WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/574

Metallurgical Examination of Ten 1 Inch Face Hardened Armor Plates Manufactured by American Car and Foundry Company

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Watertown Arsenal Laboratory

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Final Report on Problem B-4.13

31 December 1943

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ABSTRACT

A metallurgical examination was conducted on ten plates having a face hardness of 444 and a core hardness of 330 to 350 Brinell which had been subjected to ballistic tests at The Proving Center, Aberdeen (AD-563).

The metallurgical tests included chemical analyses, hardness surveys, fracture tests, hardenability, macro and microscopic examinations of plates from three heats. One heat was a 1% Ni-Cr-Mo type; the other two were a 3% Ni-Cr-Mo type.

1. Introduction

As requested by the Proving Center, Aberdeen (APG 470.5/1164, Wtn. 470.5/6883(r)), a metallurgical examination has been completed on ten (10) samples of 1" face hardened armor submitted by the American Car and Foundry. The plates under consideration were subjected to ballistic tests at The Proving Center and the results were reported in APG Armor Report AD-563.

2. Summary of Results

The results of the metallurgical examination show that all the face hardened armor plates possessed approximately the same face hardness of 444 Brinell and core hardness of 330 to 350 Brinell. The ballistic performance recorded in the ballistic report is believed to be representative of good quality armor having a hardness gradient of the subject plates. The sections examined were relatively sound and properly heat treated except for plates 1815-2 and 1815-3 which possessed a rejectable quality of nonmetallic laminations.

3. Procedure

The metallurgical examination consisted of the following tests:

a. Chemical Analysis including a carbon layer analysis of one plate from each heat.

b. Hardness Tests

c. Fracture Tests

d. Hardenability Tests

e. Macroexamination

f. Microscopic Examination including microstructure, grain size, depth of carburization on face and depth of decarburization on the back.

4. Results and Discussion

Results of the metallurgical examination are as follows:

a. Chemical Analyses

The analyses reported by the manufacturer were in fair agreement with the results obtained at this arsenal.

The results obtained on one plate from each heat are shown below:

Chemical Composition

Analyzed by	Plate No.	C	Mn	Si	S	P	Ni	Cr	Mo
WA	1815-1	.24	.90	.21	.025	.016	.83	.75	.34
Mfg.	1815	.265	.89	.21	.020	.018	.89	.71	.36
WA	1848-1	.25	.55	.20	.025	.012	3.15	.42	.35
Mfg.	1848	.245	.51	.18	.020	.018	3.40	.37	.37
WA	1849-1	.25	.62	.22	.023	.011	3.50	.37	.33
Mfg.	1849	.24	.56	.17	.020	.017	3.41	.33	.36

A layer carbon analysis taken every .020" across the carburized case of one plate from each heat is shown in Figure 1. The results may be compared with the results of the hardness surveys across the carburized cases shown in Figures 2 and 3 and the case depth evaluation from the microstructure as shown in Table II.

The high concentration of carbon present near the face of the plates is believed to impair the shock properties because of the concentration of undissolved carbides associated with it.

b. Hardness Tests

Brinell hardness tests were obtained on the face and back of each plate, core hardness readings were taken on the cross section. The

results may be compared with those reported by the manufacturer in Table I.

Table I

Brinell Hardness Tests

Plate No.	Reported Face	Reported Back	Determined at W.A. Face	Determined at W.A. Back	Determined at W.A. Core
1815-1	477	301	444	341	341/352
1815-2	474	302	444	341	341/341
1815-3	474	359	444	331	341/341
1848-1	403	351	444	331	341/352
1848-2	404	345	444	341	352/363
1848-3	403	344	444	341	341/341
1848-4	407	343	444	321	331/341
1849-1	473	353	444	341	341/341
1849-2	407	350	444	341	341/352
1849-3	408	354	444	341	341/352

The face hardnesses reported by the manufacturer were somewhat higher than those observed at this arsenal because the surfaces were probably ground somewhat deeper at this arsenal.

The hardness penetration was investigated by making a Vickers survey every .020" across the carburized zone, see Figures 2 and 3. In general, the hardened zone over 450 Vickers (425 Brinell) extended .1" in from the face of the plate, although, in a few of the plates the hardness dropped off at a slightly lower depth. This relatively thin hard zone is less efficient in breaking up projectiles than a thicker case having a higher maximum hardness. On the other hand, the subject plates exhibited good resistance to the shock type ballistic test probably as a result of the gradual hardness gradient between the case and the core.

c. Fracture Tests

Specimens were notched and broken under the forge hammer for both the fracture test for steel quality and heat treatment.

The fractures were fibrous although a relatively flat, brittle zone extended to a depth of about .2" from the face of the plates.

