WATERTOWN ARSENAL LABORATORY

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ARMOR AND WELDING

Metallurgical Examination of Armor and Welded Joints from German PzKw IV Tank, Model GF-2

OBJECT

To carry out metallurgical examination of six armor sections, two complete weld joints, four broken weld joints and three attachment welds from the subject tank.

SUMMARY OF RESULTS

Armor

1. Cross-rolled armor having the following characteristics was employed:

Description	Thickness inches	Thickness mm.	Brinell Hardness Face	Brinell Hardness Core	Type Composition C	Mn	Si	Cr	Mo
Hull Roof Plate	0.48	12.2	415	415	.42	.79	1.48	1.26	.03
Right Sponson Side Plate	1.20	30.5	578	352	.42	.48	.47	2.66	.22
Hull Right Side Plate	1.22	30.9	601	379	.42	.45	.30	2.43	.19
Turret Rear Plate	1.23	31.3	601	331	.40	.45	.44	2.51	.16
Driver's Front Plate	2.04	51.8	601	367	.42	.43	.37	2.51	.25
Final Drive Front Plate	1.99	50.4	578	331	.39	.42	.33	2.32	.20

Hull roof plate was homogeneous. All other plates were face hardened, apparently by the flame-hardening process, to a depth of .12 to .21 inches.

2. With the exception of the driver's front plate and the final drive front plate which showed excessive centerline segregation, all plates were of good quality steel.

3. Large grain size in core of the heavy section plates, inhomogeneity of microstructure, and presence of high temperature transformation products indicate improper heat treatment, possibly by a controlled air cooling directly from the finish rolling operation followed by a tempering treatment. These characteristics were reflected by presence of crystallinity in fibre fracture test and low notched bar impact values.

4. Experimental reheat-treatments indicated that satisfactory notched bar impact properties were obtained only after full quench and tempering to a hardness level of 240 Brinell which is consistent with American experience for good quality homogeneous armor of this thickness.

Welding and Joint Design

1. The design of principal joints is characterized by grooves machined in the heavy armor sections to give a fitted or mortised joint which is in compression on impact from the direction of principal ballistic attack. These joints are held by an outside weld placed in a V and having a depth of penetration of about three-quarters of thickness of lighter section armor plate, and on inside fillet weld with very slight penetration into the base metal sections.

2. Inside fillet welds and body of outside welds were made with an electrode type which gave austenitic deposits containing approximately .13% C, 1.10% Mn, 6.3/9.1% Ni, 13.5/15.9% Cr, and .50/1.75% Mo. The crown deposits of the outside welds were made with a hard-facing type electrode which gave deposits containing approximately .75% C, 1.75% Mn, 4.5% Ni, 1.80/3.80% Cr and .15/.30% W.

3. All welds appear to have been deposited, without preheat, on armor in final heat-treated condition. Hard facing type deposits did not develop high hardness due to interfusion and dilution with underlying austenitic weld metal. Extensive base metal cracks were present in the heavy base metal sections of two complete weld joint samples and failure of three broken weld joint samples was almost entirely along base metal crack systems.

4. A fourth broken weld joint sample appeared to represent an angle joint made by butting plate edges and holding with two shallow penetration weld deposits This weld joint failed by shearing through weld deposits.

5. Three small attachments were fastened to inside surface of the tank armor by single pass austenitic deposits.

6. Apparently the Germans rely principally on joint design for structural and ballistic stability of the tank since the welding of the high carbon, high hardenability, armor plate without special precautions to prevent base metal cracking during welding and with shallow penetration weld deposits produces welds with very poor resistance to ballistic shock or fatigue service.

Economic Considerations

Equally satisfactory armor could be produced in these thicknesses with considerably less total alloy content. It is obvious that, at the time these steels were made, there was no shortage of chromium in Germany. However, the low molybdenum contents possibly indicate a shortage of this element. With respect to the welding electrodes employed, it is concluded that a shortage of nickel existed since it is well known that the modified austenitic nickel-chromium electrodes employed in this country are, in general, more satisfactory. The inferior heat treatment of the armor undoubtedly reflects a shortage of facilities. On the other hand, the machined and mortised joints used in fabrication would imply a plentiful supply of machine tools of the types required, since, by adopting full-penetration joints it would be possible to eliminate a large percentage of the edge machining of the armor

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INTRODUCTION

In accordance with instructions of the Office, Chief of Ordnance[1], eight samples representing the main types of basic armor and welded joints from a German PzKw IV tank, Model F-2, were submitted to this arsenal for metallurgical examination[2].

Previous investigations, by this laboratory, of German tank armor and weldments have been summarized in two recent reports:

> "Armor - Metallurgical Examination of Eleven Sections of Enemy Armor, Including Homogeneous, Flame-Hardened, Carburized and Welded Components," Watertown Arsenal Laboratory Report No. 710/539, 25 October 1943, and
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> "Armor and Welding - Metallurgical Examination of Armor and Welded Joints from German PzKw VI Tank," Watertown Arsenal Laboratory Report No. WAL 710/542, 23 February 1944.

