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ARMOR - ROLLED

Metallurgical Examination of British Homogeneous and Face Hardened Armor

OBJECT

To make a complete metallurgical examination of three British homogeneous plates and three British face hardened plates submitted by Aberdeen Proving Ground.

SUMMARY

1. The subject plates have the following characteristics:

Mfgr. and Nom. Thickness	Type of Plate	Measured Thickness Inches	Measured Thickness MM.	Brinell Hardness Face	Brinell Hardness Core	Type Composition C	Mn	Ni	Cr	Mo	V
E.S.Co., 70mm.	Homo.	2.74	69.6	297		.31	.60	3.27	.71	.52	—
E.S.Co., 80mm.	Homo.	3.10	78.7	261		.33	.61	2.82	.76	.56	—
Firth Brown, Ltd., 120mm.	Homo.	4.68	119	273		.33	.63	.71	1.24	.46	—
Beardmore, 50mm.	Carb.	1.92	48.8	780	215	.35	.49	.41	3.52	.49	.24
Beardmore, 70mm.	Carb.	2.68	68.1	780	215	.35	.50	.46	3.13	.56	.26
Firth Brown, Ltd., 4-1/2"	Carb.	4.42	112	618	235	.29	.46	4.32	1.54	.12	.24

The plates designated by Aberdeen as face-hardened were found to be carburized. All of the above analyses are used for projectile testing plate, but only the composition from which the Firth Brown 120mm. plate was fabricated is known definitely to be used for regular production heavy tank rolled homogeneous armor. This analysis is within the range specified for the British 1½% Cr-Mo composition, from which most of present day British machineable rolled armor is made.

2. The homogeneous plate compositions differ greatly from those generally used by American industry for comparable plates since nickel content is much higher and manganese content is much lower in the British analyses. The chemistries of the carburized plates are quite different, except in carbon content, from the compositions of American heavy rolled carburized plates examined at this arsenal.

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3. Hardnesses of the British homogeneous plates are at a little higher level than that to which current American comparable rolled armor is heat treated (250-260 Brinell). Hardness levels and hardness distributions in cases and cores of the British carburized plates are similar to those determined in recent projectile testing 3" to 5" rolled carburized plates made by two American producers. Total case depth of each face-hardened plate is almost half of the cross section, but depth of hardness to Rockwell C 50 is only .25" to .34". The depth of carburization in each plate is much less than the corresponding depth of hardened case, being only .46" to .59".

4. All of the plates possess satisfactory hardenability except the Firth Brown, Ltd., 120mm. plate, which is greatly deficient in hardenability.

5. All of the plates are susceptible to temper brittleness.

6. The heat treatment of the homogeneous plates consisted of quench hardening, in water or oil, and tempering. After carburization, the face-hardened plates were hardened, probably in water or oil, and tempered; and then the cases were hardened by application of austenitizing heat to only the carburized faces, followed by quenching.

7. Inferior impact toughness, in varying degrees, was revealed by the fracture and notched-bar impact tests of several of the plates. These plates and the causes determined for their inferior properties are as follows: E. S. Co., 70mm. and 80mm. plates - temper brittleness; Firth Brown, Ltd., 120mm. plate - inadequate quench hardening; and Beardmore, 70mm. plate - excessively large grain size plus, perhaps, incomplete quench hardening.

8. The Firth Brown, Ltd. 120mm. plate and the E. S. Co. 70mm. plate are characterized by such poor impact toughness throughout most of the section that these plates would be expected to exhibit poor resistance to severe ballistic shock. From the limited data available it appears that resistance to penetration by matching and overmatching projectiles, especially at obliquities, might be inferior to that of rolled plate similar in thickness and hardness but possessed of a fibrous fracture.

9. All plates were cross rolled, but most had been rolled in one direction predominately. All plates except the Firth Brown, Ltd. 4½" plate are of satisfactory steel soundness in regard to freedom from pronounced laminations. Severe segregations of small oval shaped nonmetallic inclusions present in this plate would be expected to cause spalling under obliquity penetrations by matching and overmatching projectiles.

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INTRODUCTION

In conjunction with an extensive comparative program being fired at Aberdeen Proving Ground with American and British APC projectiles against both American and British armor plate, it was requested by the Office, Chief of Ordnance[1], that this arsenal conduct complete metallurgical examinations upon sections taken from each British plate.

MATERIALS AND TEST PROCEDURE

Six rectangular samples, each flame cut from a corner of a plate, were submitted by Aberdeen Proving Ground. Dimensions of each sample were plate thickness x 7" approx. x 14" approx. Descriptive information about the plates is as follows:

Watertown Arsenal Designation	Manufacturer	Plate No.	Nominal* Thickness	Measured** Thickness	Type
9	E. S. Co.	G23003-3609	70mm.	2.74" (69.5mm)	Homo.
50	E. S. Co.	G22487-3350	80mm.	3.10" (78.7mm)	Homo.
73	Furth Brown, Ltd.	23873-A-1	120mm.	4.68" (119 mm)	Homo.
14	Beardmore	3762B-2314T	50mm.	1.92" (48.8mm)	F.H.
45	Beardmore	6304-2945T	70mm.	2.68" (68.1mm)	F.H.
48	Furth Brown, Ltd.	5448B	$4\frac{1}{2}$	4.42" (112 mm)	F.H.

*The plate thicknesses given on all figures in this report are nominal thicknesses.

**Thicknesses were measured at this laboratory on cross sections cut through the plate and do not include the heavy scale present on each plate. All surfaces were very rough from the rolling.

Each sample was first notched at the midpoint of the 14" dimension and fractured. In accordance with the results of the fracture tests, the fractured halves farthest from the plate corners[2] were subjected to the following procedures: chemical analyses, Jominy hardenability determinations, hardness

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1. Wtn. 400.112/3022(s) - O.O. 400.112/10033(s), See Appendix A.
2. Only the fractured halves farthest from the plate corners were used in order to examine armor that was least likely to have been affected by the "edge-effect" during the original hardening process (i.e., more efficient quench hardening at the plate edge than at the rest of the plate) and by the flame cutting by both Aberdeen and the British manufacturers (the plates had been flame cut to size). Upon being macroetched, sections through the British flame cut edges showed hardened zones adjacent to the edges, proving that the plates had been flame cut to size after heat treatment. Therefore the material examined was probably distant enough from the as-quenched edges to be free of the quenching "edge effect."

surveys, V-notch Charpy impact tests, tensile tests, macroetching, and microscopic examinations.

Additional fracture bars of different shape and broken in a different manner than required by the standard procedure were taken for comparison with the fractured samples. In order to determine the nature of the cases of the face hardened plates, the cases were annealed and then examined microscopically. All plates were tested for susceptibility to temper brittleness by means of a modified Greaves and Jones procedure. Experimental heat treatments were performed on sections of Plates 9, 50, 73, and 45 in order to determine the causes of the poor impact properties of these plates.

DATA AND DISCUSSION

1. Fracture Tests

a. Entire Aberdeen Sample

Prior to fracturing each Aberdeen sample was notched in deeply at the midpoint of the 14" dimension, at both edges, perpendicular to the plate faces. To facilitate fracturing, each sample was also given a shallow notch at one face. All notching was done with a cut off wheel. Sample 48 was broken under a press; all others were fractured by the quick impact of a forge hammer. Fractures were rated for both steel soundness and fibre characteristics. The results of the tests are shown in Table I and Figures 1 and 2.

It should be noted in Figures 1 and 2 that the unnotched plate faces of the homogeneous plates and the case faces of the face hardened plates have been designated as "Face B". The corresponding opposite faces in each case have been designated "Face A". By reference to "Face B" and to "Face A" identification will be made of all test specimens taken from the fractured samples.

A discussion of the data derived from the fractured samples is given below.

(1) Homogeneous Plates

The fractures of Nos. 9 and 50 show that these plates possess good steel soundness. No soundness rating can be assigned to Plate 73 because of the almost wholly crystalline fracture, which would tend to suppress the appearance of any laminations that might be present.

Rated for their fibre characteristics, it is seen from Figure 1 that the fractures of Plates 9 and 73 exhibit crystallinity throughout most of the section. The crystallinity of No. 73 is coarse, whereas in the fracture of Plate 9 crystallinity occurs as small facets in a fibrous matrix. In Plate 50 a coarse crystallinity occurs only in the half of the fracture adjacent to Face B, the other half being fibrous. The presence of crystallinity in the fractures of all of the British homogeneous plates indicates, in a general sense, that the impact toughness of these plates is poor.

(2) Face Hardened Plates

Their fractures being free of laminations, Plates 14 and 45 possess good steel soundness ratings. The fractures are very "woody", however, indicating that many short inclusion stringers are present in these steels. Two deep laminations are present in the fracture of plate No. 48, sufficient to impart a soundness rating of D to this material.

As shown by Figure 2, fractures of the cores of Plates 14 and 48 are wholly fibrous, hence indicative of good impact toughness, while some crystalline areas, indicative of brittleness, are evident in the fracture of the core region of Plate 45. However, since the effects caused during fracture by deep laminations present in the fracture of plate No. 48 could have prevented the occurrence of crystallinity, the results of this fracture test for No. 48 must be considered inconclusive.

The characteristics of the fractures of the face hardened plate cases are described in detail in Table I. The fracture test has revealed that the total depths of the cases are as follows:

Plate No.	Case Depth
14	.60"
45	.85"
48	1.60"

b. Additional Fracture Tests

To secure additional fracture bars, each Aberdeen sample fractured half from which test specimens were to be taken was sliced through the thickness, perpendicular to the fracture, approximately 2" distant from the Aberdeen flame cut edge. These T x 7" approx. x 2" approx. bars were then notched deeply with a cut off wheel at the midpoint of the 7" dimension, perpendicular to the plate surfaces, at only the flame cut edge, and broken under a forge hammer.

The fractures are shown in Figure 3. From comparison of Figures 1 and 2 with Figure 3 the differences in method of notching and path of fracture can be seen. The Aberdeen T x 14" x 7" samples were notched and fractured so that the fracture progressed chiefly from one plate face to the other; whereas the path of fracture in the small fracture bars was perpendicular to the plate faces.

The following observations result from the fracture of the 11 test pieces:

(1) Homogeneous Plates

The fibre characteristics of these fractures are identical to those of the fractured Aberdeen samples. Since the fractures progressed across the plate thickness, the distribution of crystallinity in the section may in some cases now be correlated with the variations in impact strength throughout the section[5]. It is now evident that Plate 73 possesses poor impact strength throughout most of the section; that the impact toughness of No. 9 is somewhat poor from face to face; and that the impact toughness in the half of the section adjacent to Face B, in Plate 50, is inferior to that of the opposite half.

(2) Face Hardened Plates

As shown by Figure 3, there is no change in the fiber characteristics of the fractures of Plates 14 and 48. Again it is revealed by the fibrous nature of the fractures that impact toughness is good throughout the sections of these plates. Laminations in the fracture of Plate 48 are this time shallow and therefore incapable of influencing significantly the character of the rupture.

Only traces of crystallinity, at the center region, are apparent in the small bar fractures of Plate 45, unlike the moderate amount of crystallinity seen distributed in areas throughout the section in the corresponding Aberdeen sample fracture. The latter condition may have been due to initiation of brittle failure in the core by the brittle path of fracture through the hard case. At any event, the presence of crystallinity shows that impact toughness is somewhat inferior.

2. Nature of the Cases of the Face Hardened Plates.

Sections through the thickness were cut from the face hardened plates, annealed in neutrapak at 1700°F for 3 hours, and furnace cooled. The specimens were ground to remove decarburization, polished, and examined microscopically.

From the variations in microstructures between the case and core regions, including the presence in each plate of a carbide grain boundary network adjacent to Face B only, it was seen that Plates 14, 45, and 48 had been carburized prior to hardening. The depth of carbon penetration determined for each plate is as follows:

Plate No.	Depth of Carbon Penetration
14	.46
45	.59
48	.44

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5. In normal transition zone fractures of notched bars the center crystalline zone is surrounded by a fibrous edge. However, if the metal is free of laminations, this crystalline area should be at the center and should occupy a good proportion of the width of the fracture. *Areas of crystallinity which are not symmetrically located or which are narrow in relation to the specimen width are therefore indicative of a variation of impact properties across the section resulting from non-uniformity of structure. (*From "Notched Bar Impact Test" - Trans. A.I.M.E., Iron and Steel Division, 1944 - J. H. Hollomon)

From comparison of the above data with the case depths revealed by the fracture tests (see Table I) it is seen that the fracture case depth of each plate is appreciably greater than the corresponding depth of carbon penetration. This suggests that the hardened cases had been achieved by some method involving differential heating of the plate. In Section 10, "Microscopic Examination", it will be shown that each plate had been heat treated by the following process: (1) hardening and tempering of the entire plate; and then (2) application of heat to the case face only, followed by either quenching of the entire plate or spray quenching of the case.

3. Chemical Analyses

The chemical analyses of the six plates are given in Table II. Except for the presence in the subject plates of boron, which is probably a residual element judging from the small amount, all of the plate compositions are similar to those listed by the British[6] as being typical analyses that are used for proof of shot.

The following basic type analyses are recognizable in Table II:

a. Homogeneous Plates

(1) Ni-Cr-Mo

All of the homogeneous plates were manufactured from this type analysis. Plates 9 and 50 differ chiefly in that the former contains a higher nickel content. The main constituents in their analyses are as follows:

	C	Mn	Si	Ni	Cr	Mo
70mm Plate, No. 9	.31	.60	.22	3.27	.71	.52
80mm Plate, No. 50	.33	.61	.18	2.82	.76	.56

From the British reports and abstracts available in this laboratory it cannot be determined whether or not these analyses are used for production tank armor manufacture. There is a reference, however, to the use of 3½% Ni-Cr-Mo steel and 2½% Ni-Cr-Mo steel in the manufacture of experimental 4½" rolled plate[7].

Although the 120mm Plate, No. 73, is in the Ni-Cr-Mo category, it differs from the other two homogeneous plates by containing much less nickel

6. See Appendix B.

7. W.A. Rpt. 710/623 - British Secret Abstract - "Minutes of the 20th Meeting of the Technical Coordinating Committee on the Tank Armour Held at Adelphi on 27th January 1944 at 2:30 P.M."

and appreciably more chromium. The abbreviated analysis is:

C	Mn	Si	Ni	Cr	Mo
.33	.63	.23	.71	1.24	.46

This is within the range specified for the British regular production $1\frac{1}{2}$% Cr-Mo machineable rolled armor analysis, from which, according to a recent British report[8], most of the British armor is made at the present time. The range of this type analysis is:

C	Si	Mn	S	P	Ni	Cr	Mo
.25/.35	.15/.40	.40/.90	.05 Max.	.05 Max.	.4/1.0	1.0/1.9	.30/.60

b. Face Hardened (Carburized) Armor

(1) Cr-Mo-V

Plates 14 and 45 were fabricated from steel of this type analysis. Except for a higher chromium content in No. 14, the two analyses are almost identical, as shown below:

	C	Mn	Si	Ni	Cr	Mo	V
50mm Plate, No.14	.35	.49	.20	[illegible]	3.52	.49	.24
70mm Plate, No.45	.35	.50	.25	.46	3.13	.56	.26

(2) Ni-Cr-Mo-V

The type analysis utilized in the production of the $4\frac{1}{2}$" Plate, No. 48, is the following Ni-Cr-Mo-V type:

C	Mn	Si	Ni	Cr	Mo	V
.28	.46	.24	4.32	1.54	.12	.24

Of significance is the molybdenum content, which is much lower than that of the other five British plates.

Information was not available in the British reports and abstracts to determine whether or not the carburized plate analyses are used for tank armor production as well as for projectile testing plate manufacture.