Except for plates 1815-2 and 1815-3 the plates contained very few laminations and were rated as B fractures. Plates 1815-2 and 1815-3 contained numerous short laminations and would be rejected with a rating of E and D respectively.

d. Hardenability Tests

An end quench hardenability test was conducted on one plate from each heat using the heating cycle employed by the manufacturer in heat treating the plates. The results are shown in Figure 4. The hardenability in all three heats was sufficient so that sections well over one inch thick could be quenched out using a water quench. Using the criterion of hardness penetration to the center of the plate of 400 Brinell, the hardenability of the three heats is sufficient for a 2½" section according to conversion data developed by the Great Lakes Steel Corp.*

e. Macroexamination

Macroetched sections of the plates were photographed and the results are shown in Figures 5 and 6. Plates 1815-2 and 1815-3 contained a large amount of nonmetallic segregations as observed in both the longitudinal and transverse sections. The remaining plates were relatively free from nonmetallic segregations.

The similarity of the etched structure in the longitudinal and transverse directions indicates that the steel was reduced approximately the same amount in both directions.

f. Microscopic Examination

The two plates exhibiting poor steel quality (Plates 1815-2, 1815-3) contained numerous friable oxide stringers of the type shown in Figure 7A. Typical nonmetallic stringers observed in the plates from heats 1848 and 1849 are shown in Figure 7B.

The microstructure of the core of all the plates was a tempered martensite in which no high temperature transformation products were observed, see Figures 7C and D.

The case of the 3% Ni-Cr-Mo plates (Heat 1848 and 1849) possessed undissolved carbides in a tempered martensitic structure, see Figure 7F and H for the typical structure. The case of the low Ni-Cr-Mo plates from heat 1815 contained fewer undissolved carbides and the martensitic structure was more acicular than in the remaining plates. The structure is shown in Figure 7E and G.

The depth of carburization on the face, the depth of decarburization on the back, and the grain size of the plates were measured on the microspecimens at 100X, and the results are listed in Table II.

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*"Hardenability Comparisons" by the Great Lakes Steel Corporation, 1942,

TABLE II

Depth of Case, Decarburization, and Grain Size.

Plate No.	Depth of case inches	Decarburization inches	ASTM G.S.
1815 1	.205	.015	6-7
1815-2	.195	.015	7
1815-3	.195	.015	6 7
1848-1	.210	.010	7
1848-2	.210	.015	6-7
1848-3	.190	.015	7
1848-4	.210	.020	7
1849-1	.200	.015	7
1849-2	.210	.015	7
1849-3	.210	.015	7

The total depth of case was measured. Naturally in a carburized zone which has been tempered, the change of structure is difficult to evaluate, and so the value obtained from the microscopic examination is only approximate. The depth of the case from a ballistic standpoint may be taken as the depth to which a certain hardness level is maintained. The zone hardened over 450 Vickers (445 Brinell) is approximately 0.1 inches or 10% of the thickness of the plates under consideration. The plates from the low nickel heat 1815 possessed the same depth of case as the plates from the higher nickel heats 1848 and 1849 although there was some variation in depth within the individual heats. These data are shown in Figures 2 and 3.

The decarburization values listed are the extent of the partial decarburization. There was about .001 inch decarburization to ferrite on the back surfaces of all the plates.

The hard face of the subject plates is not believed to be very effective in breaking up projectiles, its primary function, for the maximum hardness is low and its effective hard zone is relatively thin, being only 10% of the thickness. Of course, in order to insure a quenched-out core structure of 340 to 390 Brinell it is necessary to temper at a high temperature which lowers the hardness of the case.

A 1¾" carburized armor section of German manufacture having approximately the same chemistry was examined at this arsenal*. It possessed a face hardness of 627 Brinell and a core hardness of 331 Brinell. To achieve the high face hardness and low core hardness, the steel was probably intercritically quenched, for it possesses a heterogeneous structure of tempered martensite and ferrite in the core. The formation of the heterogeneous structure lowers the impact strength of the steel, but it permits the heat treating of carburized steel to give the desired hardness gradient.

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*WAL 710/539 "Metallurgical Examination of Eleven Sections of Enemy Armor, Including Homogeneous Flame Hardened, Carburized and Welded Components", A. Hurlich, 25 October 1943.