MATERIALS AND TEST PROCEDURE

The eight samples submitted for examination were found to be made up of the following components:

Sample No.	Armor	Size	Welds
1	Right Sponson Side Plate	1.20 x 6-1/2 x 12	Broken weld joint along one 6-1/2 in. edge of armor sample 1/4 x 3/4 mild steel strap tack welded to inside face of armor sample.
2	Hull Right Side Plate	1.22 x 5-1/4 x 11	One 1-1/4 in. dia. x 1/2 in. and one 3/4 x 3/4 x 1/4 mild steel bosses were welded to inside face of armor sample.
3	Hull Roof Plate	.48 x 5-1/2 x 13-1/4	Broken through mortised weld joint along one 5-1/2 in. edge of armor sample.
4	Hull Roof Plate	.48 x 3 x 4	Mortised joint held by two weld deposits.
	Right Sponson Side Plate	1.20 x 4-1/2 x 4	
5	Turret Rear Plate	1.23 x 5-1/2 x 12-1/2	None.

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[1] O.O. 400.112/4800, Wtn. 350.05/530 (See Appendix A)

[2] A.P.G. J863/947, Wtn. 386.3/128 (r) (See Appendix A)

Sample No.	Armor	Size	Welds
6	Driver's Front Plate	2.04 x 6 x 12-1/2	Broken weld joint along one 12-1/2 in. edge of armor sample
7	Hull Roof Plate	.48 x 2-3/4 x 4	Mortised joint held by two weld deposits.
	Driver's Front Plate	2.04 x 3-1/2 x 4	
8	Final Drive Front Plate	1.99 x 6-1/2 x 11½	Broken weld joint along one 11-1/2 in. edge

Armor

The following samples, representing each type of armor component, were examined:

Sample No.	Thickness inches	Thickness mm.	Description
1A	1.20	30.5	Right sponson side plate
2A	1.22	30.9	Hull right side plate
3A	0.48	12.2	Hull roof plate
5A	1.23	31.3	Turret rear plate
6A	2.04	51.8	Driver's front plate
8A	1.99	50.4	Final drive front plate

Metallurgical examination included chemical analyses; analysis of the paint on two representative samples; Jominy hardenability tests; Brinell, Vickers-Brinell, and Rockwell "C" hardness surveys; tensile tests; fracture tests for steel soundness and fibre characteristics; V-notch Charpy impact tests; macroscopic and microscopic examination.

Tensile tests were made on .357" diameter bars taken in the longitudinal and transverse directions. The V-notch Charpy bars were machined from the transverse sections of the plate with the notch milled in the bar perpendicular to the surface of the plate. All test bars were machined from the midwall sections of the plate, that is, halfway between the surface and center.

Fracture tests for fibre were made on sections of the plate of approximately the same size as described above after notching to a square cross section. Fracture tests for steel soundness were made on properly notched sections about 6 inches long and 3 inches wide after tempering at 1200° F. in order to attain the specified hardness of about 300 Brinell for this test.

Reheat treatments were conducted on 3 x 3-inch sections cut from samples Nos. 3A, 5A, and 8A, in order to determine the V-notch impact properties at several hardness levels.

Welding and Joint Design

Transverse cross sections were obtained for macroscopic examination through each of the weld joints, attachment welds, and broken welds on all samples. Chips for chemical analyses were machined from attachment weld of steel strap on Sample No. 1, deposits of broken weld joints on Samples Nos. 3 and 6, and various deposits of complete joint Samples Nos. 4 and 7. Vickers-Brinell hardness surveys were made on cross sections through attachment weld of Sample No. 2, and complete weld joint Samples Nos. 4 and 7. These same cross sections were then repolished and suitably etched for microscopic examination of weld metal deposits and adjacent weld heat-affected zones.

DATA AND DISCUSSION

ARMOR

1. Chemical Analyses

a. Armor Compositions

The chemical analyses of the six samples are included in Table I. Two basic type analyses were used:

(1) Cr-Si

The component of this type analysis consisted of the .48 inch thick homogeneous hull roof plate. The composition is of the following:

C	Mn	Si	S	P	Ni	Cr	Mo	V	B	Cu	Al
.42	.79	1.48	.016	.007	.12	1.26	.03	Trace	.0009	.14	.02

(2) Cr-Mo

The five components of this type analysis consist of three face-hardened plates, 1.20 - 1.23 inches in thickness and two face-hardened plates, 1.99 - 2.04 inches in thickness which fall within the following limits of chemistry:

C	Mn	Si	S	P	Ni	Cr
.39/.42	.42/.48	.33/.47	.015/.026	.009/.015	.28/.64	2.32/2.66

Mo	V	B	Cu	Al
.19/.25	Trace	.0006/.0014	.09/.12	.015/.02

The carbon content of the plates tested was relatively lower than in some of the earlier German armor examined[1]. Also, the absence of vanadium in the steels is noteworthy.