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8. British Secret Report - "Firing Trials on American Rolled Plates" - 25th September 1944 - W. A. Rpt. 710/717

4. Hardenability

Since it was considered desirable in the hardenability determinations to austenitize the steels at the same temperatures used by the British for similar plate analyses, all of the British reports and abstracts available in the laboratory files were perused for these data. Except in the case of plate No. 73, the only data that could be found pertained to compositions only roughly similar to those of the subject plates, and these temperatures appeared to be lower than optimum. Therefore it was decided to make two Jominy bar hardenability determinations for each plate, in one instance using the temperature that the British probably used (judging from the data that could be secured), and in the second instance using a temperature that previous experience had indicated would be ample for achieving complete solution of the carbides. (This was not strictly true in the case of the vanadium bearing carburized plates. The temperatures chosen for these plates pertained to complete carbide solution considering only the contents of C, Mn, Ni, Cr, and Mo.) All of these austenitizing data are given below:

Plate No.	Austenitizing Temp. Used by British for Somewhat Similar Analyses	Austenitizing Temp. Used to Duplicate British Practice	Austenitizing Temp. Chosen by W.A.
		Homogeneous Plates	
9	1516-1562°F	1540°F	1650°F
50	1516-1562°F	1540°F	1650°F
73	1616°F	1616°F	1675°F
		Face Hardened (Carburized) Plates	
14	1607-1652°F	1650°F	1700°F
45	1607-1652°F	1650°F	170[illegible]°F
48	1516-1562°F	1540°F	1675°F

Jominy bars were machined from the region adjacent to the center of the plate sections, austenitized for 4 hours at the temperatures given above, and end quenched in a standard fixture. Hardness surveys were made on ground flats at the bar faces adjacent to the plate centers and then the same flats were examined metallographically.

Results of the hardness surveys are tabulated in Table III and shown graphically by Figures 4 and 5. Results of the metallographic examination and other pertinent data are summarized in Table IV. A discussion of the hardenability data is given below:

a. Homogeneous Plates

From Table III it is seen that for each steel the hardness distributions along both Jominy bars are identical. This indication that in every instance hardenability was not improved by the higher austenitizing temperature was verified by the metallographic surveys. Microscopic examination also disclosed the explanation for the lack of improvement, since it was found that carbide solution was essentially complete in the bars austenitized at the lower temperatures as well as in the bars end quenched from the higher temperatures.

The hardenability criterion that will be used in this report is the ability of a plate to be quench hardened in still water so as to contain not more than 10% of non-martensitic transformation products at the center of the section. Using this criterion, Table IV shows that Plates 9 and 50 possess more than ample hardenability (and identical hardenability), while Plate 73 is greatly deficient in hardenability.

b. Face Hardened (Carburized) Plates

Although again the hardness patterns are identical for both Jominy bars of each plate (except at 40/16" from the quenched end in the case of Plate 48), this time increased carbon solution at the higher austenitizing temperatures has caused improvement in hardenability, in regard to the occurrence of non-martensitic transformation products. Using the same criterion as before, however, the hardenability improvement is not significant. All of the plates possess adequate hardenability even when quench hardened from the lower austenitizing temperatures.

It is interesting to note that whereas the hardness distributions in both Jominy bars of Plate 14 are identical to the hardness patterns of both of the No. 45 bars (from 4/16" to 40/16" from the quenched end), at 40/16" already 30% bainite is present in the No. 45 (1650°F) bar and only less than 5% of the same constituent exists in the No. 14 (1700°F) bar at the same location.

5. Hardness Surveys

a. Homogeneous Plates

Brinell hardness surveys were made on surfaces through the thickness of the plates. The results are contained in Table V and summarized below:

Plate No.	Brinell Range
9	293/302
50	248/269
73	262/285

Hardness is uniform throughout the section in Plate 9, decreases slightly at the center region in Plate 73, and in Plate 50 is slightly lower in the section half adjacent to Face B than in the opposite half.

b. Face Hardened (Carburized) Plates

For each plate two Rockwell C surveys were made completely across the thickness on a ground specimen taken parallel to and just back of the Aberdeen sample fracture. Readings were taken at 1/16" intervals and the surveys were about $1\frac{1}{2}$" apart. These data are plotted in Figure 6 and summarized in Table VI.

Cross sectional Brinell surveys were also made on the specimens and then Brinell hardness was determined on each case face, after the removal of 1/32" by careful grinding. These data are included in Table V.

The Rockwell C surveys in Figure 6 show that the initial hardness of each case is high. However, this high hardness does not persist. Therefore, although each case is seen to be deep in regard to extent of hardness above that of the corresponding core (each case extends in approximately for one half the distance across the section), actually each case is shallow if Rockwell C 50 is the criterion used to evaluate the hardness distribution.

This hardness level is used by the U. S. Naval Proving Ground in determining the extent of "effective case" in their carburized armor, since it has been their experience that only the portion of a case hardened to or above Rockwell C 50 is effective in breaking up the opposing projectile.

Rockwell C 50 may be considered excessive by some persons and perhaps Rc 45 is preferable. Using this value as the minimum hardness of the "effective case", the case depths of all the plates remain shallow.

It is evident from Figure 6 that each plate had been severely decarburized at the rear face during heat treatment. The total depth of decarburization for each plate appears to be as follows: Plate 14, .31", Plate 45, .25", and Plate 48, .19".

Summarized briefly, the hardness distributions in each plate, given as Brinell numbers, are as follows:

Plate No.	Case Face Hardness	Core Hardness
14	780	212/217
45	780	207/217
48	601/653	229/241

A slight decrease in hardness from the outer region to the center of each core is detected from both the Rockwell C and the Brinell surveys.

6. V-Notch Charpy Impact Test

a. Material As-Received

(1) Homogeneous Plates

In order to precisely survey the degree and variations of impact toughness throughout each plate thickness, V-notch Charpy specimens were machined from all of the homogeneous plates. Specimens were taken from the region directly back of the Aberdeen sample fractures and located in the cross sections as shown in Figure 7. All specimens were transverse (i.e., their fractures were longitudinal) and were notched parallel to the thickness direction. The temperatures at which the specimens were broken and the results of the tests are included in Table VII.

A very good correlation is evident between the Charpy impact data and the fractures shown in Figure 3. Charpy specimens taken from the cross sectional regions that had ruptured in a fibrous manner during the fracture tests retain their room temperature value (and a fibrous fracture) down to or almost down to -40°C; whereas the impact values of the regions that had fractured brittlely during the fracture tests are considerably lower at -40°C than at room temperature (and the Charpy fractures are brittle at the low temperatures). Impact toughness is so poor at the center of the section in Plate 73 that the Charpy specimens fractured brittlely even at room temperature, with consequent low energy values.

Since reduction of temperature has an equivalent effect to increasing the rate of strain, with a small decrease in temperature being equal to a great increase in the strain rate[9], rapid transition from ductile to brittle type of failure as the testing temperature is lowered from room temperature indicates poor impact strength at high rates of strain. Rolled armor of hardnesses up to about 360 Brinell is considered to possess very good impact toughness when the room temperature Charpy fracture is fibrous and the character of the fracture does not change substantially at -40°C (i.e., the Charpy value at -40°C is about the same as the value at room temperature).

Although the room temperature fractures of the No. 9 and No. 50 Charpy specimens are fibrous, the values are considerably below those of good quality cross rolled materials of the same hardnesses. This suggests that the plates had been rolled in one direction essentially and the "woodiness" of the Charpy fractures prove that they had been.

(2) <u>Face Hardened (Carburized) Plates</u>

Since plates No. 14 and 48 exhibited completely fibrous fractures during the fracture tests of Section 1, no Charpy testing of these plates was done.

The Charpy impact properties of Plate 45 were determined by the same procedure as was used for the homogeneous plates. Location of specimens is likewise in Figure 7 and the data are in Table VII also.

Impact toughness at the center of the section of this plate is seen to be below that of superior quality rolled armor of 220 Brinell. The impact level of the fibrous Charpy specimens (the room temperature specimens) is lower than that of good quality 220 Brinell cross rolled plate, and again "woodiness" of the fractures indicates non-uniform rolling reduction to be the cause.

b. <u>Susceptibility to Temper Embrittlement</u>

A modified form of the Greaves and Jones standard test was

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9. C. Zener and J. H. Hollomon - "Plastic Flow and Rupture of Metals" - Trans. Amer. Soc. Metals (1943) Vol. 33.

used to determine the susceptibility of each material to temper embrittlement. Since it is known that the higher the original hardening temperature the greater may be the temper embrittlement, the test was conducted on each material using both sets of austenitizing temperatures previously used in the Jominy hardenability determinations. The procedure for each plate, for each austenitizing temperature, is given below:

> Small specimens, sufficient in size or else in quantity to later furnish four transverse Charpy specimens, were cut from each plate. Size of the largest specimen was 2.3"x.70"x3.0". All specimens were austenitized for 4 hours, hardened in oil, and tempered at 1200°F for 4 hours, after which half the specimens of each plate were quenched in water and the remaining half were furnace cooled at 5°F/minute. Standard V-notch Charpy impact bars were machined from the specimens, notched parallel to the plate thickness direction, and broken at -40°C.

The Charpy data are given in Table VIII and interpreted as follows:

(1) Homogeneous Plates

As shown by the lower impact energies of the furnace cooled specimens compared to the energies of the corresponding water quenched samples, all of these steels are found to be appreciably susceptible to temper embrittlement when slow cooled from above the embrittlement range. However, austenitizing at the higher temperatures has not increased the degree of embrittlement.

(2) Face Hardened (Carburized) Plates

All of the carburized plates likewise show great susceptibilit to temper embrittlement, with no significant increase being caused by the higher of the two hardening temperatures used for each steel. The embrittlement developed in the furnace cooled specimens of Plate 48 is especially severe. It will be recalled that this plate contains much less molybdenum than is present in each of the other five plates.

Since good impact toughness was revealed by the fracture tests of Plates 14 and 48, it is evident that these plates had been quickly cooled from the draw, probably by immersion in water, in order to overcome temper embrittlement.

The cause of the poor impact strength which occurred from austenitizing the No. 14 and No. 45 specimens at 1700°F is not known.

c. Effect of a Redraw on Impact Properties

(1) Homogeneous Plates

Additional experimentation was now carried out to determine whether or not temper embrittlement had been responsible for the brittleness exhibited by these plates. From each material a section T(thickness)x2.3"x.6" was secured having the 2.3" dimension parallel to the transverse rolling direction. Each section was drawn for $2\frac{1}{2}$ hours at a temperature that was believed to be above the embrittling range and sufficiently low so as not to soften the material, and then water quenching followed. Charpy specimens were machined from each section at locations identical to those shown in Figure 7, notched parallel to the plate thickness, and broken at -40°C.

The resulting data, given in Table IX, show that the brittleness exhibited by Plates 9 and 50 was due solely to temper embrittlement, which occurred during the cooling from the draw, and that this malady had not been responsible for the poor impact toughness of Plate 73. The cooling rate following the tempering of Plate 73 was sufficiently fast that temper embrittlement did not occur.

(2) Face Hardened (Carburized) Plates

By a similar procedure it was revealed that the brittleness manifested by Plate 45 had not been caused by temper embrittlement.

7. Tensile Tests

Standard .357" diameter tensile specimens were machined, from all the plates that had displayed brittleness, to the extent of the material remaining after all other tests had been performed. Locations of the specimens within the plate cross sections are shown by Figure 7. Test data are included in Table X.

The elongation and reduction of area values in the transverse direction of Plates 9 and 50 are considerably lower than the corresponding longitudinal direction values. This checks the remarks made in Section 6 in regard to the essentially uni-directional rolling of the plates.

8. Macrostructure

a. Homogeneous Plates

The macroetched structures of the homogeneous plates are shown in Figure 8. All of the plates appear to have been cross rolled, with the rolling of Plates 9 and 50 having been done in one direction predominantly. No excessive non-metallic segregations that might cause planes of weakness have been revealed by the hot acid etch. Numerous short inclusion stringers are present in each plate, however.

b. Face Hardened (Carburized) Plates

The hot etched structures of the carburized plates, shown in Figure 9, reveal that all had been cross rolled. From the pronounced "woodiness" of their fractures it was expected that the macrostructures of Plates 14 and 45 would contain more inclusion stringers and would evidence more indications that rolling had occurred in one direction mainly. Numerous long stringers exist throughout the section in the macrostructure of Plate 48, explaining the occurrence of deep ruptures in the fracture of this plate (see Section 1).

In addition many short inclusion stringers are distributed throughout the section.

Of interest is the shallowness of the case of Plate 48 that has been revealed by the macroetch.

Short cracks are present in the cases of Plates 14 and 45. It is not unusual, however, for hard carburized cases to show cracks after macroetching.

9. Microscopic Determination of Non-Metallic Inclusions

a. Homogeneous Plates

Numerous small groups of inclusions, which have the appearance of sulphides, were found throughout the sections in all the homogeneous plates (see Figures 10A, B, and C). Except for one concentration in the whole of the Plate 73 cross section, the non-metallics do not occur as severe linear segregations.

b. Face Hardened (Carburized) Plates

The inclusions which compose the short stringers revealed by all the macrostructures of these plates also resemble sulphides (Figures 10D and E). Plate 48 contains, in addition, numerous long stringers of oval light pink inclusions (Figure 10F). These inclusions are responsible for the poor steel soundness of the plate.

10. Microscopic Examination

a. Homogeneous Plates (Figures 11 and 12)

70mm. Plate No. 9 - The structure of this plate is free from banding, has an ASTM grain size of No. 5, and consists of tempered martensite plus some tempered bainite. The presence of bainite is indicated by the occurence, throughout the section, of fractions of grains wherein the carbides are lined up in rows (Figure 11A) and by the presence of small amounts of a ferritic constituent, mainly at the center of the section (Figure 11B). Metallographic examination of the No. 9 Jominy bars showed that whenever the above content of ferrite exists, more than 10% of bainite is present. In additio some of the Jominy bar bainite possessed the same carbide lineup pattern as is shown in Figures 11A.

The presence of the nonmartensitic constituents noted above indicates inefficient quench hardening technique since hardenability was ample for still water quenching. However, the impact toughness imparted by the microstructure would have been good had the plate not been embrittled by temper embrittlement.

80mm. Plate No. 50 - Microstructure in this plate is complex and varies from plate face to plate face. Adjacent to and for a distance of 1.2" from Face B there occurs a tempered ferritic constituent, resulting from austenite decomposition at high temperatures, (the light etching areas in Figures 12A and 12B) in which are bands and scattered needles of tempered bainite (the brown etching carbide structure in Figures 12A and 12B). Thereafter an abrupt transition begins, the amount of bainite increasing and the ferritic constituent decreasing so that at the center of the section the bainite predominates in the structure (Figures 12C and 12D). The ferritic constituent persists up to about one inch from Face A. Continuing toward Face A, tempered martensite appears, as evidenced by acicularity at low magnification (X100), and at .35" from Face A the structure is entirely or predominantly tempered martensite (Figures 12E and 12F). Grain size throughout the section is ASTM No. 6-7. The above variations in microstructure reveal that following austenization Plate 50 had been quenched either at Face A only or more severely at Face A than at Face B (this was undoubtedly accidental) and that quenching efficiency had been poor besides.

Although microstructure appears undesirable, it has been previously shown that temper brittleness, not microstructure, was responsible for the brittle behaviour of the region that is adjacent to the center in the Face B half of the plate.

120mm. Plate No. 73 - A large amount of tempered ferritic and nonferritic, nonmartensitic, austenite decomposition products exists in the 120mm. plate, the amount increasing from the surface to the center (Figures 11C,D,E,F). From the hardenability data (see Table IV) the poor quench hardening of the plate is seen to have been caused primarily by inadequate hardenability. The quenching efficiency appears to have been poor also, as evidenced by the considerably larger amount of ferrite in the plate than exists at the air cooled end of the Jominy bar. Grain size of the plate is ASTM No. 5.

Since it was learned in Section 6C that Plate 73 had not been embrittled by temper brittleness, the poor impact toughness revealed by the fracture and V-notch Charpy tests can be attributed to the excess amount of nonmartensitic constituents in the plate.

General Remarks - From heat treating experiments conducted with small specimens in connection with Section 6C, the tempering temperatures used for the plates are indicated to have been as follows: Plate 9, 1150°F; and Plates 50 and 73, 1200°F.

All the plates exhibited total decarburization of .04" to .05" and severe decarburization of about .015".

b. Face Hardened (Carburized) Plates (Figures 13, 14, and 15)

Microstructure variations from core to case surface are identical in essential respects in each of the carburized plates. The microstructure of each case consists of light etching and structureless martensite in which are present large globular and elongated carbides plus many smaller carbides, at just below the surface (Figures 13A, 14A, and 15A), and numerous small carbides, farther back from the case face (Figures 13B and 15B). The core to case transition zone of each plate consists of martensite patches in a highly tempered core structure (Figures 13C, 14B, and 15C). Proceeding from core to case, the initial appearance of martensite corresponds to the beginning of the case as designated by the Rockwell C surveys (see Figure 6), and the amount of martensite increases, with the amount of core structure decreasing, until the entire structure is martensite.