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1" Face Hardened Armor

Made by American Car and Foundry Company

Carbon Content in the Carburized Cases of

Plates 1615-1, 1548-1, and 1549-1

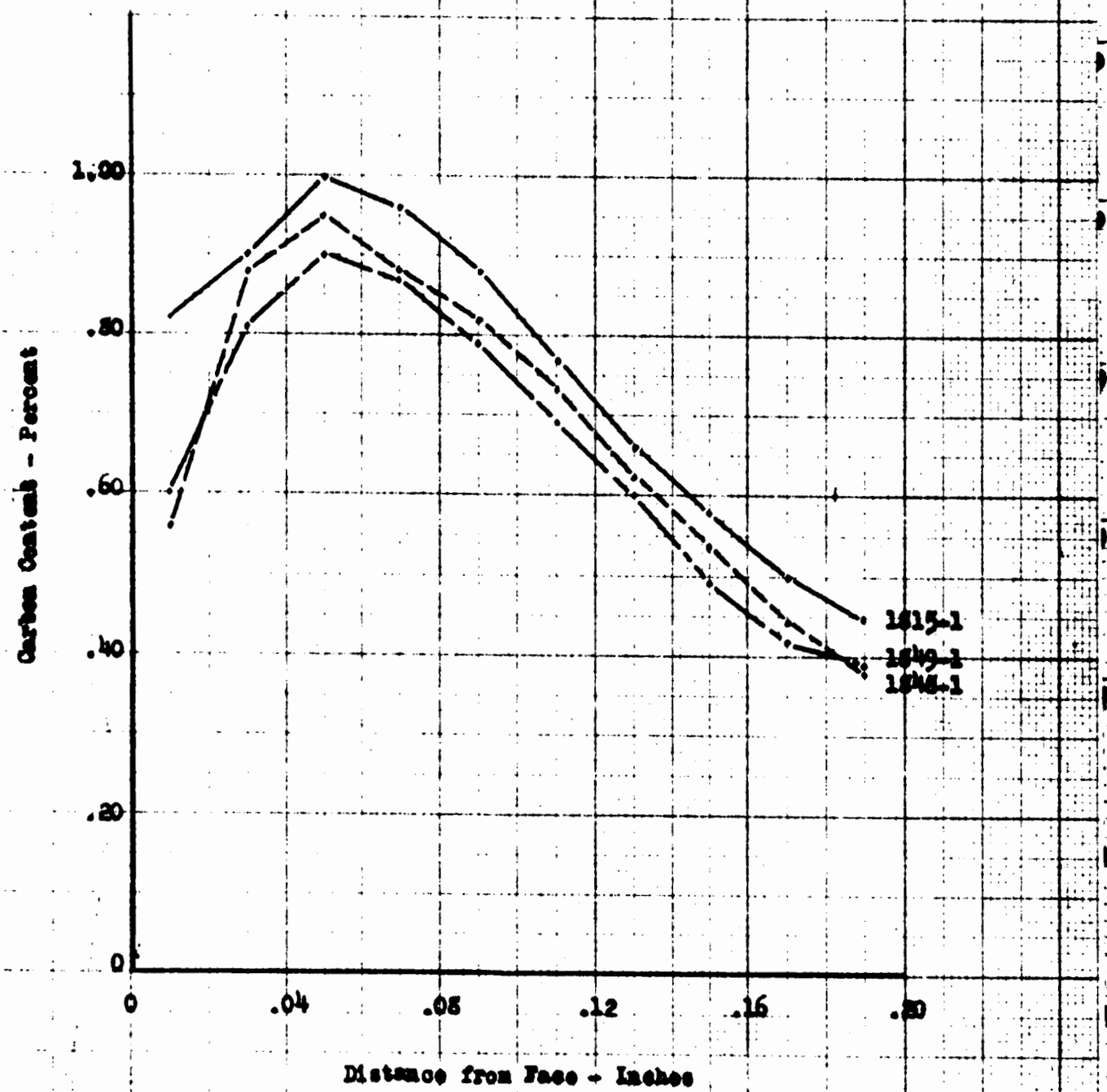


FIGURE 1

1" Face Hardened Armor
Made by American Car and Foundry Co.