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[1] WAL Report No. 710/485, "Armor Plate - Metallurgical Examination of German Armor from a PzKw III Tank," 15 March 1943, and
WAL Report No. 710/539. "Armor - Metallurgical Examination of Eleven Sections of Enemy Armor, Including Homogeneous, Flame-Hardened, Carburized, and Welded Components," 25 October 1943.

The nickel content reported is probably the result of scrap additions, while a trace of boron was evident in the samples. It is believed, however, that these steels were not treated with boron due to the low percentage of this element present.

b. Carbon Content of the Hard Face

The results of the carbon determinations made on samples taken from the face of plates 5A and 8A after carful annealing are given below:

Sample No.	Thickness inches	mm.	Description	Analysis of Carbon Face	Core (see Table I)
5A	1.23	31.3	Turret Rear Plate	0.39	.40
8A	1.99	50.4	Final Drive Front Plate	0.39	.39

It is evident that the plates examined were not carburized.

c. Spectrographic Analysis of Paint

Samples of the greenish-gray paint were removed from the inside surfaces of plates Nos. 3A and 8A, analyzed spectrographically, and found to be a titanium-base paint similar to that used in this country.

2. Hardenability

A Jominy bar machined from the 2-inch thick Final Drive Front Plate was austenitized for 3 hours at 1675° F. and end-quenched by the standard practice. The hardenability curve (see Figure 1) shows adequate hardenability for this 2-inch thick section when properly quenched, and more than adequate hardenability for the lighter gauge sections which were of the same type alloy composition.

3. Hardness Surveys

Brinell, Vickers-Brinell, and Rockwell "C" hardness surveys were made on the surfaces and cross sections of each armor sample. The results of the hardness tests are summarised in Table II, and a graphical presentation of Vickers-Brinell hardness surveys is shown in Figure 2.

Generally speaking, the uniformity of hardness of the face-hardened surface was very good, although some soft areas were observed in the Vickers-Brinell survey on the hardened face of the 2-inch thick Driver's Front Plate (see Figure 2). The hardness pattern from case to core, with a slight tempering effect at junction of case and core, is typical of that found in flame-hardened plate. Slight irregularities noted in the Vickers-Brinell hardness of the core are probably due to metallic segregation (see discussion of microstructure).

4. Tensile Tests

The results of the tensile tests are reported in Table III. No marked directional properties are evident in the tensile test data, indicating that the armor plate was cross rolled The reduction of area and elongation are slightly low for the yield strength involved in the case of the Hull Roof Plate, while the values obtained in the Turret Rear Plate and Final Drive Front Plate are consistent with the observed strength and hardness.

5. Fracture Tests

The results of the fracture tests for steel quality and fibre characteristics are given in Table IV.

The results of the fracture tests for steel soundness indicate that the 2-inch thick samples, Nos. 6A and 8A, contained pronounced centerline segregations, whereas the lighter gauge plates were relatively free from laminations.

The fracture tests for fibre characteristics revealed either total or partial crystallinity in all plates, indicating that the armor was not thoroughly quenched out to a martensitic structure before tempering.[1] The fractures of the hardened surfaces of each plate were in all cases silky in appearance. This type of fracture is generally encountered with steels of high hardness.

In an attempt to reproduce the heat treatment given the subject plates, sections 3" x 3" of Samples Nos. 1A and 8A were heated to 1675° F. for 2 hours, air cooled and drawn at 1050° F. for 2 hours, followed by air cooling and fractured for fibre. These samples had crystalline fractures at a Brinell hardness of 352 and 375 respectively. Although the crystallinity noted in these samples was slightly coarser than that found in the German armor, it is believed that the tank armor was given this type of heat treatment.

6. V-Notch Charpy Impact Tests

Results of V-notch Charpy impact tests determined on representative samples as received and after reheat treatments are given in Table V.

Impact values were low and correlate fairly well with the fractures obtained in the fibre tests. The Cr-Si plate, No. 3A, was tempered to a Brinell hardness of 285 and also requenched and drawn to a Brinell hardness of 331 in an attempt to improve its impact properties. As shown in Table V, these heat treatments increased the V-notch Charpy impact values 29 to 17 ft /lbs. respectively at +70° F., whereas at -40° F. very little improvement in the impact resistance was evident. Recent experiments indicate that silicon has a deleterious effect on impact resistance and tends to promote crystallinity in certain types of heat-treated alloy steels.

Samples Nos. 5A and 8A, Cr-Mo analysis, exhibited poor impact properties at 331 Brinell hardness. After redrawing to 285 - 302 Brinell hardness, the impact values were improved, but after requenching and drawing to 241 Brinell hardness, the impact values were very much increased both at +70° F. and -40° F. On the other hand, this composition when requenched

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[1] WAL Report No. 710/530, "Armor - Metallurgical Investigation of the Fiber Fracture Test Used by the Union Steel Castings Division of Blaw-Knox Company," 28 July 1943.

and drawn to the original high hardness level of 352 Brinell hardness failed to retain its high impact properties at +70° F. and at -40° F.

