plate 93. Alumina type inclusion clusters occurring near face of plate.

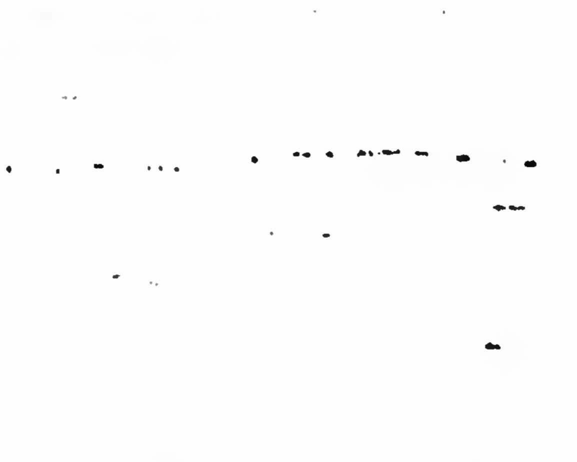

Plate 173. Alumina inclusion streaks near center [illegible]

Plate 107. High concentrations of silicate and alumina inclusions.

REPRODUCED AT GOVERNMENT EXPENSE

FIGURE 5

Great Lakes Steel Corporation Armor
Typical Nonmetallic Inclusions and Microstructures

Unetched - X100. | Picral Etch - X1000.

Plate 112. High concentration of silicate inclusions at center of section.

Plate 85. Tempered martensite, temper[illegible] upper bainite, and possible traces of ferrite and pearlite.

Plate 114. Small silicate inclusions well distributed.

Plate 87. Tempered martensite and upper bainite, traces of ferrite and pearlite.

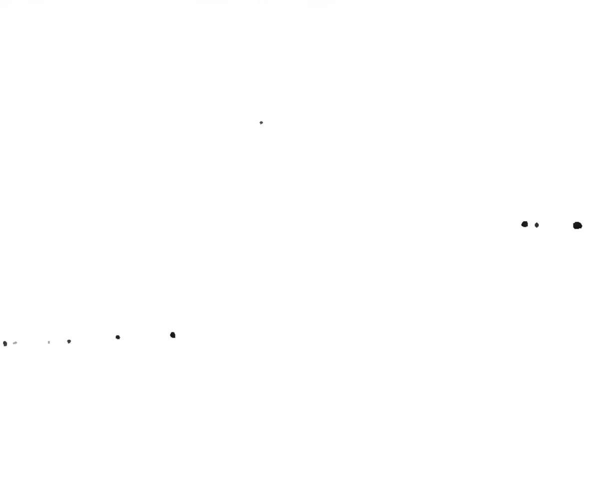

Plate 123. Scattered silicate and alumina inclusions.

Plate 95. Tempered martensite and [illegible]bainite, traces of ferrite [illegible]lite.

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FIGURE 6

Great Lakes Steel Corporation Armor
Typical Microstructures
Picral Etch - X1000.

Plate 173. Tempered martensite and bainite, possible traces of ferrite and pearlite.

Plate 112. Tempered martensite and tempered bainite.

Plate 99. Tempered martensite and bainite with possible traces of ferrite and pearlite.

Plate 123. Tempered martensite and upper bainite.

Plate 107. Tempered martensite and tempered upper bainites.

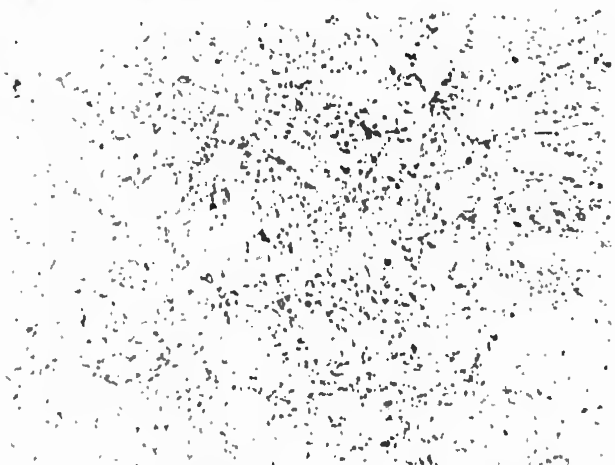

Plate 177. Tempered martensite and [illegible] bainite.

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FIGURE 7.

STANDARD TYPES OF NOTCHED BAR IMPACT FRACTURES.