Vickers Hardness Surveys across the
Carburized Cases

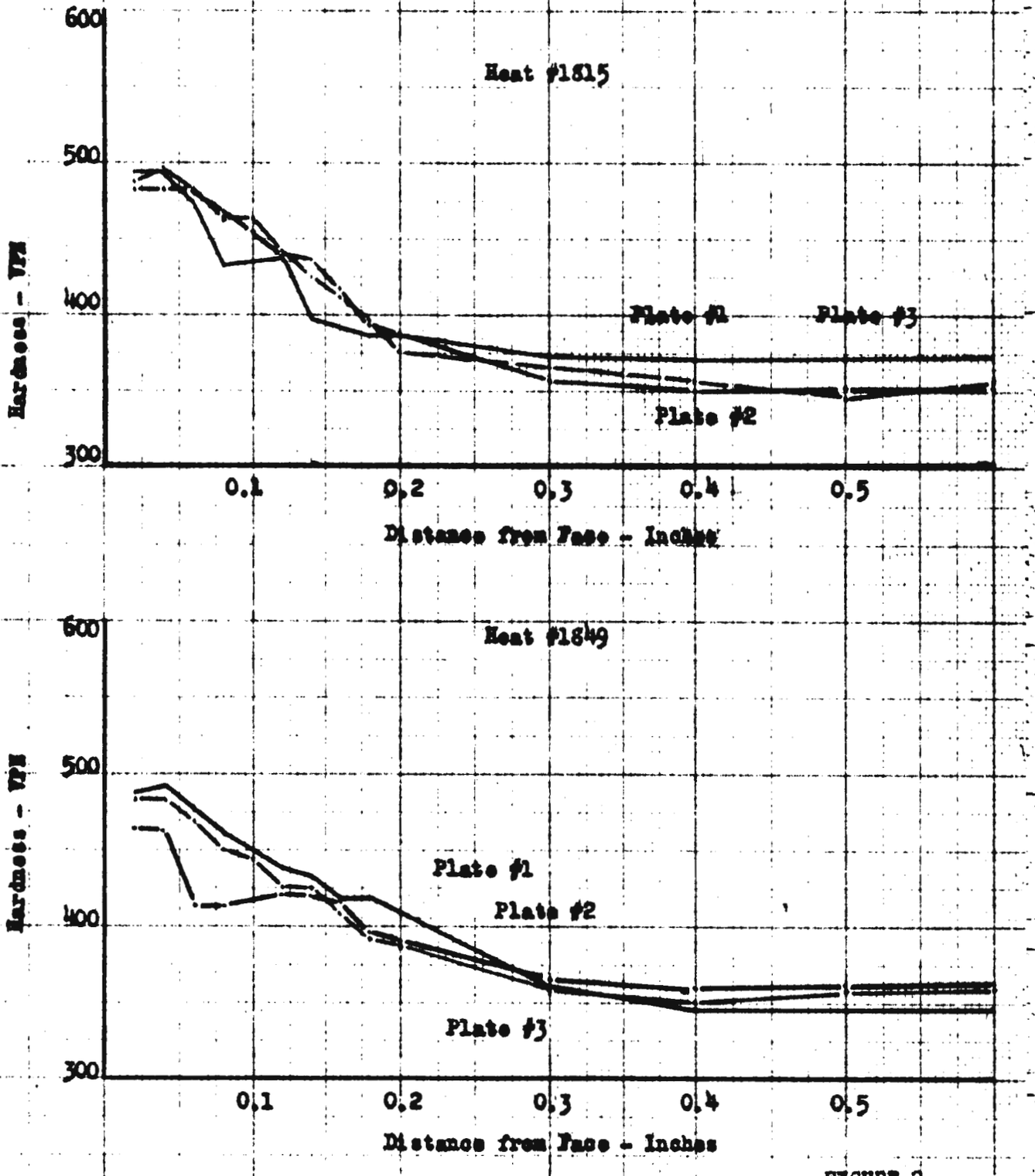
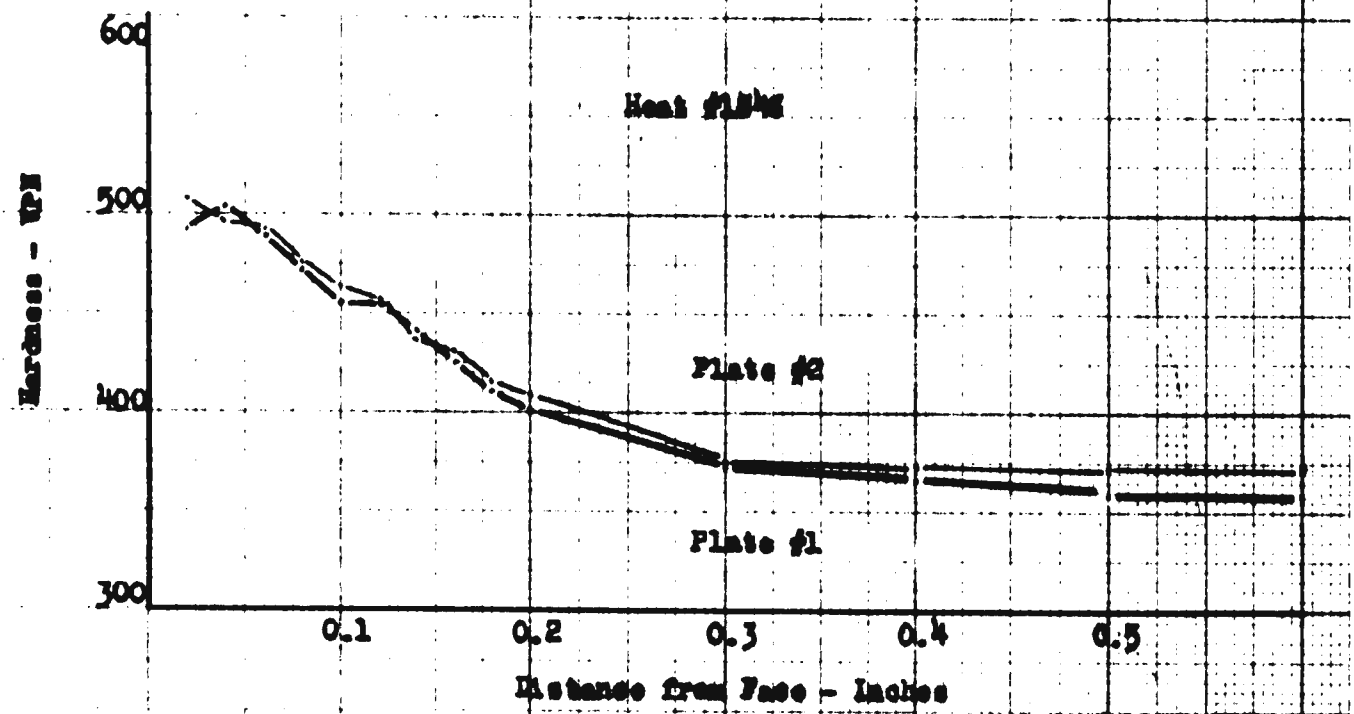


FIGURE 2

1" Face Hardened Armor
Made by American Car and Foundry Co.