The nature of the core to case transition zone is proof that in each instance the hardened case had been produced by reheating the previously heat treated plate at only the carburized face and by then quenching either the entire plate or only the case face.[10] Probably a water spray directed against the case face was used. No tempering or else only a low temperature draw followed this treatment, as indicated by the light etching and structureless nature of the martensite in the case.

In each plate the greater depth of the hardened case compared to the corresponding depth of carbon penetration was caused by some of the plate region back of the carburized zone having been heated to above or within the critical temperature range. The "shelf" in the hardness survey of Plate 48 was due to this whole region of uncarburized core having been heated to above the critical range.

For ready comparison of case depth revealed by one procedure against depth of case shown by the other procedures, all case depth data have been tabulated in Table XI.

A discussion of the core microstructure is given below:

70mm. Plate, No. 45 - Microstructure in the core is complex and non-uniform. Figures 14C and 14E show the predominant structures at the center of the section and adjacent to the back surface of the plate. Both structures resemble tempered martensite or tempered low temperature bainite, but the carbides are much more widely spaced at the first location. This difference may possibly have been due to the retempering received by the center of the section during the case hardening process. Throughout the section grains or fractions of grains exist wherein occur ferritic patches and carbides arranged in chains or concentrations (Figure 14D). Whether or not the latter structure is bainite is not known, for a somewhat similar structure was detected in a small specimen which had been rehardened in water and drawn to a hardness in little above that of Plate 45. Grain size throughout the core is unusually large (ASTM #1, Figure 14F).

Since it was previously learned that Plate 45 had not been affected by temper embrittlement, the embrittlement exhibited in previous sections of this report was probably caused by either large grain size or a combination of large grain size and incomplete hardening. That grain size had been an important factor was indicated by the presence of large facets in the fractures of the fracture bars and Charpy specimens.

50mm. Plate, No. 14 - Except that the carbides are more closely packed and less randomly distributed in the center of the section matrix of Plate 14, the microstructural constituents are similar to those detected in Plate 45 (Figures 13D, E, and F). Grain size of the plate is only ASTM #5-6, however.

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10. Such a method of hardening the case of a heavy carburized plate (60mm. or thicker) is described in detail in the British document "Armour for Fighting Vehicles" - The Ministry of Supply - June 1941 (O.O. 461/26 Aberdeen Proving Ground(c) - W.A. 461/5188(c) Incl. 1. The British procedure consists of placing the plate on a furnace bogie, with the carburized face up, and carefully bricking in the plate so that the hot gases have access only to the top (i.e. carburized) surface. Following the heating cycle, the plate is removed from the furnace and a water spray is applied to the face.

$4\frac{1}{2}$" Plate, No. 48 - Microstructure at the center of the section consists of light and dark etching bands. Ferrite patches are present in the light bands (Figure 15E), indicating that some high temperature austenite decomposition products of the type seen in the 1540°F Jominy bar of the plate are present. The dark bands at X1000 resemble tempered martensite or tempered low temperature bainite. Microstructure adjacent to the back surface of the plate (Figure 15F) is not banded and has an appearance which is between the two types detected at the center of the section. The plate possesses a fine grain size (ASTM #6-7).

General Remarks - It is probable that the heat treatment of all the carburized plates, after carburizing and prior to the hardening of the cases, consisted of liquid quench hardening, in water or oil, followed by tempering. This cannot be stated definitely in regard to Plates 14 and 45. From the heat treating experiments mentioned in the Homogeneous Plate Section above, the tempering temperatures appear to have been approximately as follows: Plates 14 and 45, 1275°F; and Plate 48, 1225°F.

Each plate exhibited decarburization at the back surface to the extent revealed by the Rockwell C hardness survey.

11. General Considerations

a. Homogeneous Plates

The analyses of the subject plates differ considerably from those generally used for American rolled homogeneous plates of comparable thicknesses. The British compositions contain substantially more nickel (except the analysis of Plate 73) and substantially less manganese. The tendency in this country is to use about 1.20% to 1.80% manganese in order to attain hardenability adequate for proper quench hardening and to limit the nickel content to below 1.00% for conservation purposes.

Whereas hardenability of the Plate 9 and Plate 50 compositions is satisfactory, hardenability of the much thicker Plate 73 is less than that of these plates and decidedly inadequate for the thickness. Present British machineable rolled armor is mainly of the $1\frac{1}{2}$% Cr-Mo type analyses from which Plate 73 was made.

Hardness of Plate 73 (273 Brinell) is a little higher than that of current American production $2\frac{1}{2}$" to 4" rolled homogeneous armor (250-260 Brinell). A development program is in progress in this country to ascertain whether or not armor of these thicknesses can be heat treated to and above the hardness of Plate 9 (297 Brinell) while at the same time retaining good impact toughness, as shown by a fibrous fracture.

Although Plates 9 and 50 were found to have been embrittled by temper brittleness because of insufficiently fast cooling following tempering, the thicker Plate 73, which as also susceptible to this malady, had been cooled fast enough from the draw to overcome temper brittleness.

Because of their poor impact toughness Plates 9 and 73 would be expected to exhibit brittle behavior when subjected to severe ballistic shock. It is indicated also from firing conducted against cast plate at Aberdeen Proving Ground (although it must be noted that the data are scanty) that the resistance to penetration of these plates by matching and overmatching projectiles would be improved if they possessed fibrous fractures. This indication is supported, perhaps, by the following two items seen in a recent British abstract[12]; (1), As a result of firing trials against heavy rolled homogeneous tank armor which showed that a "reverse Ni-Cr analysis" gave better ballistic performance than the $1\frac{1}{2}$% Cr-Mo analysis, Beardmore were now limiting the latter composition to plate up to 3" thick and were using the "reverse Ni-Cr analysis" for plates of greater thickness. (2), The use of fracture tests for application to heavy armor production was discussed, apparently for the first time, at a subcommittee meeting of the Armour and Bullet Proof Technical Committee No. 1. It should be noted that British ballistic testing consists only of resistance to penetration tests.

Recently a report was written by the British concerning comparison between American and British rolled homogeneous armor of thicknesses $\frac{1}{2}$" to 4", the American plate dating from about June 1943 to July 1944. The British summary of this report in included in Appendix C as a matter of general interest.

b. Face Hardened (Carburized) Plates

The analyses of the British carburized plates are much different, except in carbon content, from those of American $2\frac{1}{2}$" to 5" rolled carburized projectile testing plates that have been examined at this arsenal.

Hardness distributions and hardness levels in cases and cores are similar to those of comparable plates made by two American producers.

The severe segregations of nonmetallics noted in Plate 48 would be expected to cause spalling during attack by matching and overmatching projectiles at obliquities.

It is worthy of note that although the steel from which Plate 48 was rolled is greatly embrittled upon being slowly cooled from the draw, this $4\frac{1}{2}$" thick plate was cooled sufficiently fast following tempering to overcome temper embrittlement.

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12. Wtn 350.05/801(s) - British Secret Abstract - "Armour and Bullet Proof Technical Committee No. 1; Subcommittee No. 2 - Tanks; Special Meeting to Discuss Heavy Tank Plates, held at William Beardmore and Co., Ltd., Glasgow, on 10 October, 1944."

NOTE: RECORDS - The original records of this investigation are contained in Laboratory Notebook No. 9, pages 132 to 151.

TABLE I

Results of Fracture Tests on Samples of British Homogeneous and Face Hardened Armor

Homogeneous Plates

Plate No.	Measured Thickness	Direction of Fracture	Steel* Soundness Rating	Fibre Fracture Test Characteristics**
9	2.74"	Trans.	B	Crystalline spots in a fibrous matrix throughout the section. (Slightly more crystalline spots at center of section than at the outer regions.)
50	3.10"	Trans.	B	Fibrous in the region adjacent to Face A and crystalline in the region adjacent to Face B.
73	4.68"	Trans.	Indeterminate	Largely coarse crystalline.

Face Hardened Plates

Plate No.	Measured Thickness	Direction of Fracture	Steel* Soundness Rating	Fibre Fracture Test Characteristics**: Core	Case: Outer Case	Case: Inner Case	Total Depth of Case
14	1.92"	Long.	B (woody)	Fibrous	(.3" deep) Silky	(.3"deep) Streaks in crystalline matrix.	.60"
45	2.68"	Long.	B (woody)	Fibrous areas and crystalline areas (crystalline areas consist of large, bright facets).	(.28" deep) Silky and (.14" deep) Large shiny facets on silky matrix.	(.43" deep approx.) Large, bright facets (i.e., crystalline).	.85"
48	4.42"	Trans.	D	Fibrous but contains deep laminations.	(.4" deep) Silky	(1.2" deep approx.) Dull crystalline.	1.60"

(Cont'd)

TABLE I (Cont'd)

*Ratings were made according to steel quality standards in Appendix I of Specification 488, Rev. 2, which define B and D as follows:

B – Small laminations present but well distributed and not concentrated in any one plane. No lamination exceeding $\frac{1}{2}$ thickness of plate.

C – Lamination or laminations present exceeding limits for B fracture. No single lamination exceeding twice plate thickness in length. No single lamination exceeding $1\frac{1}{2}$ thickness in length in conjunction with another disconnected lamination in the same plane.

D – Lamination or laminations present exceeding limits for C fracture. Continuous or essentially continuous laminations (total length of lamination or laminations in same plane exceeding 75% of length of fracture) in not more than three planes.

**Descriptions of appearances of fibrous, crystalline, and silky fractures are as follows:

Fibrous Fracture – Non-reflecting, gray, and rough.

Crystalline Fracture – Bright silvery sheen caused by reflection from facets.

Silky Fracture – Slightly shiny and smooth.

TABLE II

Chemical Analyses of British Homogeneous and Face Hardened (Carburized) Plates

Plate No.	Type of Plate	Measured Thickness	C	Mn	Si	S	P	Ni	Cr	Mo	V	B	Cu	Al	Ti	Zr	W
9	Homo.	2.74"	.31	.60	.22	.034	.022	3.27	.71	.52	Tr	.0009	.09	.009	Tr	Nil	Nil
50	"	3.10"	.33	.61	.18	.033	.021	2.82	.76	.56	Tr	.0008	.08	.009	Tr	Nil	Nil
73	"	4.68"	.33	.63	.23	.032	.031	.71	1.24	.46	Tr	.0007	.07	.007	Tr	Nil	Nil
14	Carb.	1.92"	.35	.49	.20	.030	.030	.41	3.52	.49	.24	.0008	.08	.009	Tr	Nil	Nil
45	"	2.68"	.35	.50	.25	.031	.032	.46	3.13	.56	.26	.0008	.08	.015	Tr	Nil	Nil
48	"	4.42"	.29	.46	.29	.030	.020	4.32	1.54	.12	.24	.0007	.05	.01	Tr	Nil	Nil

TABLE III

Rockwell "C" Hardness Surveys of Jominy Bars of

British Homogeneous and Face Hardened (Carburized) Plates

Distance From Quenched End (Sixteenths)	Homogeneous Plates						Carburized Plates					
	Plate 9		Plate 50		Plate 73		Plate 14		Plate 45		Plate 48	
	1540°F	1650°F	1540°F	1650°F	1615°F	1675°F	1650°F	1700°F	1650°F	1700°F	1540°F	1675°F
1	49.5	49.0	50.0	48.0	51.0	50.5	53.5	56.0	54.0	56.0	46.5	47.5
2	48.0	49.0	48.5	48.5	48.5	49.5	52.5	55.0	53.5	54.5	45.5	48.0
3	47.5	47.5	48.5	47.0	49.5	49.5	52.5	54.0	53.0	53.0	46.5	47.5
4	47.5	47.5	47.5	46.5	48.5	48.5	53.0	52.5	52.5	52.5	46.0	47.5
5	46.5	47.5	46.5	46.0	49.5	49.5	52.5	53.0	52.0	52.5	46.5	46.0
6	47.5	48.0	47.5	46.0	50.0	48.5	52.5	52.5	51.5	52.5	46.5	46.5
7	48.0	48.5	46.5	46.5	49.5	49.5	51.5	51.5	51.5	52.5	46.5	45.5
8	47.5	48.0	45.5	46.5	49.5	49.0	51.0	52.0	51.0	51.5	46.0	46.0
9	47.5	48.0	46.5	47.5	49.5	48.5	52.5	52.0	51.0	51.5	45.5	45.5
10	47.5	47.5	46.5	46.5	49.5	48.5	52.0	51.5	50.5	51.0	46.5	45.5
12	47.5	45.5	46.0	47.5	48.5	48.5	51.5	52.0	51.5	51.5	46.0	46.5
14	47.5	46.5	46.5	45.5	47.5	48.0	52.0	52.5	51.0	51.5	45.0	46.5
16	47.5	45.5	47.0	45.5	46.5	47.5	51.5	52.5	51.5	51.0	45.5	46.5
18	47.0	47.0	47.0	45.5	45.5	47.0	52.0	52.5	52.0	53.0	47.5	45.5
20	46.5	47.0	46.5	46.0	44.5	44.5	52.0	52.5	52.5	51.5	45.0	45.0
23	46.0	46.5	46.5	45.5	44.5	44.5	52.0	52.0	52.5	52.0	45.5	45.0
24	45.5	46.5	46.5	46.5	42.5	42.5	51.5	52.0	51.5	52.5	43.5	45.0
31	46.5	45.5	44.5	44.0	39.5	39.0	52.5	52.5	52.5	51.5	45.5	45.0
32	44.5	45.5	44.5	44.5	38.5	38.0	52.5	53.5	52.5	52.5	45.0	44.5
39	42.5	42.5	43.5	43.0	36.0	38.5	52.0	53.0	52.5	52.0	43.5	45.5
40	42.5	43.0	42.5	42.5	37.5	37.5	50.5	52.0	51.5	51.0	41.0	46.0

TABLE IV

Jominy Bar Hardenability of British Homogeneous and Face Hardened (Carburized) Plates

(Results of Metallographic Examination)

Plate No. and Austenitizing Temperature	Measured Thickness	Carbide Solution at 1/16" From Quenched End	Distance From Quenched End to Beginning of Non-martensitic Products.	Distance From Quenched End to 10% Non-martensitic Products.	Plate Thickness* Quenchable in Still Water to 10%(or less) Non-martensitic Products at center sect.	% and Character of** Non-martensitic Products at 2½" From Quenched End
Homogeneous						
9(1540°F)	2.74"	Essentially complete.	14/16"	26/16"	3-7/16"	55-60%(Bainite. Traces of Ferrite.)
9(1650°F)		Same as above.	14/16"	27/16"	3-9/16"	55%(Same as above.)
50(1540°F)	3.10"	Essentially Complete.	13/16"	25/16"	3-3/8"	65% (Bainite. Traces of ferrite.)
50(1650°F)		Same as above.	12/16"	25/16"	3-3/8"	55%(Same as above.)
73(1615°F)	4.68"	Complete.	8/16"	13/16"	2"	85% (Bainite. Small amount of ferrite.)
73(1675°F)		Same as above.	7/16"	15/16"	2-1/4"	80-85% (Same as above.)
Face Hardened (Carburized)						
14(1650°F)	1.92"	Many undissolved carbides.	28/16"	40/16"	>3-3/4"	10% (Bainite. No ferrite.)
14(1700°F)		Little more solution than above.	36/16"	>40/16"	>3-3/4"	<5%(Same as above.)
45(1650°F)	2.68"	Many undissolved carbides.	26/16"	36/16"	>3-3/4"	30% (Bainite. No ferrite.)
45(1700°F)		Little more solution than above.	30/16"	>40/16"	>3-3/4"	5% (Same as above.)

(Cont'd)

TABLE IV (Cont'd)

Plate No. and Austenitizing Temperature	Measured Thickness	Carbide Solution at 1/16" From Quenched End	Distance From Quenched End to Beginning of Non-martensitic Products.	Distance From Quenched End to 10% Non-martensitic Products.	Plate Thickness* Quenchable in Still Water to 10% (or less) Non-martensitic Products at center sect.	% and Character of** Non-martensitic Products at $2\frac{1}{2}$" From Quenched End.
			Face Hardened (Carburized)			
48(1540°F)	4.42"	Many undissolved carbides.	31/16"	>40/16"	>3-3/4"	Trace (Carbide in ferrite.)
48(1675°F)		Much more solution than above.	32/16"	>40/16"	>3-3/4"	<5% (Carbide in ferrite plus bainite.)

The cooling rate at $2\frac{1}{2}$" from the Jominy bar quenched end is equivalent to that in the center of a still water quenched plate of **greater than 3-3/4" thickness.