The results of these tests indicate that the Cr-Mo analysis has excellent notched bar impact properties when quenched and tempered to a hardness in the vicinity of 240 Brinell, which is consistent with American experience for good quality homogeneous armor of this thickness.

7. Macroscopic Examination

Macroetched cross sections from each armor sample are shown in Figures 3 and 4. Macrostructure reveals presence of finely divided nonmetallic inclusions throughout all plates except for Hull Roof Plate (see discussion of microstructure). Excessive centerline segregation is shown in Driver's Front Plate and Final Drive Front Plate.

8. Microscopic Examination

Figures 5 through 9 illustrate microstructures of the various armor components. The .48 inch thick homogeneous Cr-Si type analysis Hull Roof Plate was free from pronounced segregations of nonmetallic inclusions (Figure 5). The microstructure of this plate consisted of tempered coarse martensite associated with tempered upper Bainite (Figure 7). The Cr-Mo type analysis used for the heavier gage face-hardened plates contained complex friable oxides which were found distributed throughout the sections of the plates and also segregated in the central areas of the sections (Figure 5). Plate No. 8A contained a pronounced segregation of nonmetallics near the surface. In plate 1A, a few fine elongated nonmetallics of the silicate type were evident (Figure 5).

The hard cases of Plates Nos. 1A, 2A, 5A, and 8A, were typical of flame-hardened plates. The outer cases consisted of untempered white martensite and the center cases showed the presence of a martensitic matrix with remnants of the prior tempered structures. The microstructures of the junction of case and core revealed the presence of fine carbides in tempered martensite. The microstructure of the steel bases in all cases consisted of coarse tempered martensite and tempered upper bainite (Figures 6, 7 and 8). This microstructure of the tempered base steel is associated with crystalline fractures and poor V-notch impact properties discussed previously.

Pronounced banding of metallic segregation indicated by the Oberhoffer etch was revealed in the center sections of Plates Nos. 2A, 5A, and 8A, while the areas near the surfaces of these plates were relatively free from this type of segregation (Figure 7). The grain size of the steel bases varied from ASTM No. 1 to No. 8, while the hard faces of the samples had a grain size of ASTM No. 7 to No. 8 (Figure 9).

A summary of the thicknesses of the cases and grain size of the plates is given below:

	Average Thickness of Case					ASTM Grain Size No.	
Sample No.	Thickness inches	mm.	Outer Zone of Martensite inches	Zone of Incomplete Austenitization inches	Total Hardened Case inches	Face	Core
1A	1.20	30.5	.06	.06	.12	7 - 8	4 - 6
2A	1.22	30.9	.11	.10	.20	7 - 8	8
3A	0.48	12.2	--	--	--	---	4 - 7
5A	1.23	31.3	.05	.10	.15	8	7 - 8
6A	2.04	51.8	.11	.11	.21	7	1 - 5
8A	1.99	50.4	.04	.08	.12	8	3 - 7

The thickness of case as determined under the microscope and that determined by the hardness surveys shown in Figure 2 vary slightly in some cases. This is probably due to the irregularities in case thickness on the several samples examined.

9. General Considerations (Armor)

The Cr-Si type analysis used for the light gage homogeneous Hull Roof Top was improperly heat treated as shown by microstructure containing high temperature transformation products and having coarse austenitic grain size. At the hardness employed, approximately 50 points Brinell higher than American practice, impact characteristics were poor.

The Cr-Mo type analysis possessed adequate hardenability for the 2-inch thick plate and more than adequate hardenability for the lighter gages, but optimum properties were not obtained by the treatment employed. An attempt was made to reconstruct the heat treatment of the Cr-Mo steels at this arsenal, the results of which indicate that these plates were normalized and annealed previously to face hardening, probably by the flame-hardening process. In some cases, these plates were heated well into the grain coarsening temperature range prior to hardening. This suggests the possibility that the plates may have been hardened by a controlled air cooling directly from the finish rolling operation.

The hardness of the core of the 2-inch thick face-hardened plates is somewhat higher than that of good quality carburized American armor of the same thickness, although the hardness of the steel base of the 1.2-inch thick plate is not considered excessive.

Flame hardening as applied to the 1.2-inch and 2-inch thick plates may offer a slight increase in penetration resistance, but due to the improper heat treatment given the base plates, it is believed that the face-hardened plates would behave unsatisfactorily under the attack of over-matching projectiles.

Generally speaking, the quality of the steel examined was inferior to the early types of German armor tested, a factor which may also contribute to low impact values at high hardnesses.