Vickers Hardness Surveys across the
Carburized Cases



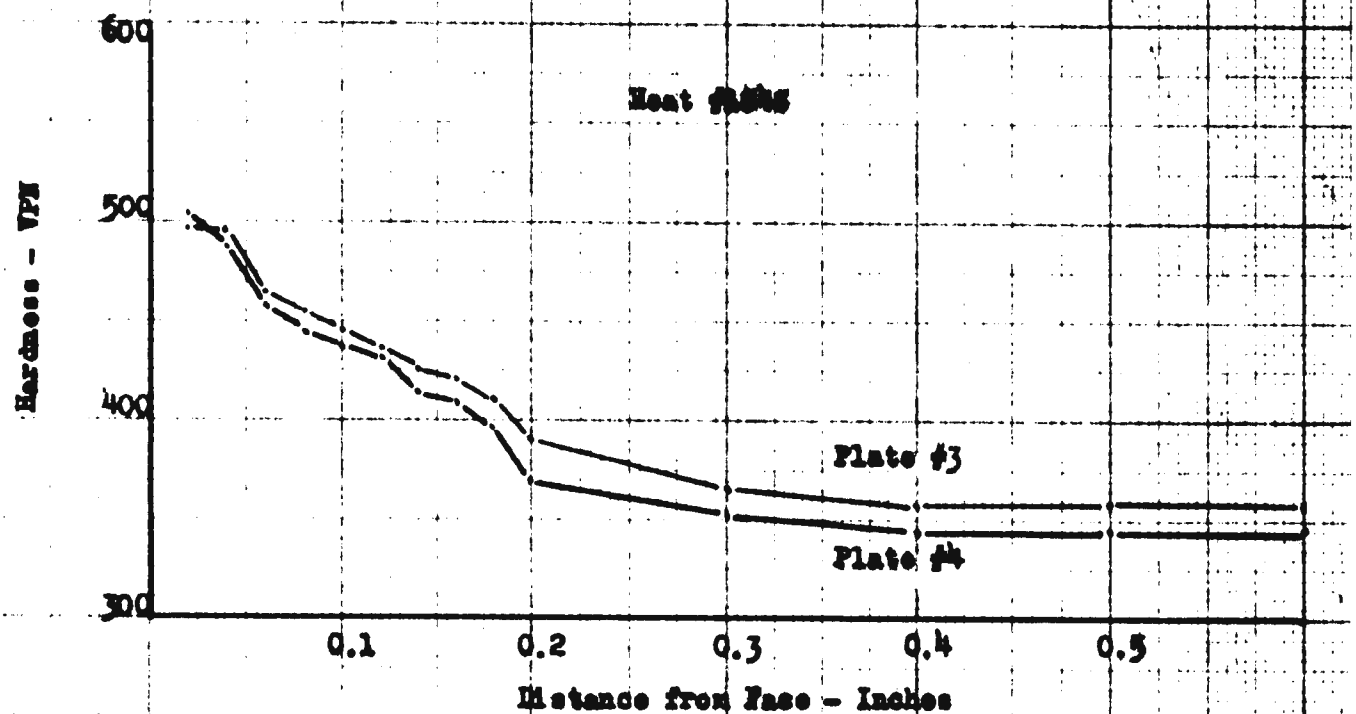