*Substitution of equivalent plate thickness for distance from Jominy bar quenched end was accomplished by means of data and graphs reported by the Battelle Memorial Institute in the report "Correlation of Cooling Velocity of the Standard Jominy Hardenability Test with the Cooling Velocity Within the Cross Section of Plates" – John G. Kura and C. H. Lorig – 24 August 1942.

TABLE V

Brinell Hardness Surveys on Cross Sections of British Homogeneous and Face Hardened (Carburized) Plates

Homogeneous Plates

Plate No.	Measured Thickness	1/4" From Face A				Center of Section				1/4" From Face B
9	2.74"	293 293		302 293		302 293		302 293		302 293
50	3.10"	269 269	269 269		269 262	255 255	255 255		248 255	255 269
73	4.68"	285 277	277 269		269 269	277 269	262 269		277 269	277 277

Face Hardened (Carburized) Plates

Plate No.	Measured Thickness	Case Face	Center of Section	Midway Center and Core Face	1/4" From Core Face
14	1.92"	780,780	212	217	217
45	2.68"	780,780	207	217	217
48	4.42"	601,601,653	229	235	241

TABLE VI

Rockwell "C" Hardness Surveys Across Sections of British Face Hardened Plates

Plate No.	Measured Thickness	Hardness at 1/16" From Case Face	Depth of Case to Rc 50	Depth of Case to Rc 45	Depth of Case to Rc 40	Total Depth of Case	Core Hard-ness
14	1.92"	61.5	1/4"=.25"	5/16"=.31"	13/32"=.41"	7/8"=.88"	14.5/1
45	2.68"	62.5	3/8"=.38"	13/32"=.41"	9/16"=.56"	1-1/8"=1.13"	13/16.
48	4.42"	60.0	11/32"=.34"	1/2"=.50"	1-5/32"=1.16"	2-1/4"=2.25"	18/20.

TABLE VII

V-Notch Charpy Values of As-Received British

Homogeneous and Face Hardened (Carburized) Plates

(All specimens are transverse - i.e., their fractures are longitudinal, and notches are perpendicular to the plate faces.)

Location of Specimen*	+20°C. (Room Temp.) Ft. Lbs.	+20°C. (Room Temp.) Fracture**	-10°C. Ft. Lbs.	-10°C. Fracture**	-40°C. Ft. Lbs.	-40°C. Fracture**	-70°C. Ft. Lbs.	-70°C. Fracture**
Plate 9 (293/302 Brinell)								
Face B - Surface	26.4	F	22.2	Fc	20.5	Fc	13.1	Fc
Face A - Surface	25.8	F	23.7	Fc	19.6	Fc	15.3	Fc
Face B - Center	27.6	Fc	23.4	Fc	20.2	Fc	13.6	Fc
Face A - Center	26.2	Fc	22.6	Fc	19.3	Fc	14.7	Fc
Plate 50 (248/269 Brinell)								
Face B - Surface	37.3	F			34.1	F	25.0	Cdf
Face A - Surface	36.9	F	36.6	F	35.0	F	27.1	Cdf
Face B - Center	37.3	Cbf	35.8	Cbf	18.1	Cbf	15.7	Cbf
Face A - Center	36.6	F	35.8	F	34.2	F	24.6	Cdf
Plate 73 (262/285 Brinell)								
Face B - Surface	45.8	F			34.2	Cbf		
Face A - Surface	41.5	F			31.8	Cbf		
Face B - Center	31.1	Cbf			15.6	Cb		
Face A - Center	26.8	Cbf			13.9	Cb		
Plate 45 (207/217 Brinell)								
Face B - Center	55.1	F			36.4	Cbf		
Face B - Center	59.7	F			29.5	Cbf		
Face A - Center	54.9	F			32.9	Cbf		
Face A - Center	59.8	F			32.3	Cbf		

(Cont'd)

TABLE VII (Cont'd)

*See Figure 7

**Symbols denote descriptions of fractures, as follows:

- F – Fibrous
- Fc – Fibrous matrix with spots of crystallinity.
- Cdf – Dull crystalline patch surrounded by fibrous border.
- Cbf – Bright crystalline patch surrounded by fibrous border.
- Cb – Bright crystalline (complete).

NOTES: Charpy fractures of Plates 9 and 50 are somewhat "woody".
Charpy fractures of Plate 45 are very "woody". Crystallinity in the Charpy fractures of Plate 45 consists of large facets.

TABLE VIII

Temper Brittleness Susceptibilities of the British Homogeneous Plates and Face Hardened (Carburized) Plates

V-Notch Charpy Impact Tests at -40°C on Small Samples Quenched

in Oil and Then Either Water Quenched or Furnace Cooled from the Draw

Lower Austenitizing Temperatures						Higher Austenitizing Temperatures					
Water Quenched From Draw			Furnace Cooled From Draw			Water Quenched From Draw			Furnace Cooled From Draw		
** Rockwell C Hardness	*** Ft.Lbs.	**** Fracture	** Rockwell C Hardness	*** Ft.Lbs.	**** Fracture	** Rockwell C Hardness	*** Ft.Lbs.	**** Fracture	** Rockwell C Hardness	*** Ft.Lbs.	**** Fracture
Homogeneous Plates*											
Plate 9 (1540°F)						Plate 9 (1650°F)					
(24.5)	39.9	F	(25.5)	22.2	Fc	(26.5)	37.4	F	(25.5)	16.8	Fc
(26.0)	37.4	F	(26.5)	19.1	Fc	(26.0)	39.5	F	(26.5)	15.1	Fc
Plate 50 (1540°F)						Plate 50 (1650°F)					
(25.5)	39.1	F	(26.0)	21.5	Cbf	(26.0)	39.5	F	(25.0)	23.2	Cbf
(25.0)	37.0	F	(26.5)	20.1	Cbf	(25.5)	37.8	F	(25.0)	21.1	Cbf
Plate 73 (1615°F)**						Plate 73 (1675°F)					
(27.5)	54.6	F	(30.0)	29.5	Fc	(29.5)	47.5	F	(29.0)	26.9	Fc
(27.5)	55.5	F	(30.0)	25.8	Fc	(30.0)	43.6	F	(29.0)	26.5	Fc
Carburized Plates*											
Plate 14 (1650°F)						Plate 14 (1700°F)					
(28.5)	36.2	?	(29.0)	15.1	Cb	(32.5)	34.6	?	(31.5)	11.2	Cb
(28.5)	39.9	?	(28.5)	14.2	Cb	(30.5)	19.4	Cbf	(32.5)	9.7	Cb
Plate 45 (1650°F)						Plate 45 (1700°F)					
(30.5)	30.7	?	(29.5)	14.2	Cd	(31.0)	19.1	Cbf	(32.5)	8.6	Cb
(29.5)	32.6	?	(30.5)	13.8	Cd	(32.0)	16.8	Cbf	(33.5)	8.6	Cb

(Cont'd)

TABLE VIII (Cont'd)

Carburized Plates*

Lower Austenitizing Temperatures						Higher Austenitizing Temperatures					
Water Quenched From Draw			Furnace Cooled From Draw			Water Quenched From Draw			Furnace Cooled From Draw		
Rockwell C** Hardness	Ft.Lbs.***	Fracture****	Rockwell C** Hardness	Ft.Lbs.***	Fracture****	Rockwell C** Hardness	Ft.Lbs.***	Fracture****	Rockwell C** Hardness	Ft.Lbs.***	Fracture****
Plate 46 (1540°F)						Plate 46 (1675°F)					
(23.5)	58.6	F	(22.5)	5.8	Cd	(25.0)	55.9	F	(24.5)	1.8	Cd
(24.0)	55.5	F	(22.5)	5.6	Cd	(24.0)	54.1	F	(24.5)	1.8	Cd

*The largest of the samples was 2.3"x.70"x3.0". Samples were austenitized for four hours at the same temperatures used to determine Jominy hardenabilities (the temperature indicated above.) The draw cycle in each instance consisted of 4 hours at 1200°F.

**Hardness values are inclosed in parentheses for clarity in reading the table.

***All Charpy specimens except 73 (1615°F) are transverse - i.e., their fractures are longitudinal and notches are perpendicular to the plate faces.

****Symbols denote descriptions of fractures, as follows:
F - Fibrous Fc - Fibrous matrix with spots of crystallinity. Cbf - Bright crystalline patch surrounded by fibrous border. Cdf - Dull crystalline patch surrounded by fibrous border. Cb - Bright crystalline - (complete). Cd - Dull crystalline (complete). ?- Fracture could not be interpreted because of rust.

NOTE: Charpy fractures of Plates 9 and 50 are somewhat "woody" and Charpy fractures of Plates 14 and 45 are very "woody".

TABLE IX

Comparison Between As-Received -40°C V-Notch Charpy Values and -40°C Values Resulting From Redraw Plus Water Quench From the Redraw - British Homogeneous Face Hardened (Carburized) Plates

* Location of Specimen	As-Received ** Rockwell C Hardness	*** Ft.Lbs.	**** Fracture	Water Quenched from Redraw ** Rockwell C Hardness	*** Ft.Lbs.	**** Fracture
			Plate 9			
Face B - Surface	(31.5)	20.5	Fc	(31.0)	26.5	F
Face A - Surface	(30.0)	19.6	Fc	(31.5)	25.0	F
Face B - Center	(31.0)	20.2	Fc	(30.5)	25.4	F
Face A - Center	(30.5)	19.3	Fc	(31.0)	28.0	F
			Plate 50			
Face B - Surface	(25.0)	34.1	F	(25.0)	35.0	F
Face A - Surface	(25.5)	35.0	F	(26.5)	33.4	F
Face B - Center	(22.5)	18.1	Cbf	(24.5)	34.6	F
Face A - Center	(24.0)	34.2	F	(25.0)	34.6	F
			Plate 73			
Face B - Surface	(26.5)	34.2	Cbf	(27.5)	35.8	Cbf
Face A - Surface	(27.5)	31.8	Cbf	(29.5)	37.4	F
Face B - Center	(25.5)	15.6	Cb	(25.5)	11.4	Cb
Face A - Center	(24.5)	13.9	Cb	(26.0)	11.4	Cb
			Plate 45			
Face B - Center	(15.5)	36.4	Cbf	(14.5)	32.2	Cbf
Face B - Center	(15.5)	29.5	Cbf			
Face A - Center	(14.0)	32.9	Cbf	(15.0)	32.2	Cbf
Face A - Center	(15.0)	32.3	Cbf			

*See Figure 7

**Hardness values are inclosed in parentheses for clarity in reading the table.

***Sizes of the redrawn samples were thicknessx2.3"x.6". The draw cycles were as follows: Plate 9, 1125°F for 2½ hrs; Plate 50, 1150°F for 2½ hrs; Plate 73, 1150°F for 2½ hrs; and Plate 45, 1200°F for 2½ hrs.
All Charpy specimens are transverse - i.e., their fractures are longitudinal - and all notches are perpendicular to the plate faces.

****Symbols denote descriptions of fractures as follows:
F - Fibrous   Fc - Fibrous matrix with spots of crystallinity   Cbf - Bright crystalline patch surrounded by fibrous border   Cb - Bright crystalline - (complete)

NOTE: Charpy fractures of Plates 9 and 50 are somewhat "woody" and those of Plate 45 are very "woody".

TABLE X

Tensile Test Properties of British Homogeneous and Face Hardened (Carburized) Plates

Location of Specimen*	Direction of Specimen	Y.S. 0.1% Offset psi	T.S. psi	El.%	R.A.%	BHN Range
		Plate No. 9				
Face B - Surface	Long.	134,000	149,200	17.9	57.8	
Face A - Surface	"	129,000	146,000	17.9	59.2	
Face B - Center	"	130,000	147,400	18.6	59.9	293
Face A - Center	"	130,000	147,400	17.9	59.6	
Face B - Surface	Trans.	134,000	148,800	16.4	47.4	to
Face A - Surface	"	131,000	147,000	15.7	47.0	
Face B - Center	"	130,000	145,800	15.7	46.5	302
Face A - Center	"	131,000	146,200	15.7	44.5	
		Plate No. 50				
Face B - Surface	Long.	100,000	122,600	20.0	60.6	
Face A - Surface	"	116,000	133,400	20.7	62.7	
Face B - Center	"	102,000	123,800	20.7	63.4	248
Face A - Center	"	108,000	128,600	20.7	63.7	
Face B - Surface	Trans.	114,000	131,800	17.1	51.4	to
Face A - Surface	"	—	134,400	17.1	51.0	
Face B - Center	"	105,000	126,000	17.9	55.2	269
Face A - Center	"	113,000	131,200	17.1	52.1	
		Plate No. 73				
Face B - Surface	Long.	114,000	135,200	18.6	59.6	
Face A - Surface	"	122,000	140,200	17.9	58.9	262
Face B - Center	"	108,000	133,000	17.9	55.2	to
Face A - Center	"	114,000	133,200	18.6	56.3	283
		Plate No. 45				
Face B - Center	Trans.	69,500	108,000	23.6	57.0	207
Face B - Center	"	69,000	107,800	22.9	57.0	to
Face A - Center	"	71,500	107,000	22.9	60.5	217
Face A - Center	"	71,000	107,000	22.1	61.7	

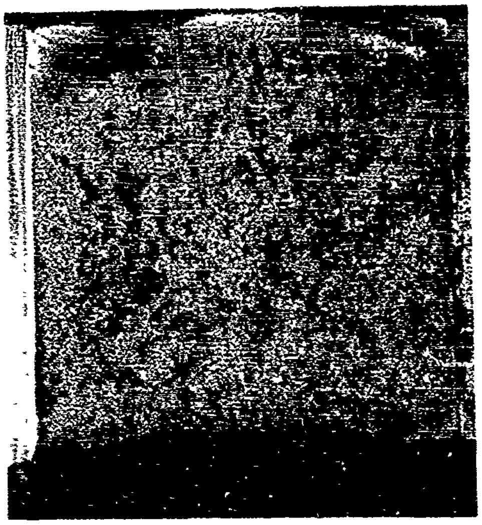
*See Figure 7.

TABLE XI

Summary of Measurements of Case Depths of British Face Hardened (Carburized) Plates

			Fracture Tests			Rockwell C Hardness Surveys				Macro-Etch
Plate No.	Measured Thickness	Annealed Samples (Depth of Carbon Penetration)	Outer Case	Inner Case	Total Depth	To Rc 50	To Rc 45	To Rc 40	Total Depth	Total Depth
14	1.92"	.46"	.30"	.30"	.60"	.25"	.31"	.41"	.88"	.90"
45	2.68"	.59"	.42"	.43"	.85"	.38"	.41"	.56"	1.13"	1.08"
48	4.42"	.44"	.40"	1.20"	1.60"	.34"	.50"	1.16"	2.25"	.30"