WELDING AND JOINT DESIGN

1. Visual Examination

The surface appearance of the welds, after removal of a heavy coat of paint, was rought and there was severe undercutting of armor plate at inside weld deposits - evidence of inexperience or carelessness on the part of the welder. The outside deposits of the two joint samples appear to have been welded in the flat position, the inside deposits in the horizontal fillet position, with the heavy section in the vertical plane.

A crack was visible at surface of heavy base metal section parallel and immediately adjacent to the outer weld deposit of Sample No. 7.

2. Chemical Analyses

Results of chemical analyses of samples machined from weld deposits are given in Table VI.

Two types of electrodes evidently were used. Inside fillet welds and body of outside weld deposits of the joint samples, as well as attachment welds, were made with an electrode which gave austenitic deposits containing approximately .12/.14% C, 1.01/1.20% Mn, .39% Si, .020% S, .020% P, 6.36/9.07% Ni, 13.51/15.93% Cr, and .51/1.77% Mo. The crown deposits of the outside welds of joint samples were made with a hard-facing type electrode which gave deposits containing approximately .73/.81% C, 1.61/2.02% Mn, .26% Si, .016% S, 0.31% P, 4.37/4.99% Ni, 1.79/3.77% Cr, .30/.54% Mo, and .17/.28% V. Insufficient size of weld samples prevented complete analyses of all of the weld deposits and it is possible that various modifications of electrodes were used to obtain the two type analyses; however, the percentage variations for each type are not greater than would be expected for a type electrode since considerable dilution of the weld deposits results from interfusion of the molten filler metal with base metals and previous weld metal deposits.

3. Hardness Surveys

Results of Vickers-Brinell hardness surveys of weld deposits and weld heat-affected zones of base metals are summarized in Table VII.

Hardness of austenitic weld metal ranges from 218 to 242 standard Brinell* for attachment welds and root and body of outside weld deposits of joint samples, and as high as 300 Brinell at the root of inside deposits where the carbon pickup from the armor plate was high.

The hardness of the crown deposit of the outside weld of joint samples Nos. 4 and 7 were respectively 298 - 389 and 232 - 272 Brinell. Since the chemical analysis indicates that a hard-facing type of electrode was used for these deposits, the relatively low range of hardness actually attained in the latter deposit is surprising.

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* See Note, Table VII.

Maximum heat-affected zone hardnesses approach the full martensitic hardness of the .40% carbon armor plate. At the outer edge of the heat-affected zone is a band which has been tempered by the welding heat to a lower hardness than the base metal.

4. Macroexamination

Figures 10 through 14 are photographs of macroetched sections through each of the weld joints, broken welds, and attachment welds of the various samples.

Complete weld joints of samples Nos. 4 and 7 and broken weld joints of samples Nos. 1, 3, and 6, were each prepared by machining a groove in the heavy armor section to give a fitted or mortised joint which is in compression on impact from the direction of principal ballistic attack.

The outside deposits were placed in a V machined to give an included angle of approximately 60° and a depth of penetration of about three-quarters of thickness of lighter section armor plate. The inside deposits were fillet welds made without bevelling the plate and with very slight penetration into the base metal sections.

The outside welds were made up of multiple overlapping beads, austenitic for the root and body, and two layers of dark etching hard-facing weld metal analysis in crown of samples Nos. 3 and 4, one layer in crown of sample No. 7. Inside weld is a multiple bead fillet in samples Nos. 1, 3, and 4, a single bead fillet in samples Nos. 6 and 7.

Photomacrographs of samples Nos. 4 and 7 show base metal cracks in heavy base metal sections. The severity of these cracks is strikingly illustrated by the fact that failure of broken weld joints, samples Nos. 1, 3, and 6, was almost entirely along these crack systems.

The broken weld of sample No. 8 apparently represents a joint made by grinding edge of plate flat and butting another plate against it at an angle to be held by the two shallow penetration weld deposits. This weld joint has failed by shearing through weld metal. The trace of heat-affected zone along top edge of photomicrograph indicates flame cutting prior to heat treatment and grinding.

Attachment welds on samples Nos. 1 and 2 represent respectively: (1) a mild steel strap tack welded by single pass deposits with austenitic electrode to inside of right sponson side plate; and (2) a round boss welded with a single continuous pass of an austenitic electrode and a square boss tack welded with single pass austenitic deposits to inside face of Hull Right Side Plate.

All welds appear to have been deposited, without preheat, on armor in the final heat-treated condition.

4. Microexamination

Figure 14 shows microstructures at junction of hard-facing crown, austenitic body weld deposit and base metal of joint samples Nos. 4 and 7, and junction of base metal, austenitic deposit and mild steel attachment (1-1/4 dia. boss, Sample No. 2). Upper picture shows a small fusion zone crack. Diamond shaped marks are Vickers-Brinell impressions and afford comparison of heat-affected zone and austenitic weld metal hardnesses.