FIGURE 3

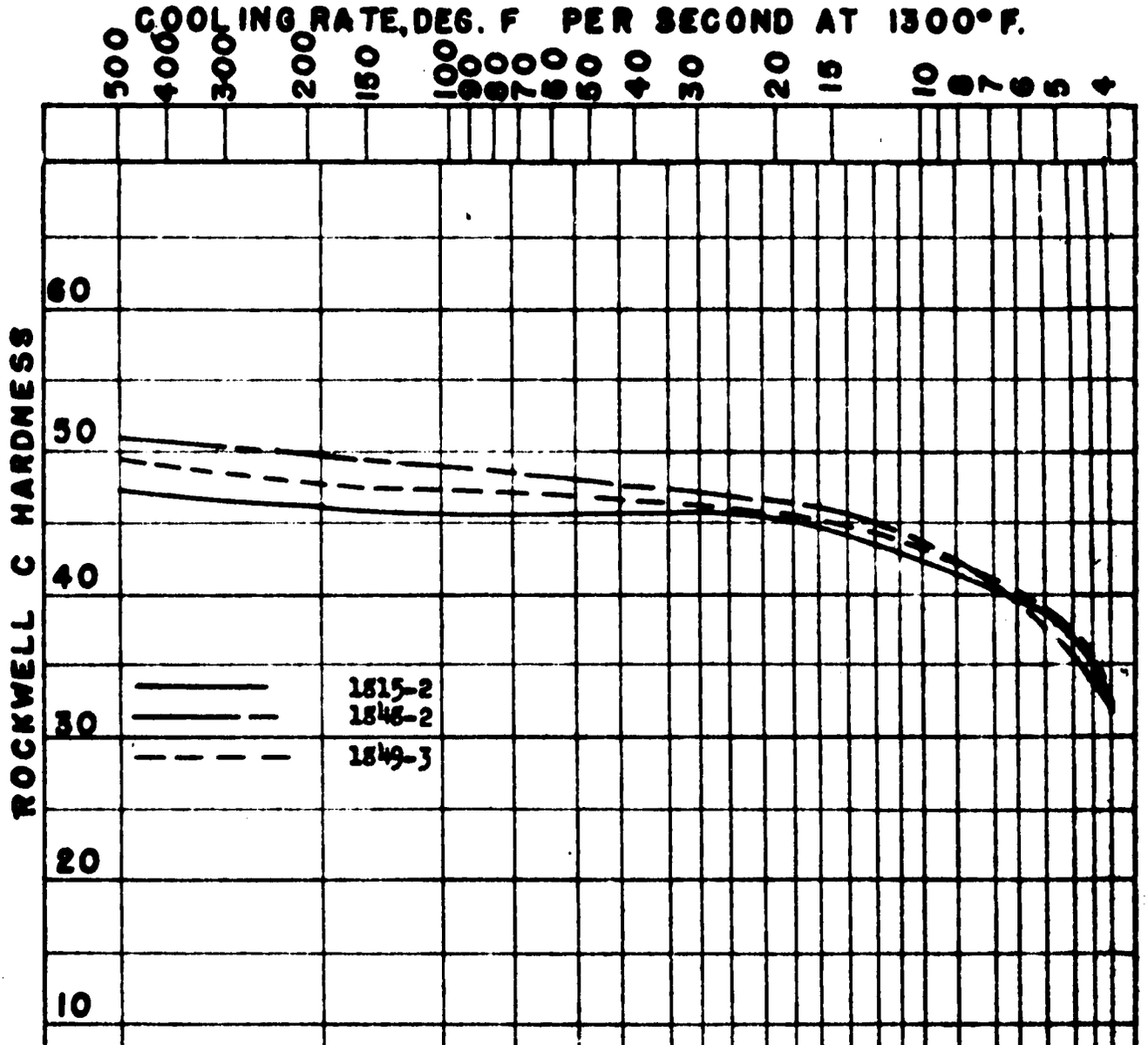
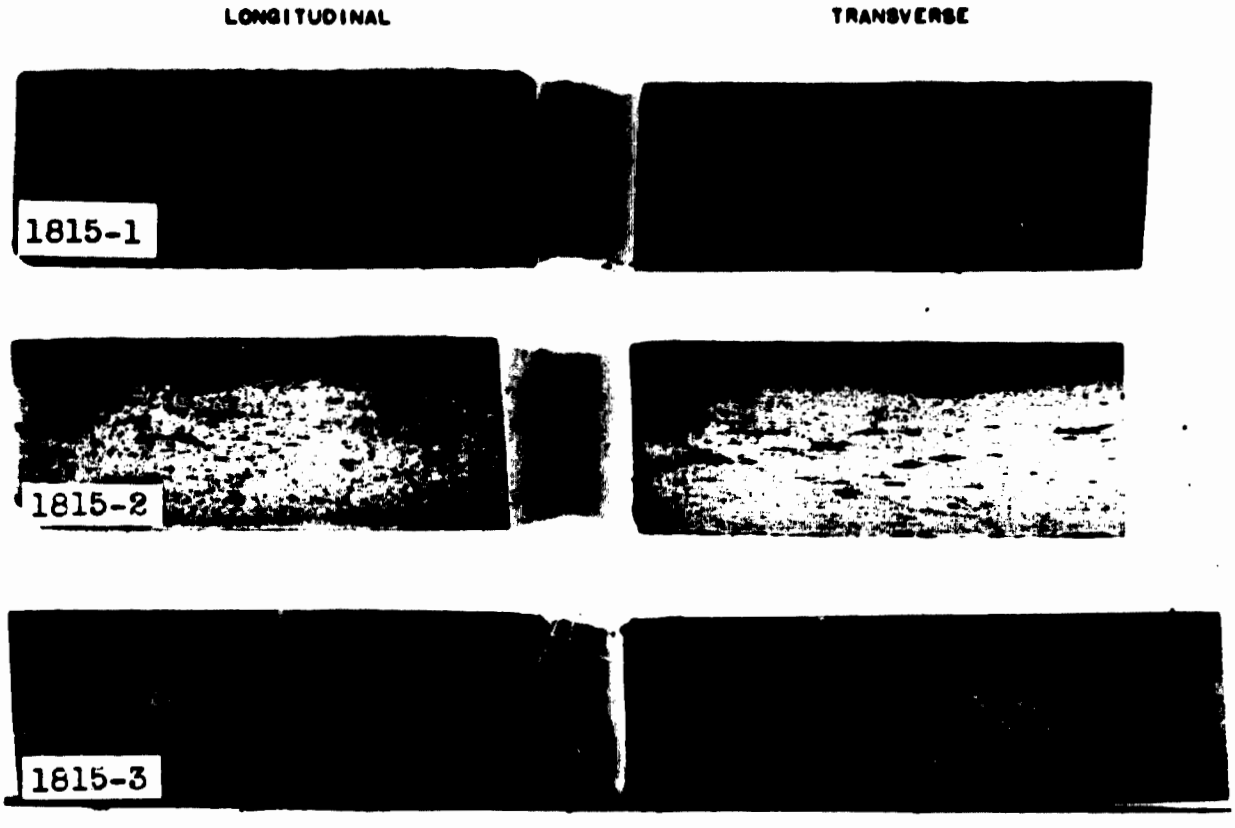