FACE B

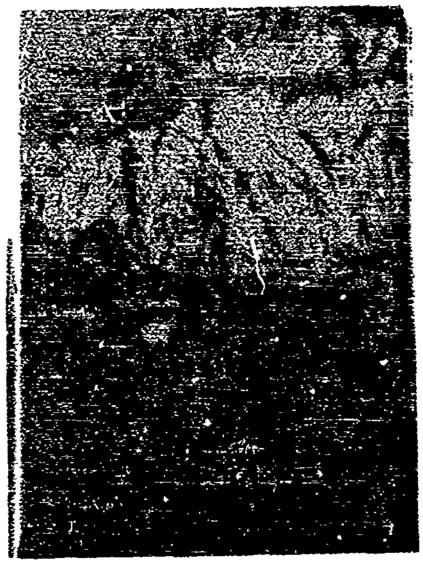


FACE A

E. S. CO. 70MM PLATE
NO. Q23003-3609

W.A. NO. 9

FACE B



FACE A

E. S. CO. 80MM PLATE
NO. Q22487-3350

W.A. NO. 50

FACE B

FACE A

FURTH BROWN LTD. 120MM PLATE
NO. 23873-A-1

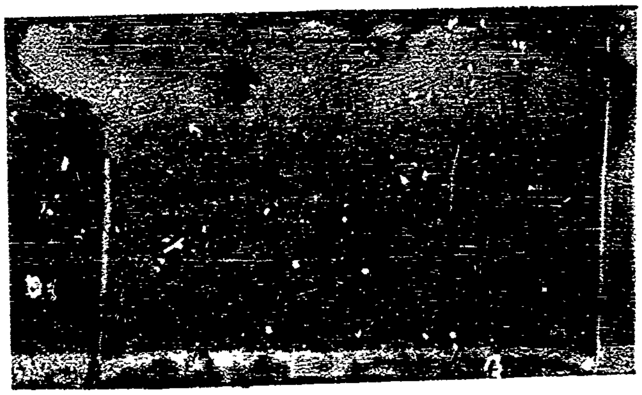
W.A. NO. 73

WATERTOWN ARSENAL

BRITISH HOMOGENEOUS ARMOR
MAG. X1 WTN.710-2281

FIGURE 1

FACE B



FACE A

BEARDMORE 50MM PLATE
NO. 3762B-2314T

W.A. NO. 14

FACE B

FACE A

BEARDMORE 70MM PLATE
NO. 6304-2945T

W.A. NO. 45

FACE B

FACE A

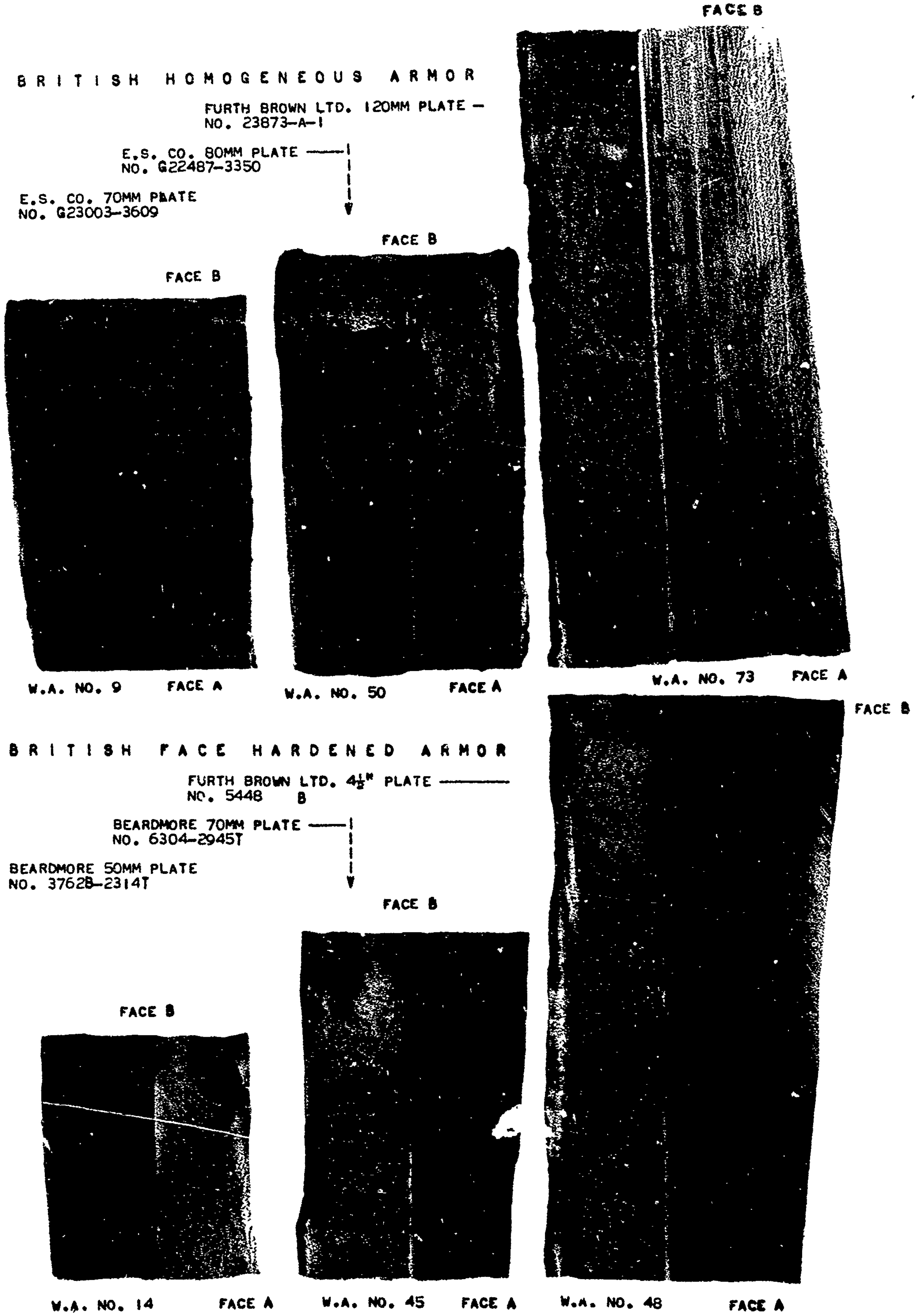
FURTH BROWN LTD. 4 1/2" PLATE
NO. 5448B

W.A. NO. 48

WATERTOWN ARSENAL

BRITISH FACE HARDENED ARMOR
MAG. X1 WTN.710-2282

FIGURE 2



WATERTOWN ARSENAL
BRITISH ARMOR PLATE - MAG. X1 - WTN.710-2331

FIGURE 3

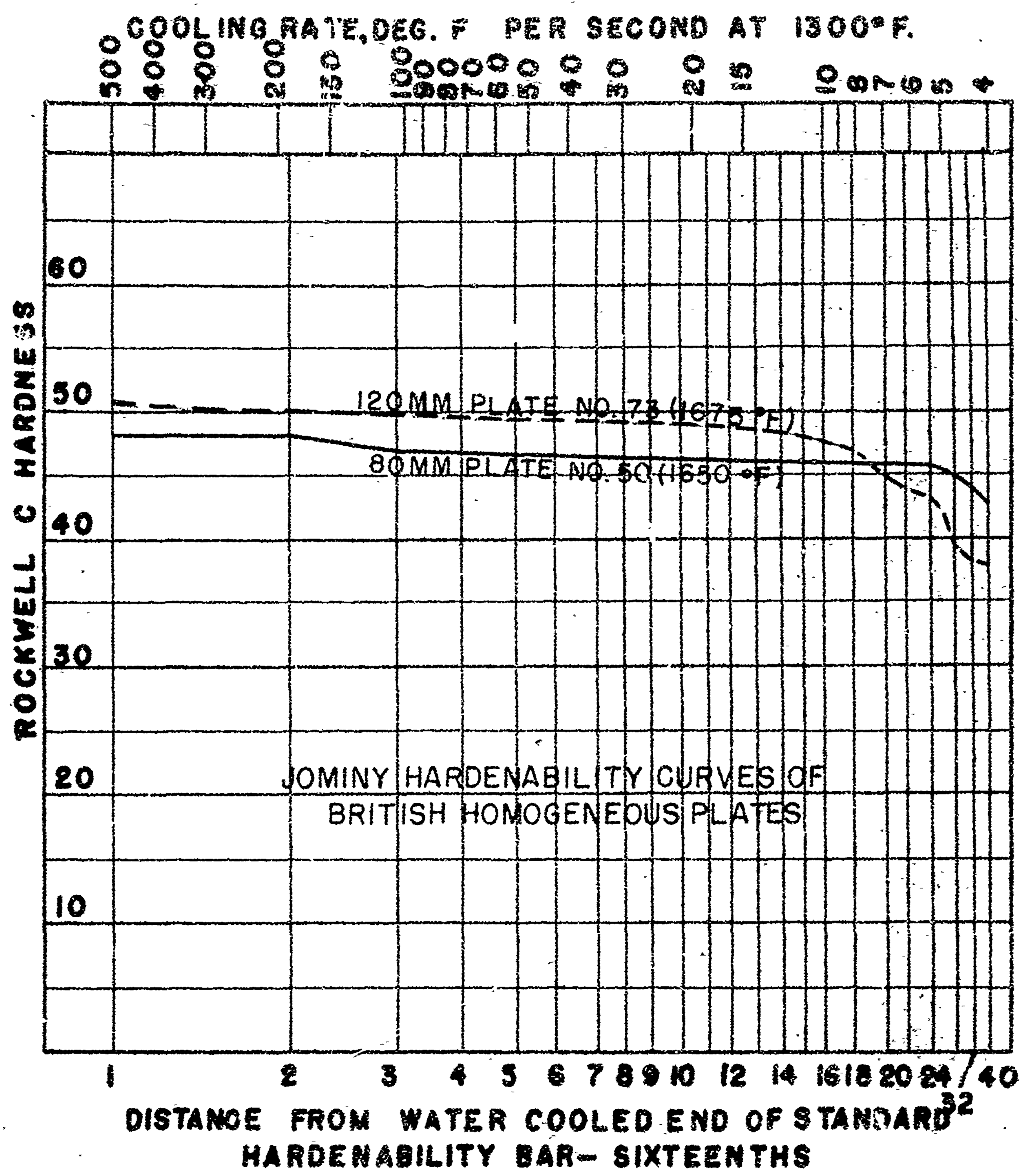


PLATE	HEAT												QUENCH		
NO.	NO.	C	MN	SI	S	P	NI	CR	MO	V	B	Al	TEMP	TIME	G.S.
50	——	.33	.61	.18	.033	.021	2.82	.76	.56	Tr.	.0008	.009	1650°F	4 hrs.	
NOTE: Curves for Plate 50 (1540°F) and 70mm Plate 9 (1650°F and 1540°F) are identical to this one.															
73	— — —	.33	.63	.23	.032	.031	.71	1.24	.46	Tr.	.0007	.007	1675°F	4 hrs.	
NOTE: The curve for Plate 73 (1615°F) is identical to this one.															

FIGURE 4

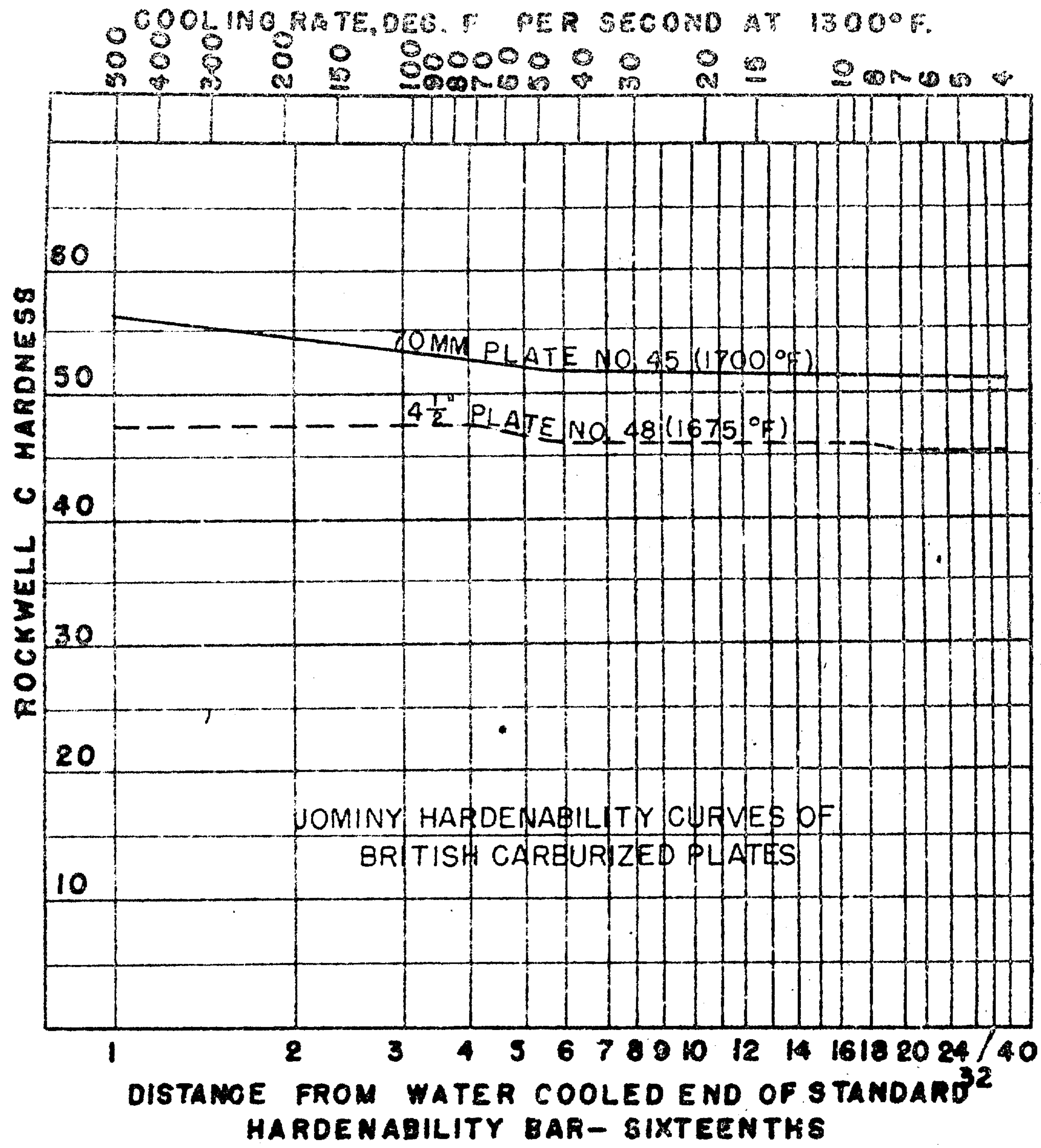


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	V	B	Al	QUENCH TEMP	QUENCH TIME	G.S.
45	———	.35	.50	.25	.031	.032	.46	3.13	.56	.26	.0008	.015	1700°F		
NOTE: Curves for Plate 45 (1650°F) and 50mm Plate 14 (1700°F and 1650°F) are almost identical to this one.															
48	— — —	.29	.46	.29	.030	.020	4.32	1.54	.12	.24	.0007	.01	1675°F		
NOTE: The curve for Plate 48 (1540°F) is almost identical to this one.															

FIGURE 5

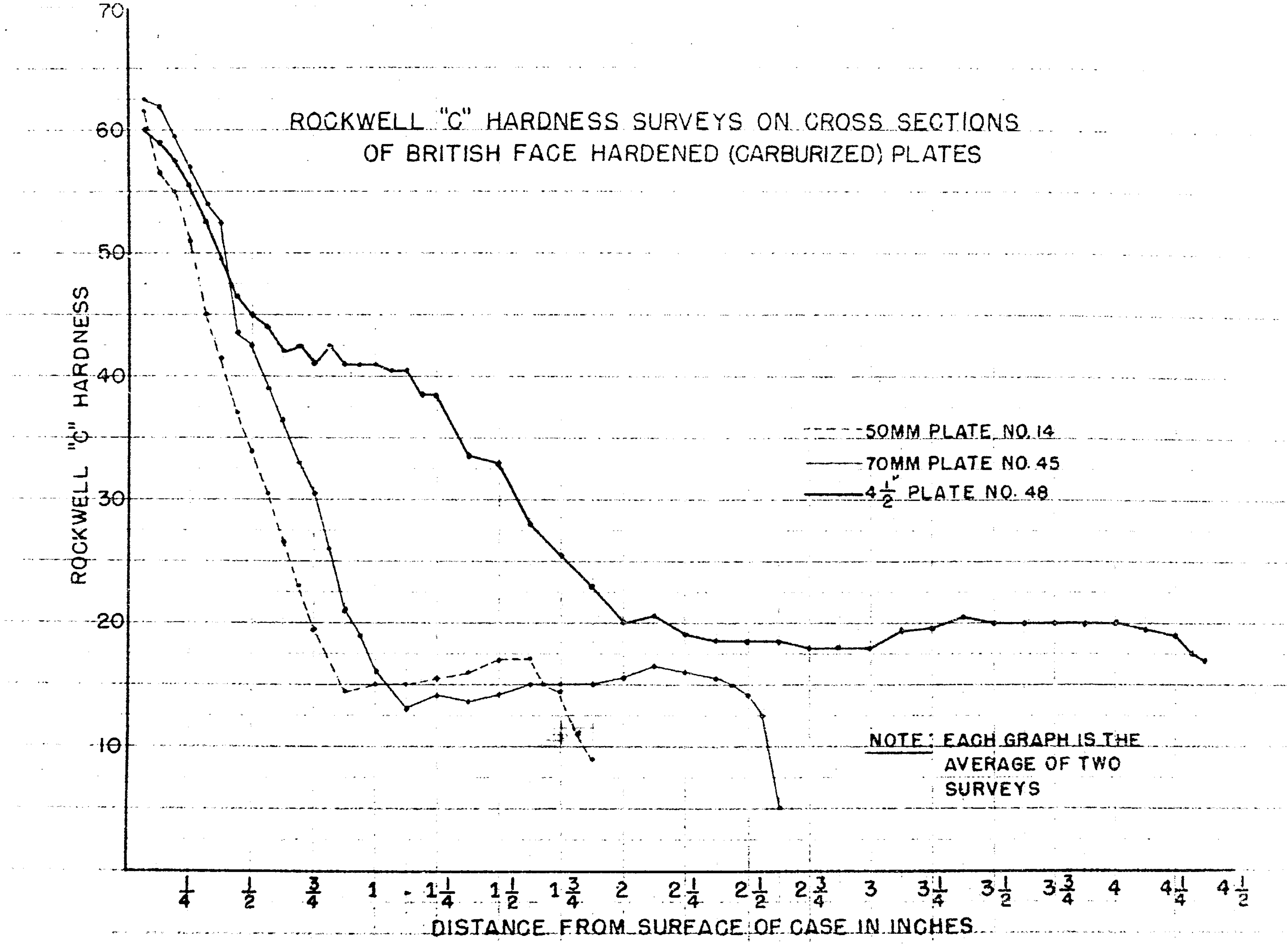

ROCKWELL "C" HARDNESS SURVEYS ON CROSS SECTIONS
OF BRITISH FACE HARDENED (CARBURIZED) PLATES
ROCKWELL "C" HARDNESS
70
60
50
40
30
20
10
50MM PLATE NO. 14
70MM PLATE NO. 45
4 1/2" PLATE NO. 48
NOTE: EACH GRAPH IS THE
AVERAGE OF TWO
SURVEYS
1/4
1/2
3/4
1
1 1/4
1 1/2
1 3/4
2
2 1/4
2 1/2
2 3/4
3
3 1/4
3 1/2
3 3/4
4
4 1/4
4 1/2
DISTANCE FROM SURFACE OF CASE IN INCHES