SYMBOL	DESCRIPTION
F	Fibrous
S	Silky (generally encountered with steels of high hardness)
Fc	Fibrous matrix with spots of crystallinity
Cdf	Dull crystalline patch surrounded by fibrous border
Cbf	Bright crystalline patch surrounded by fibrous border
Cd	Dull crystalline (complete)
Cb	Bright crystalline (complete)

Note 1: Additional terms such as: dendritic, conchoidal, etc., used to describe the fractures, should be written out in full following the fracture type symbol.

Note 2: If it is desired to estimate the relative amounts of fibrous and crystalline surface areas, a fraction will be placed following the fracture symbol. This fracture will refer to the estimated surface area which is crystalline.

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GREAT LAKES STEEL CORPORATION HOMOGENEOUS ARMOR

V-NOTCH CHARPY AS FUNCTION OF HARDNESS

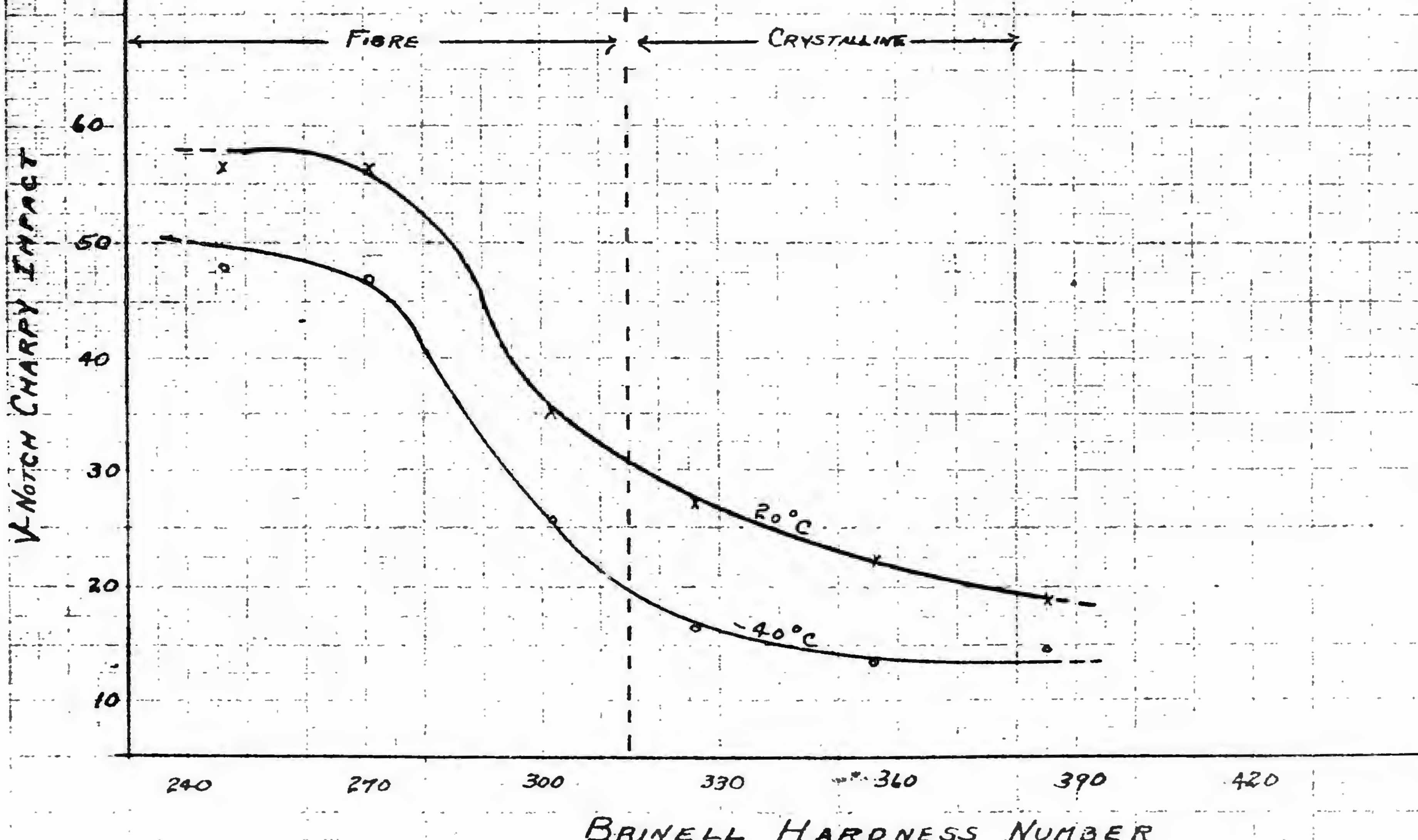

FIGURE 9