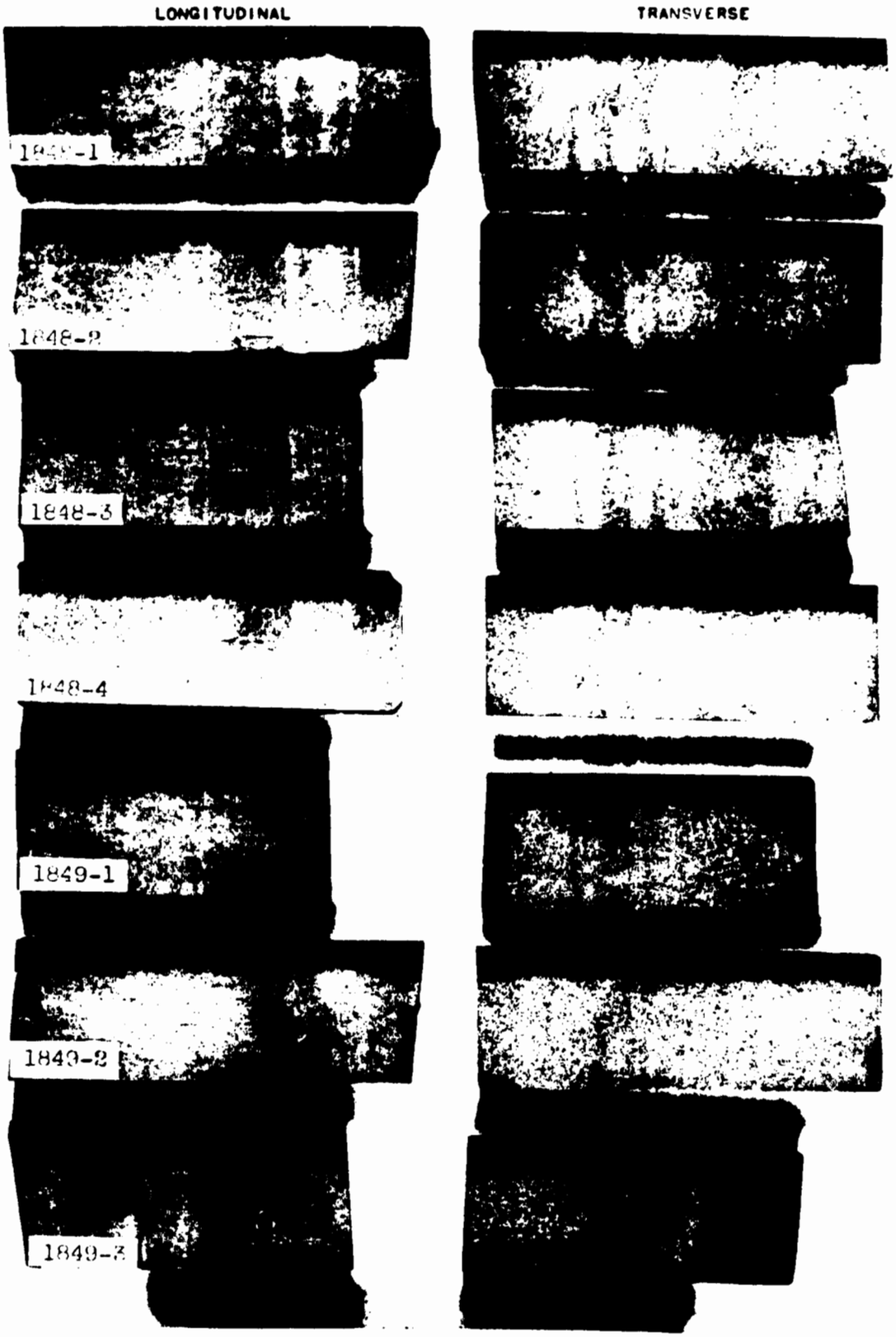
PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	B	AL	V	QUENCH TEMP	QUENCH TIME	G.S.
2	1515	.31	.90	.21	.025	.016	.83	.75	.34	Nil	.02	Nil	1625°	2 Hrs.	
2	1548	.25	.55	.20	.025	.012	3.15	.42	.35	Nil	.015	Nil	1650°	2 Hrs.	
3	1549	.25	.62	.22	.023	.011	3.50	.37	.33	Nil	.02	Nil	1650°	2 Hrs.	