FIGURE 6

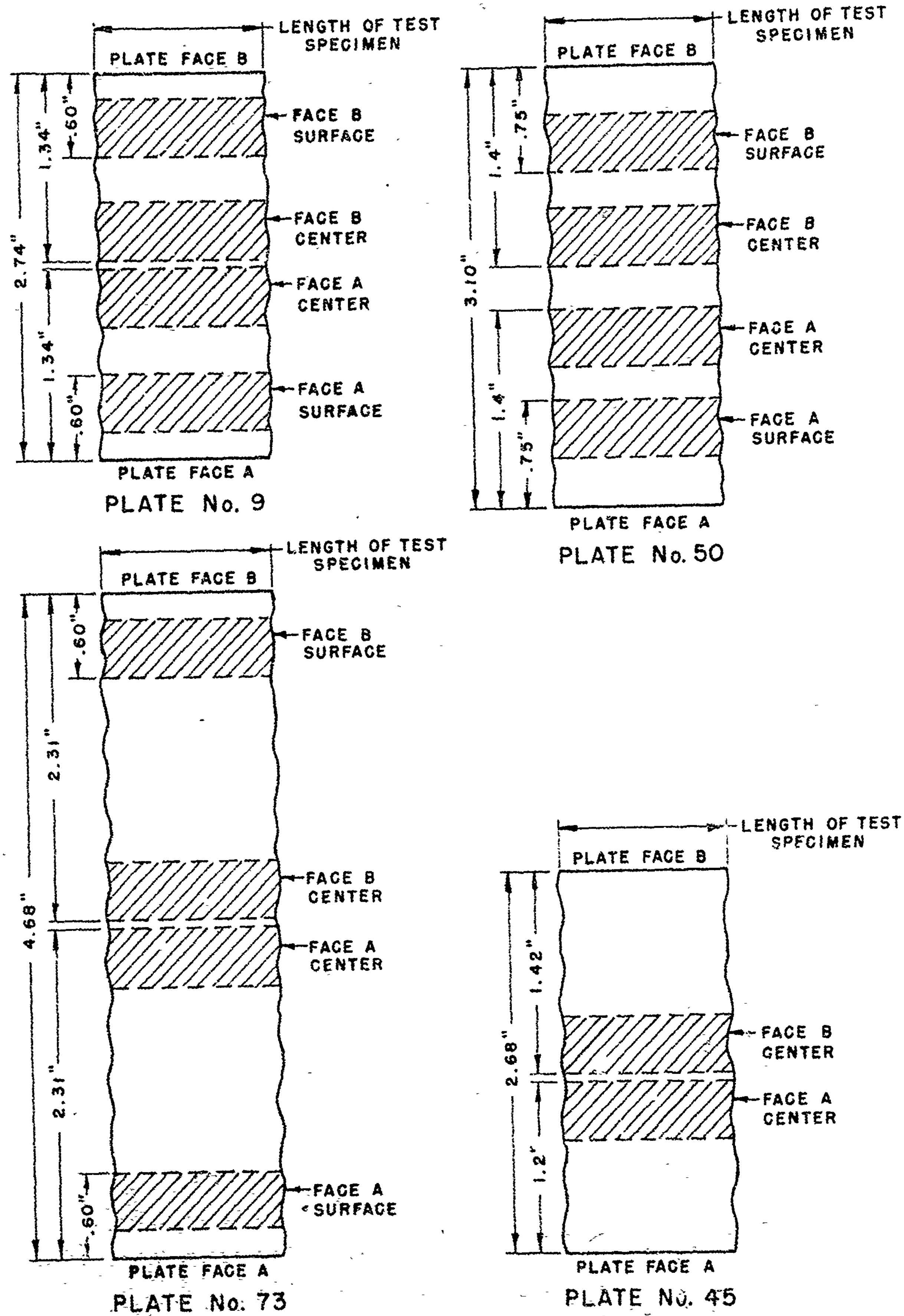
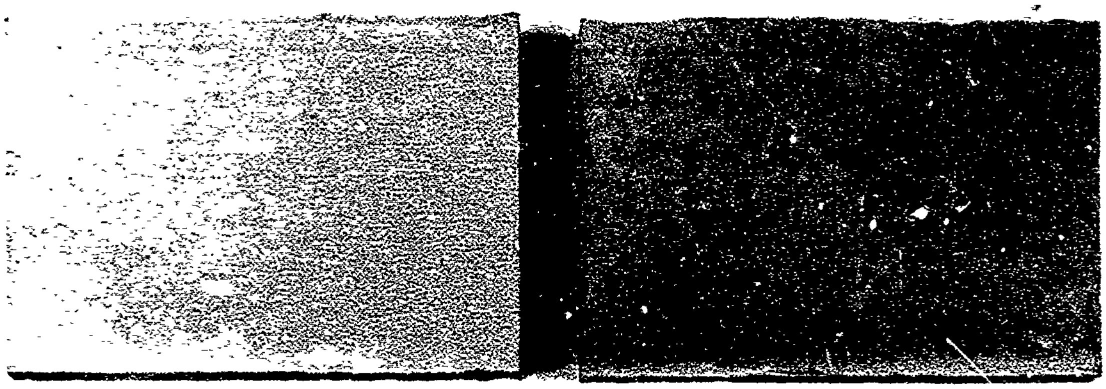


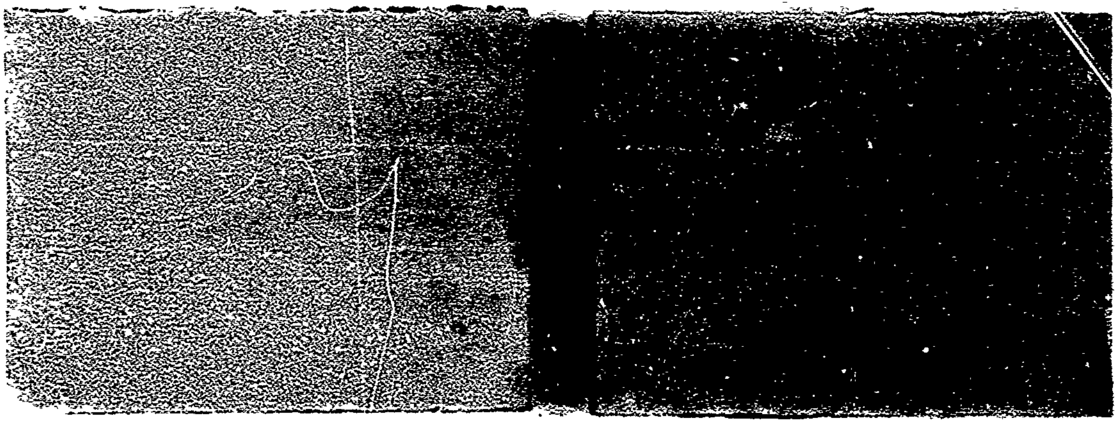
FIGURE 7

POSITIONS OF THE V-NOTCH CHARPY AND TENSILE TEST SPECIMENS WITHIN THE CROSS SECTIONS OF THE BRITISH HOMOGENEOUS AND CARBURIZED PLATES.

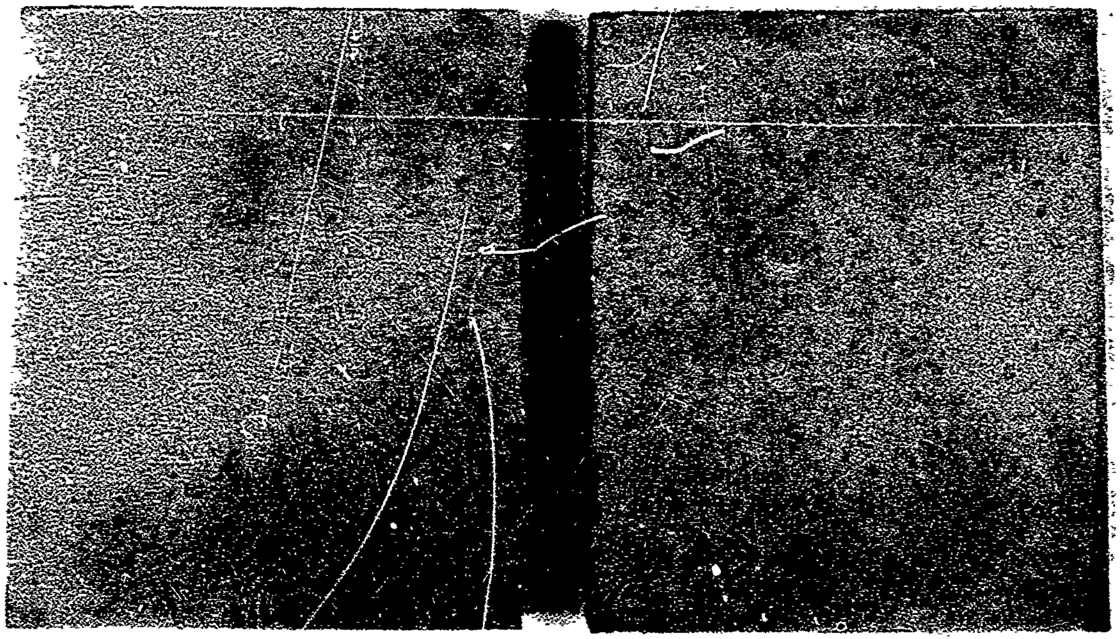
LONGITUDINAL TRANSVERSE



W.A. NO. 9 – E. S. CO 70MM PLATE NO. Q23003-3609



W.A. NO. 50 – E. S. CO 80MM PLATE NO. Q22487-3350



W.A. NO. 73 – FURTH BROWN LTD. 120MM PLATE NO. 23873-A-1

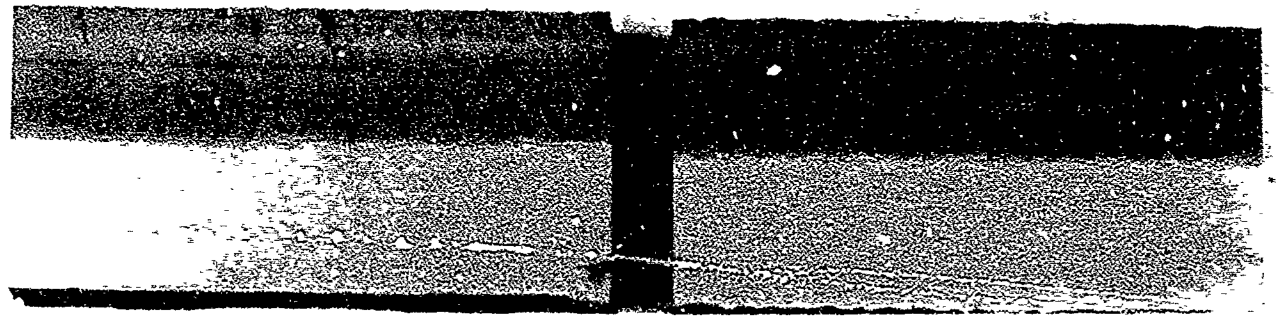
INCHES 1 2 3

ORDNANCE DEPT U.S.A.
WATERTOWN ARSENAL

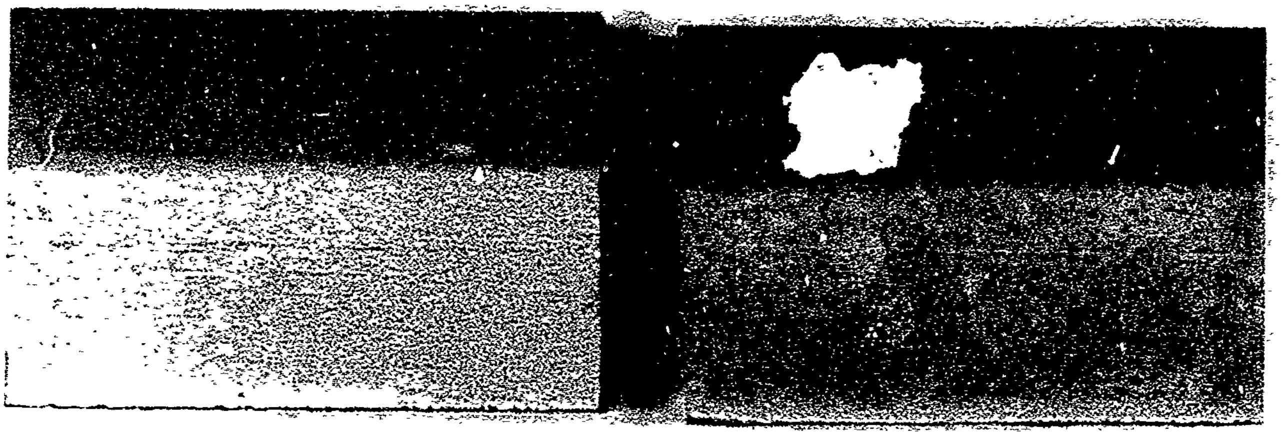
MACROETCHED SECTIONS OF BRITISH HOMOGENEOUS ARMOR