Upper photomicrograph of Figure 15 shows microstructure of hard-facing weld metal deposit of crown of Sample No. 4 to consist of martensite needles in background of austenite. Hardness of deposit varies with amount of martensite present, and low hardness of crown deposit of Sample No. 7 is due to dilution of this single layer deposit with metal from previous austenitic passes resulting in high proportion of retained austenite.

Middle photomicrograph of same figure shows structure of austenitic weld metal in location where carbides have been precipitated at grain boundaries by heat of subsequent weld metal passes.

Lower photomicrograph of this figure shows structure of inside weld where carbon pickup from plate has resulted in precipitation of intermediate transformation temperature carbides.

Most of the heat-affected zone cracking observed in these specimens is of the type illustrated in a previous report on German armor and welding[1]. The cracks are believed to have occurred while the metal was at a relatively high temperature and under stresses due to thermal expansion resulting in plastic deformation or "upsetting" and followed by thermal contraction against the restraint of adjacent unheated metal sections.

Heat-affected zone microstructures vary from a coarse-grained martensite near the fusion line to a fine-grained martensite at greater distances from the fusion zone and finally there is a tempered zone where carbides of original plate structure have been coarsened. Usual recrystallizing and retempering effects of multiple pass welding are seen.

5. General Considerations (Welding)

These samples indicate continued use of the German practice of machining grooves in heavy armor sections to obtain mortised joints. This structural design places less importance on quality of joints than conventional American practice, but the combination of shallow penetration weld deposits and a welding procedure which causes extensive base metal cracking produces a weld joint which has very poor resistance to ballistic shock or fatigue service.

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[1] WAL Report No. 710/542, "Armor and Welding - Metallurgical Examination of Armor and Welded Joints from German PzKw VI Tank," 23 February 1944.

The relatively high carbon armor plate heat treated to hardnesses of 331 to 415 Brinell is very susceptible to base metal cracking. Rewelding experiments on armor from a previously examined German PzKw VI tank indicated that a preheat of 300° F. was required to prevent base metal cracking when welding with commercial American austenitic electrodes.

The use of a hard-facing type electrode for crown of outside welds is apparently intended to confer resistance to ballistic penetration. The location of the weld and the low degree of hardness actually attained in the weld metal make questionable both the necessity and the effectiveness of this practice.

TABLE I

Chemical Analyses of Samples from German PzKw IV Tank, Model GF-2

Sample No.	Thickness Inches	Description					Chemical Analysis							
			C	Mn	Si	S	P	Ni	Cr	Mo	V	B	Cu	Al
1A	1.20	Right Sponson Side Plate	.42	.48	.47	.018	.009	.58	2.66	.22	Trace	.0009	.11	.015
2A	1.22	Hull Right Side Plate	.42	.45	.30	.015	.012	.54	2.43	.19	"	.0014	.09	.015
3A	0.48	Hull Roof Plate	.42	.79	1.48	.016	.007	.12	1.26	.03	"	.0009	.14	.02
5A	1.23	Turret Rear Plate	.40	.45	.44	.020	.015	.28	2.51	.16	"	.0016	.10	.02
6A	2.04	Driver's Front Plate	.42	.43	.37	.026	.013	.32	2.51	.25	"	.0006	.12	.02
8A	1.99	Final Drive Front Plate	.39	.42	.33	.015	.011	.36	2.32	.20	"	.0006	.12	.015

TABLE II

Hardness Surveys of Samples from German PzKw IV Tank, Model GF-2

Sample No.	Description	Thickness Inches	Brinell Hardness Face	Brinell Hardness Core	Vickers-Brinell Hardness Face	Vickers-Brinell Hardness Core	Rockwell "C" Hardness Face	Rockwell "C" Hardness Core
1A	Right Sponson Side Plate	1.20	578	352	599/613	354/380	53.5/55.0	36.5/37.5
2A	Hull Right Side Plate	1.22	601	379	606/642	363/397	54.5/55.0	38.5/40.0
3A	Hull Roof Plate	0.48	415	415	---	---	---	---
5A	Turret Rear Plate	1.23	601	331	627/681	327/339	53.5/54.5	32.5/35.0
6A	Driver's Front Plate	2.04	601	367	425/613	366/409	53.5/54.5	36.5/40.5
8A	Final Drive Front Plate	1.99	578	331	592/613	339/357	53.5/54.5	33.5/35.5

TABLE III

Physical Properties of Samples of Armor from German PzKw IV Tank, Model GF-2

Direction of Tensile Specimen	Yield Strength 0.1% Offset psi.	Tensile Strength psi.	Elongation %	Reduction of Area %	Brinell Hardness Core
Sample No. 3A - 0.48 inch (12.2 mm.) thick - Hull Roof Plate (Homogeneous)					
Longitudinal	194,000	212,600	10.7	34.0	415
Transverse	190,000	212,600	10.0	33.5	
Sample No. 5A - 1.23 inch (31.3 mm.) thick - Turret Rear Plate (Face Hardened)					
Longitudinal	134,000	160,600	16.4	58.5	331
Transverse	134,000	158,000	14.3	52.1	
Sample No. 8A - 1.99 inch (50.4 mm.) thick - Final Drive Front Plate (Face Hardened)					
Longitudinal	136,000	163,400	15.0	51.7	331
Transverse	136,000	164,400	14.3	48.2	