FIGURE 4



MACROETCHED SECTIONS OF 1" FACE-HARDENED ARMOR PLATE
MADE BY AMERICAN CAR AND FOUNDRY COMPANY.
12 NOVEMBER 1943 WTN.710-2192

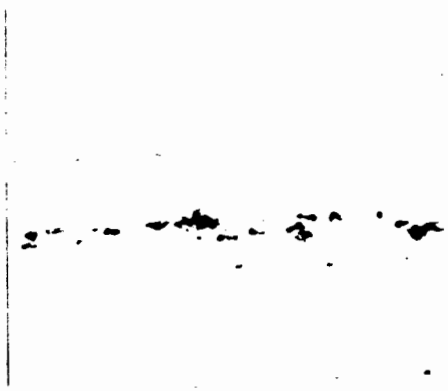
FIGURE 5



MACROETCHED SECTION OF 1" FACE-HARDENED ARMOR PLATI
MADE BY AMERICAN CAR AND FOUNDRY COMPANY.
12 NOVEMBER 1943 WTN.710-2193

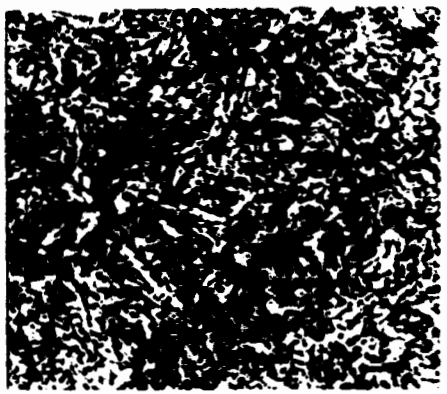
FIGURE 6

Plate 1615-3
Typical Structures of the Plates from the 1% Ni-Cr-Mo Heat 1615

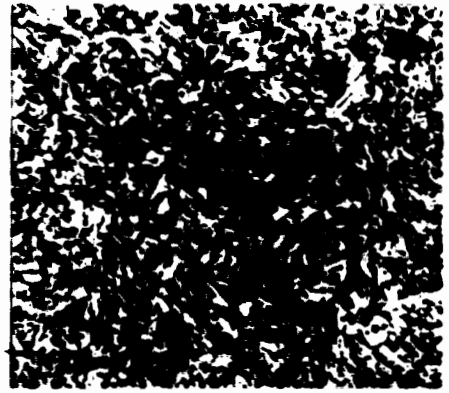


X100 A Unetched
Typical friable oxide type stringers in Heat 1615.

X1000 C Picral
Core: Tempered martensite.

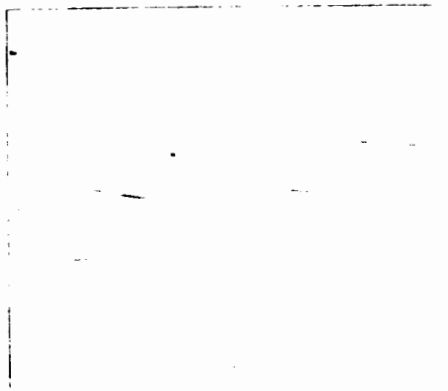


X1000 E Picral
Case: .040" from face.
Carbides in tempered martensite.

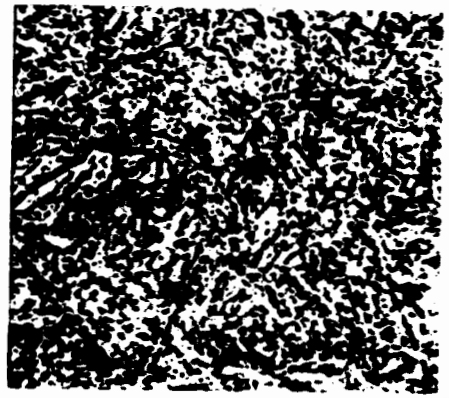


X1000 G Picral
Case: .015" from face.
Carbides in tempered martensite.

Plate 1646-3
Typical Structures of the Plates from the 3% Ni-Cr-Mo Heats 1646 and 1649



X100 B Picral
Typical stringers in Heats 1646 and 1649.



X1000 D Picral
Core: Tempered martensite.

X1000 F Picral
Case: .040" from face.
Carbides in tempered martensite.

X1000 H Picral
Case: .015" from face.
Carbides in tempered martensite.