WTN.710-2317
FIGURE 8

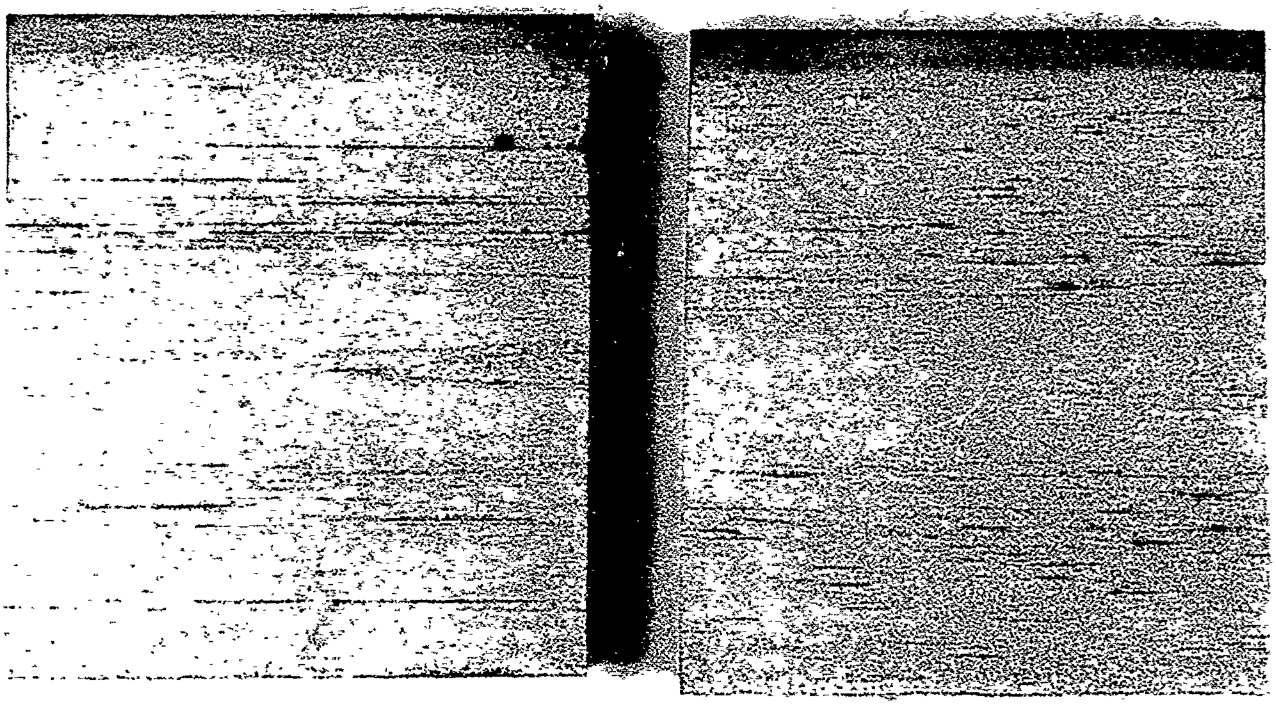
LONGITUDINAL TRANSVERSE



W.A. NO. 14 – BEARDMORE 50MM PLATE NO. 37628 – 2314T



W.A. NO. 45 – BEARDMORE 70MM PLATE NO. 6304 – 2945T



W.A. NO. 48 – FURTH BROWN LTD. $4\frac{1}{8}$" PLATE NO. 5448B

INCHES 1 2 3

ORDNANCE DEPT U.S.A.
WATERTOWN ARSENAL

WTN.710-2316

MACROETCHED SECTIONS OF BRITISH FACE HARDENED ARMOR

FIGURE 9

Typical Nonmetallic Inclusions in Homogeneous and Face Hardened Plates

Photomicrographs of Unetched Longitudinal Sections

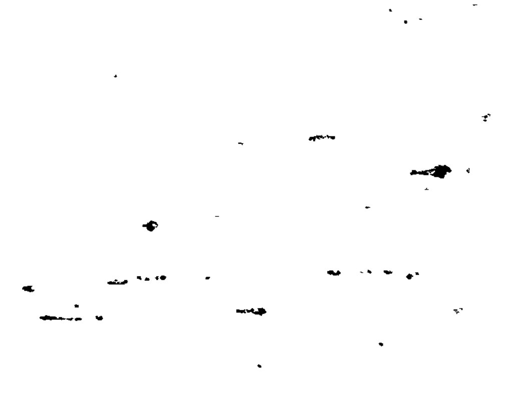


Plate 9 -A- X100
Many sulphides throughout the section but no long stringers.

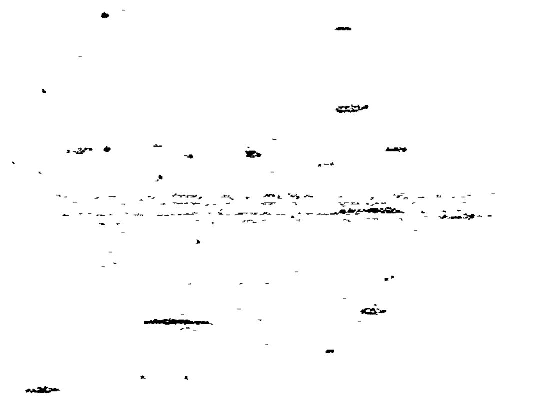


Plate 50 -B- X100
Many sulphides throughout the section but no long stringers.

Plate 73 -C- X100
Many sulphides throughout the section but no long stringers except once in entire section.

Plate 14 -D- X100
Typical inclusions are sulphides but quantity in specimen examined was small.

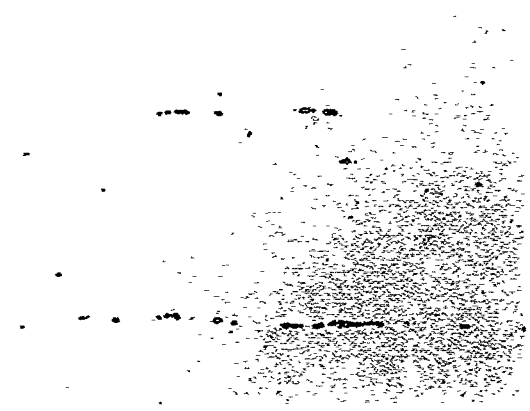


Plate 45 -E- X100
Many sulphides in short stringers throughout the section. Cause of extremely "woody" fracture.

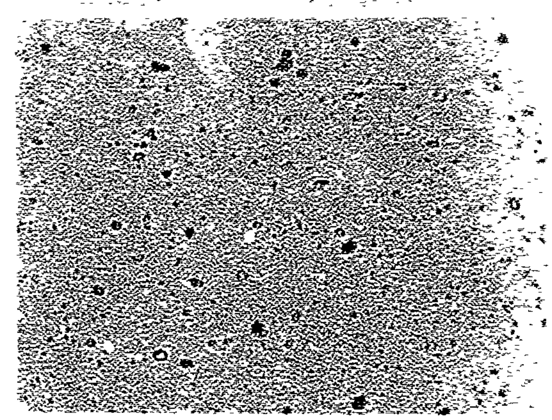


Plate 48 -F- X1000
Oval, light pink inclusions in long stringers throughout the section. Cause of poor steel soundness.

Microstructure of Plates 9 and 73

All photomicrographs Taken after Etching in 4% Picral

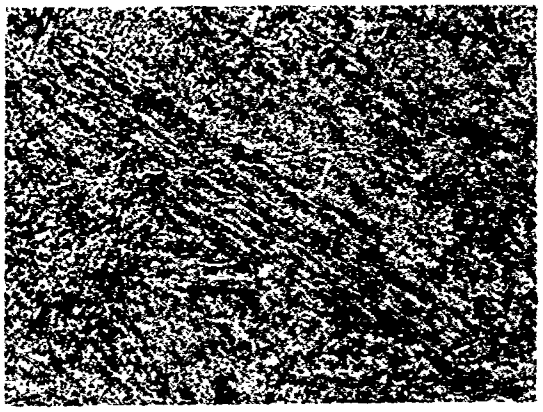


Plate 9 -A- X1000
Typical structure. Tempered martensite plus some tempered bainite. ASTM grain size No. 5.

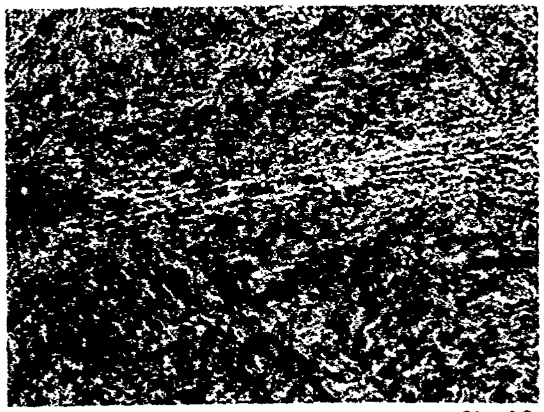


Plate 9 -B- X1000
Ferritic constituent found in small amounts chiefly at the center of the section.

Plate 73 -C- X200
Center of section. Pronounced banding. Light bands are rich in ferrite. ASTM grain size No. 5.

Plate 73 -D- X1000
Light bands in -C-. Only tempered non-martensitic austenite decomposition products are present.

Plate 73 -E- X200
.35" from Face B. Slight banding. Same grain size as in -C-.

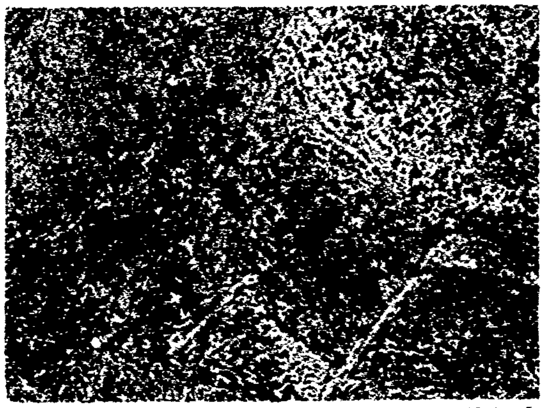
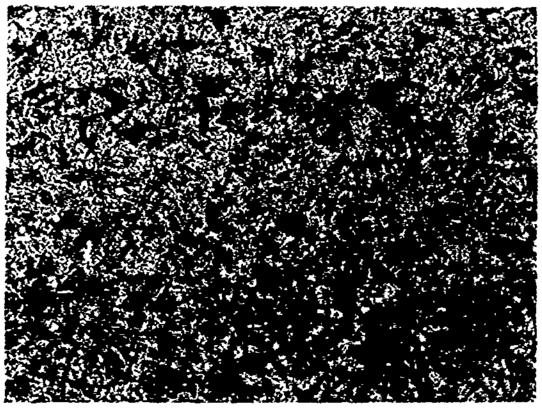


Plate 73 -F- X1000
-E- at X1000. Same type constituents as in -D- plus some tempered martensite. Much less ferrite than in -D-.

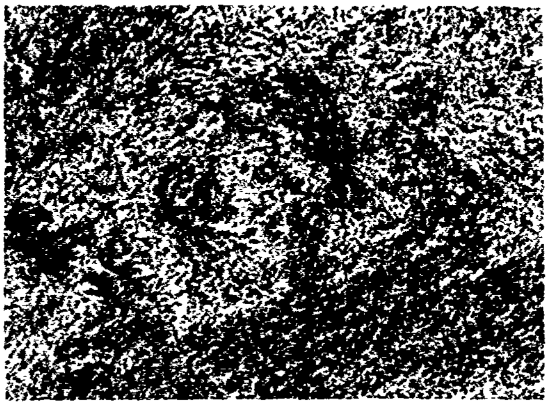
FIGURE 11

Microstructure of Plate 50

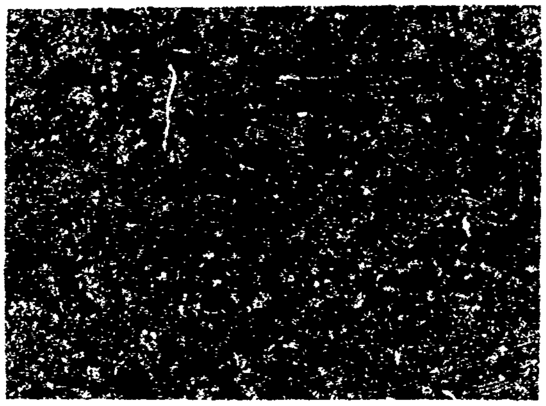
All Photomicrographs Taken after Etching in 4% Picral



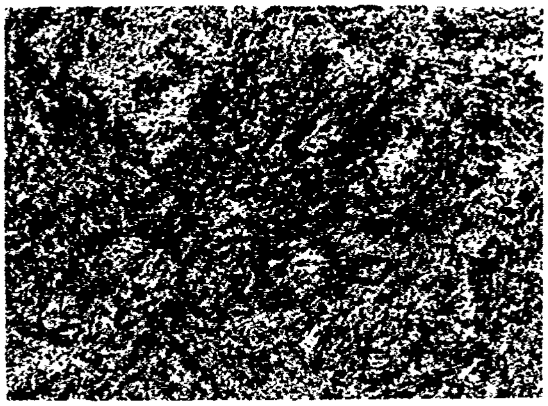
1.2" from Face B -A- X100
Bands and scattered needles of dark etching constituent in light etching matrix.



Same location as -A-. -B- X1000
Dark structure is tempered bainite. Light matrix is ferritic austenite decomposition product.

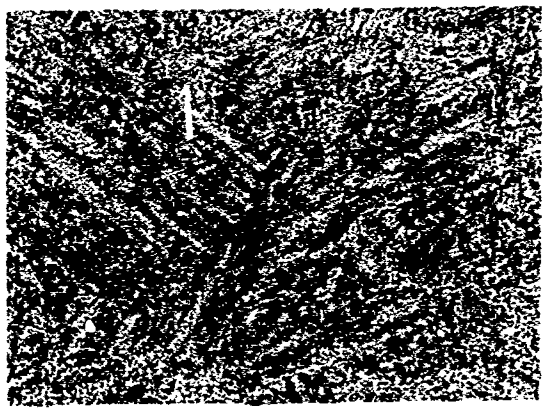


Center of section. -C- X100
Banded structure. Transition from ferritic constituent to bainite.



Same location as -C-. -D- X1000
Structure is chiefly tempered bainite. Remainder is the ferritic constituent.

.35" from Face A. -E- X100
Slight banding. Acicular structure. Grain size in whole of section is ASTM No. 6-7.



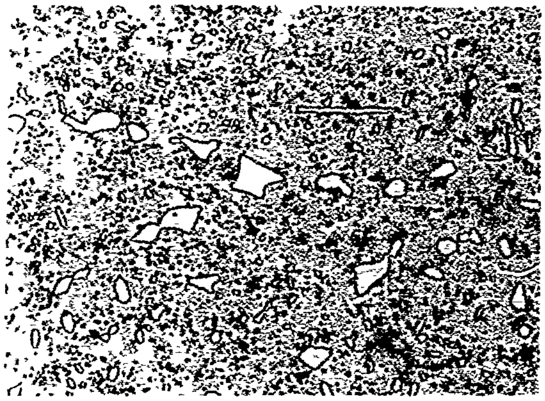
Same location as -E-. -F- X1000
Predominantly or entirely tempered martensite.

FIGURE 12

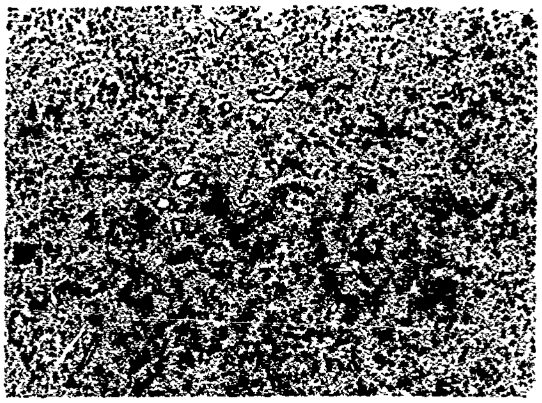
WTN.639-7733

Microstructure of Plate 14

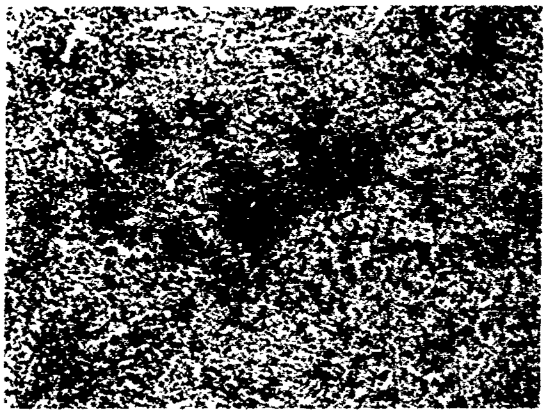
4% Picral Etch - All Photomicrographs X1000



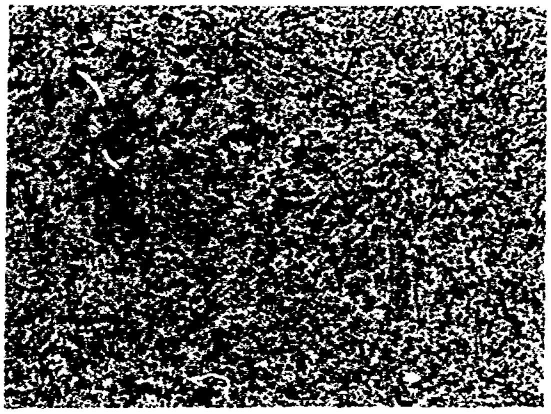
Case - .06" below surface. -A
Large carbides in light etching, structureless martensite.



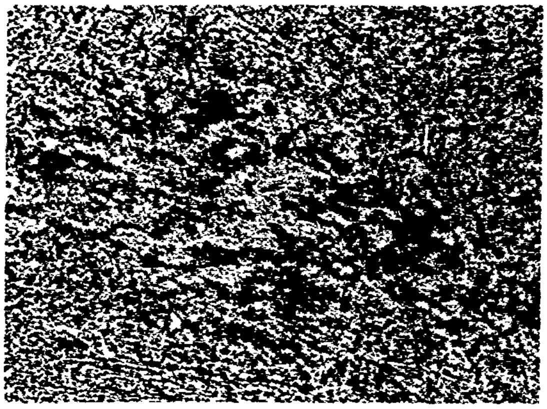
Case - .2" below surface. -B
Many smaller carbides in light etching, structureless martensite.