TABLE IV

Results of Fracture Tests on Samples of Armor from German PzKw IV Tank, Model GF-2

Sample No.	Thickness Inches	Description	Steel Quality Test* (Notched Samples Broken Under Press) Longitudinal Fracture	Steel Quality Test* (Notched Samples Broken Under Press) Transverse Fracture	Fiber Test (Notched Samples Broken Under Hammer)
1A	1.20	Right Sponson Side Plate	B	B	Crystalline
2A	1.22	Hull Right Side Plate	B	B	Crystalline
3A	0.48	Hull Roof Plate	B	B	Crystalline
5A	1.23	Turret Rear Plate	B	B	Fibrous and Crystalline
6A	2.04	Driver's Front Plate	D	D	Crystalline
8A	1.99	Final Drive Front Plate	D	D	Fibrous and Crystalline

* 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 1/2 thickness of plate.

C - Lamination or laminations present exceeding limits for B fracture. No single lamination exceeding twice thickness in length. No single lamination exceeding 1-1/2 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.

TABLE V

V-Notch Charpy Impact Tests on Representative Samples
As-Received and after Several Heat Treatments

Sample No.	Thickness Inches	BHN	As-Received +70° F.	As-Received -40° F.	BHN	After Tempering[x] 70° F.	After Tempering[x] -40° F.	No. 1** After Reheat Treatment BHN	No. 1** 70° F.	No. 1** -40° F.	No. 2*** After Reheat Treatment BHN	No. 2*** 70° F.	No. 2*** -40° F.
3A	.48	415	11.2(Cd)*	9.7(Cd)	285	41.0(Fc)	23.6(Fc)	331	31.4(Cd)	12.6(Cd)	---	---	---
5A	1.23	331	39.3(Cdf)	20.0(Cdf)	285	74.6(f)	54.9(Fc)	241	96.0(F)	88.5(F)	352	34.2(F)	17.9(Cdf)
8A	1.99	331	28.7(Fc)	19.7(Fc)	302	49.2(F)	33.7(Fc)	241	96.5(F)	101.0(F)	352	38.6(F)	17.2(Fc)

* Symbols denote description of fractures of V-Notch Charpy bars.

F - Fibrous
Fc - Fibrous matrix with spots of crystallinity
Cdf - Dull crystalline patch surrounded by fibrous border
Cd - Dull crystalline (complete)

[x] 2 hrs. at 1200° F.

HEAT TREATMENT

** No. 1

No. 3A - 1675° F. - 1 hr. - Oil quench, temper 2 hrs. at 1200° F. - Air cool.
No. 5A - 1675° F. - 2 hrs. - Oil quench, temper 2 hrs. at 1250° F. - Air cool.
No. 8A - 1675° F. - 2 hrs. - Water quench, temper 2-1/2 hrs. at 1250° F. - Air cool.

*** No. 2

No. 5A - 1675° F. - 2 hrs. - Oil quench, temper 3 hrs. at 1100° F. - Air cool.
No. 8A - 1675° F. - 2 hrs. - Water quench, temper 3 hrs. at 1100° F. - Air cool.

TABLE VI

Chemical Analyses of Weld Metal Deposits

Sample	Weld Deposit	C	Mn	Si	S	P	Ni	Cr	Mo	W	Va
No. 1	Attachment weld	*	1.01	*	*	*	9.07	15.93	.51	Nil	Tr
No. 3	Outside weld										
	Crown	.81	1.67	.26	.016	.031	4.37	1.79	.32	.17	"
	Body	.12	1.43	*	*	*	6.88	15.12	1.69	Nil	"
No. 4	Outside weld										
	Crown	.85	2.02	*	*	*	4.45	1.63	.30	.28	"
	Body	*	1.69	*	*	*	6.36	12.32	1.31	Nil	"
	Inside weld	.11	1.20	*	*	*	7.57	15.25	1.77	"	"
No. 6	Inside weld	.14	1.10	.39	.020	.020	6.68	13.51	1.62	"	"
No. 7	Outside weld										
	Crown	.73	1.61	*	*	*	4.09	3.77	.54	.18	"
	Body	.14	1.18	*	*	*	8.10	14.79	1.75	Nil	"
	Inside weld	.14	1.12	*	*	*	7.07	14.17	1.65	"	"

* Sample insufficient to obtain complete analysis.