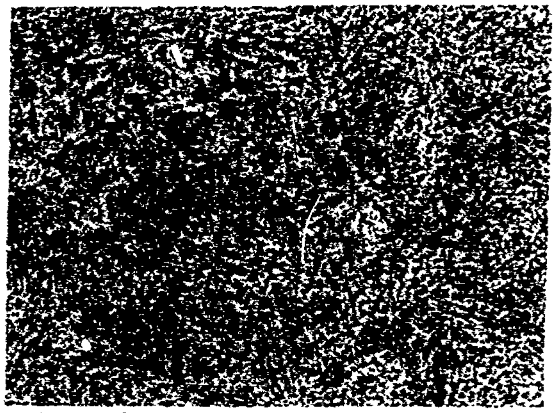
Transition zone - deep etch. -C
.6" below case surface. Martensite in highly tempered core structure.



Core - .95" below case surface. -D
Predominant structure. Tempered martensite and/or tempered bainite.



Core - .95" below case surface. -E
Peculiar structure detected throughout the core.

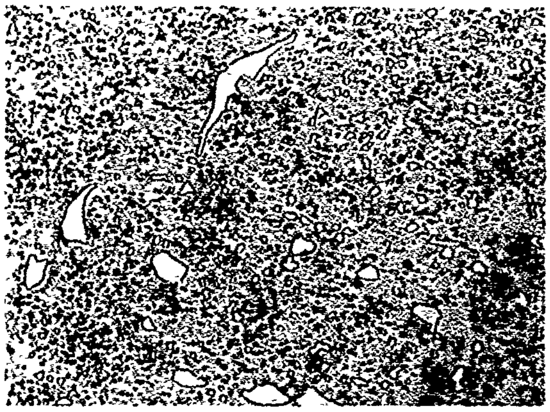


Core - .5" from back of plate. -F
Predominant structure. Tempered martensite and/or tempered bainite. Grain size is ASTM No. 5-6 in entire core.

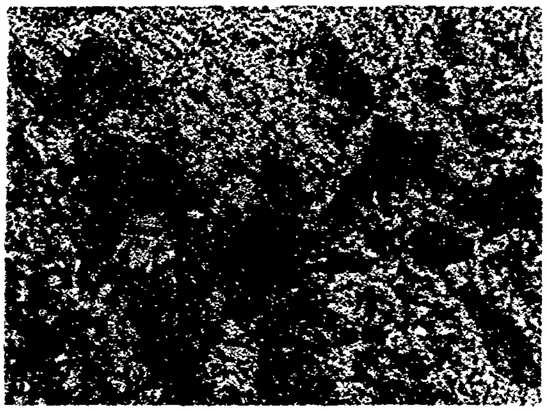
FIGURE 13

WTN.639-7734

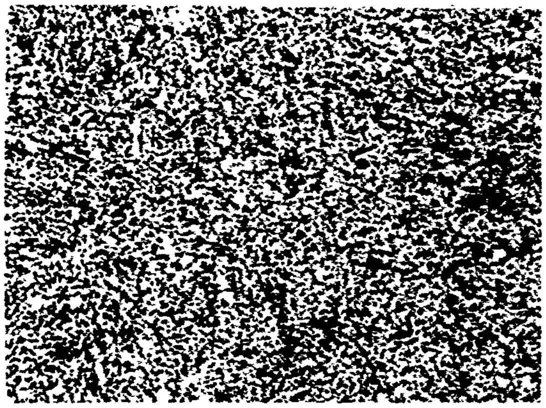
Microstructure of Plate 45



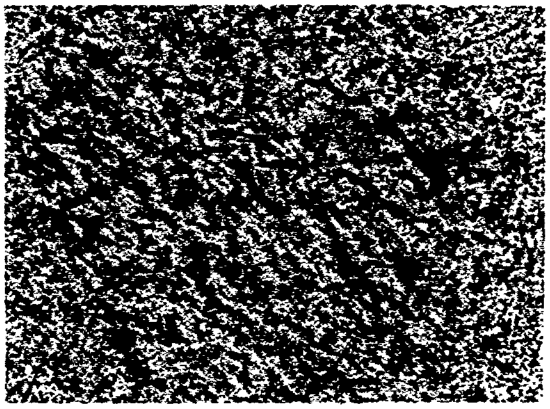
4% Picral Etch -A- X1000
Case - .06" below surface. Large carbides in light etching, structureless martensite.



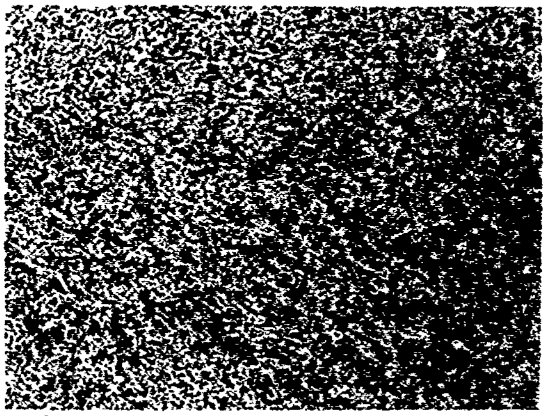
4% Picral Etch -B- X1000
Transition zone - .8" below case surface. Deep etch. Martensite in highly tempered core structure.



4% Picral Etch -C- X1000
Core - 1.3" below case face. Predominant structure. Tempered martensite and/or tempered bainite.



4% Picral Etch -D- X1000
Core - .5" from back surface of plate. Peculiar structure found throughout the core.

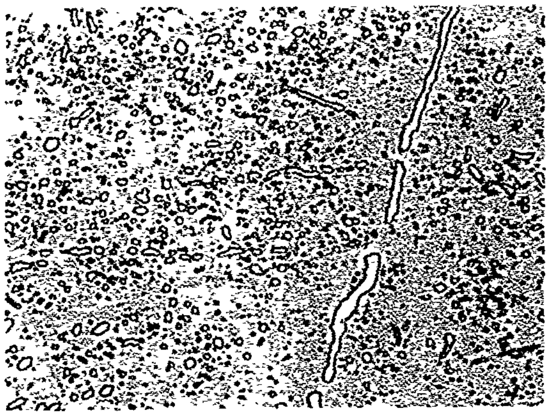


4% Picral Etch -E- X1000
Core - .5" from back of plate. Predominant structure. Tempered martensite and/or tempered bainite.

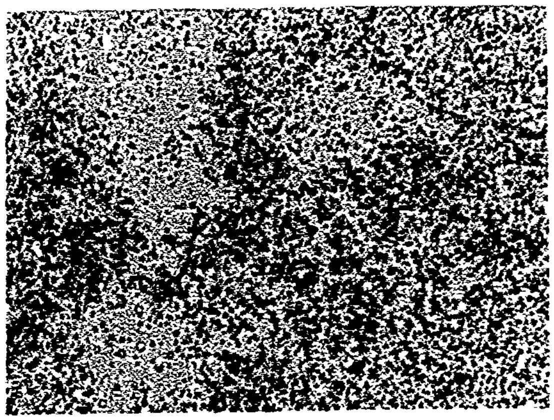
Villella's Reagent Etch -F- X100
Grain size of entire core - ASTM No. 1.

Microstructure of Plate 48

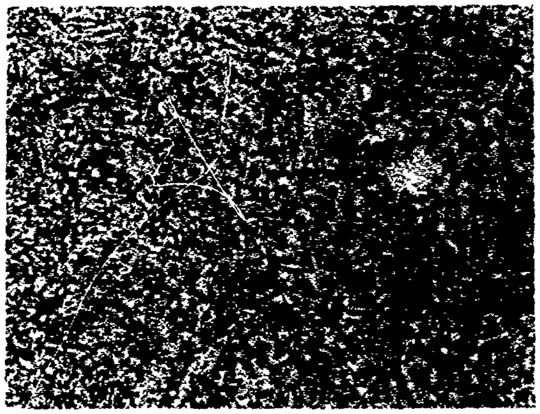
4% Picral Etch - All Photomicrographs X1000



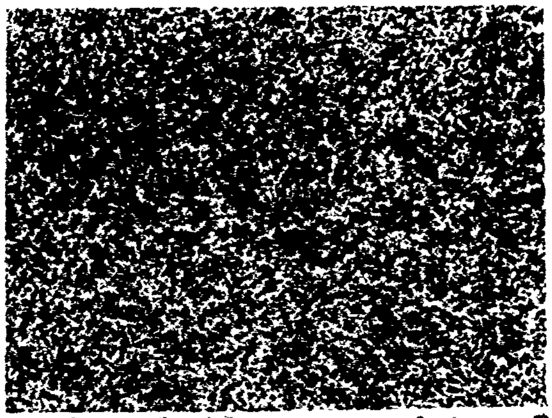
Case - .06" below surface. -A
Large carbides in light etching, structureless martensite.



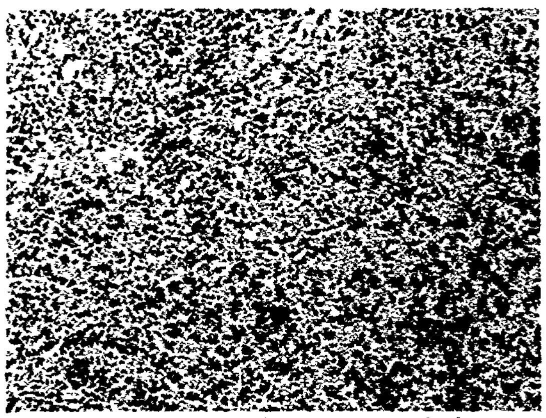
Case - .2" below surface. -B
Many smaller carbides in light etching, structureless martensite.



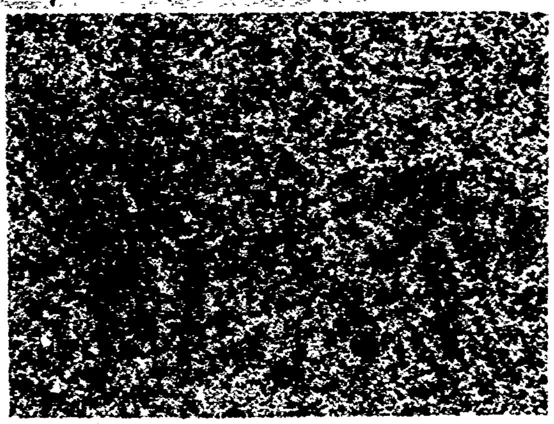
Transition zone - deep etch. -C
1.6" below case surface. Martensite in highly tempered core structure.



Core - 2.7" below case surface. -D
Structure of dark etching bands present here. Tempered martensite and/or tempered bainite.



Core - 2.7" below case surface. -E
Structure in the light etching bands present here. Tempered high temperature austenite transformation products.



Core - .5" from back of plate. -F
No banding. Structure resembles both -D- and -E-. Grain size in the entire core is ASTM No. 6-7.

APPENDIX A

Basic Correspondence

C O P Y

WAR DEPARTMENT
OFFICE OF THE CHIEF OF ORDNANCE
WASHINGTON

O.O. 400.112/10033(s)
SPOTB
Special Steel and Welding

6 November 1943

Subject: Metallurgical Examination of Armor and Projectiles Received from England for Comparative Tests with American Material

To: Commanding Officer
Watertown Arsenal
Watertown, Mass.

Attn: H. H. Zornig
Col., Ord. Dept.

1. An extensive comparative program is being fired at Aberdeen with American and British APC projectiles against both American and British armor plate.

2. The attached Chart I, dated 3 November 1943, outlines all materiel to be investigated.

3. It is requested that Watertown Arsenal conduct complete metallurgical examination on one projectile of each lot of projectiles received from England. It is further requested that complete metallurgical examination be conducted upon sections on each British plate.

4. Aberdeen Proving Ground will forward these samples and projectiles to his arsenal with a letter of transmittal as soon as practical after receipt of the materiel from England.

By Order of the Chief of Ordnance:

G. ELKINS KNABLE
Col., Ord. Dept.
Assistant

1 Incl.

cc: Director
The Proving Ground
Aberdeen Proving Ground, Md.

APPENDIX B

Properties of Typical Armor Plates
Used for Proof of Shot (by the British)

PROPERTIES OF TYPICAL ARMOR PLATES USED FOR PROOF OF SHOT

?	Mn	Cr	Ni	Mo	V	Test	Yld.	U/S	El.	R/A	Izod	Brinell	For Proof of	Result & C.V.
27	.36	1.82	3.58	.45	.02	1X	51.5	57.5	22	54	38/42	269	2 pdr.AP	2068 fs.
						2X	53	59	20	52	32/34	269		
15	.56	1.63	.46	.31	—	—	—	60.8	19.0	—	—	262/277	40mm.AP	1986 fs.
30	.51	3.02	.54	.53	.24	1X	38	49	26	63.7	59/58	230	2 pdr.APC BC	2047 fs.
						2X	39	50	24	61.5	56/56	235		
27	.26	1.77	3.74	.49	.02	1X	52	58.5	21	54	45/46	262	25 pdr.AP	1288 fs.
						2X	54	60	21	55	45/44	269		
028	.63	1.46	.65	.40	—	—	—	56.0	20	—	—	277/285	"	1284 fs.
026	.64	.63	2.55	.57	—	TL	52	60	21	57	—	273	6 pdr.AP	2025 fs.
035	.50	2.05	1.10	.51	Tr	2L	53.2	60	18	47.2	51/47	272	"	2063 fs.
030	.57	3.42	.38	.58	.24	1X	38	49	24	61.5	60/61	230	"	2024 fs.
						2X	37	49.5	24	63	61/61	223		
029	.65	.74	2.63	.59	—	A	60	67.5	17.0	41.9	—	304	6 pdr.APC BC	2300 fs.
						L	60	67.0	19.0	47.2	—	304		
030	.36	2.07	3.64	.43	.10	1X	47	56	21	57.2	47/47	258	17 pdr.AP	1959 fs.
						2X	43	52	25	63.7	53/52	248		
029	.42	1.56	3.50	—	.20	TL	46.6	53.2	22	59	—	240	17 pdr.APC	2253 fs.
						BX	44.8	51.8	23.5	59	—	235		
034	.64	1.4	.69	.39	—	TX	56.3	61.6	17.5	48	—	275	17 pdr.APC	2515 fs.
						BX	53.6	59.4	17.5	45	—	273		
033	.52	1.91	1.30	.45	.08	TX	59.6	64.0	18	50	—	290	3.7 AP	1918 fs.
						BX	58.4	63.0	18	52	—	286		

(signed) H. Oxford
for
A. D. A.
A. G. (Proof)
Ministry of Supply

14 February 1944

SECRET
Abstract
T.& M.T. Lib. Ref. AR2 4b

eputy Director, for Director of Tanks & M.T.
944.

Best Available Copy

APPENDIX C

Summary of British Secret Report
"Firing Trials on American Rolled Plates"
Dated 25th September, 1944

[redacted]
(This page is unclassified)

Summary of British Secret Report, "Firing Trials on American Rolled Plates", dated 25 September 1944 (WAL 710/717)

"This report covers the firing trials of 54 machineable rolled armour plates of current American manufacture in thicknesses ½" to 4" from the the three manufacturers: Great Lakes Steel Corporation, Carnegie-Illinois Steel Corporation and Jones and Laughlin Steel Corporation. (W.A. Note: The plate thicknesses were 14mm., 1", 1½", 2", 2½", and 4"). The object of the trials was to make a comparison between British and American armour plate in current production when tested under British conditions. (W.A. Note: The American plates arrived in Britain during the period January to July 1944. Arrangements were made in June 1943 to secure these plates.)

Whereas British machineable rolled armour is mainly of 1½% Cr.Mo. type material, two of the American makers use a Mn.(Ni.Cr.) Mo. type and the other maker uses a Si.Mn.(Cr.)Mo. type material.

The results of firing trials show that all the American plates meet the ballistic and overmatching requirements of Specifications I.T. 100E (tentative) and I.T. 80E with the exception of some of the 4" plates which were appreciably softer than the British plates of the same thickness, and failed I.T. 80E by a few feet/sec.

In America it has apparently been decided, as in Britain, that the best hardness for plates of varying thicknesses decreases as the thickness increases. In general, the American plates are treated to the same hardness level and are of similar ballistic quality to the British plates. Exceptions to this general conclusion are that some of the American 1" plates are harder and have higher ballistic limits than the British plates, and the 4" American plates are softer and have lower ballistic limits than the British plates."

[redacted]
(This page is unclassified)