TABLE VII

Summary of Hardness Survey Results on Welded Joints

Sample	Weld Metal Hardness Vickers	Weld Metal Hardness Brinell*		Weld Heat-Affected Zone - Max. Hardness Vickers	Weld Heat-Affected Zone - Max. Hardness Brinell*	Minimum Hardness of Tempered Zone Vickers	Minimum Hardness of Tempered Zone Brinell*	Base Metal Brinell
No. 2								
Attachment weld (austenitic)	218-236	218-234	Hull right side					
1-1/4" dia. boss			plate	657	577	376	349	379
			Mild steel boss	178	179	---	---	152
No. 4								
Outside weld								
Crown (hard facing)	314-421	298-339	Hull roof plate	649	573	342	321	415
Body & Root (austenitic)	227-254	227-248	Right sponson					
Inside weld (austenitic)	232-254	231-248	side plate	627	557	339	318	352
No. 7								
Outside weld								
Crown (hard facing)	233-285	232-273	Driver's front					
Body & Root (austenitic)	215-247	216-242	plate	613	546	345	324	367
Inside weld (anstenitic)	281-317	270-300	Hull roof plate	620	551	357	333	415

* Converted from Vickers-Brinell to Standard Brinell (Steel Ball, 3000 KG load)

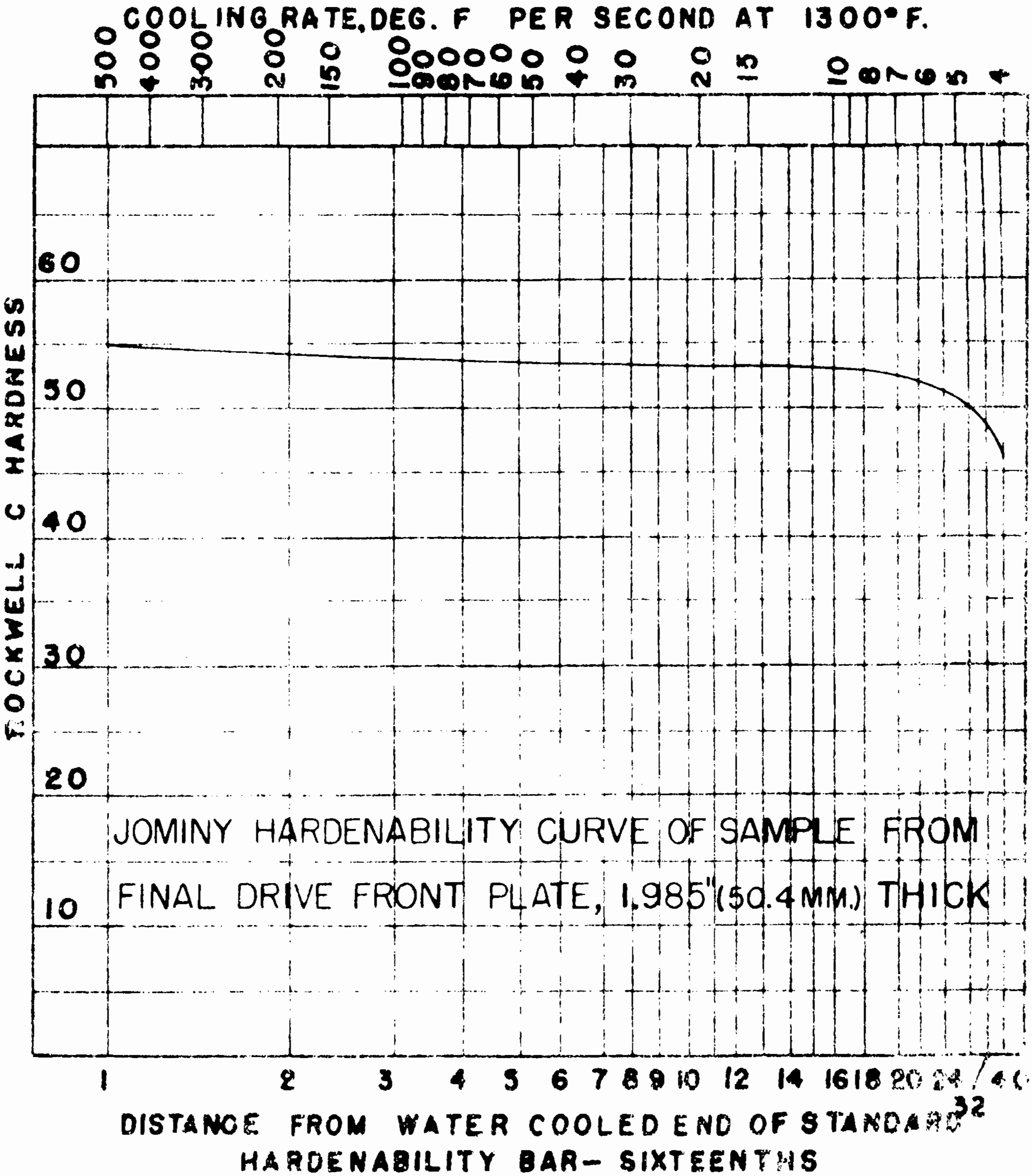
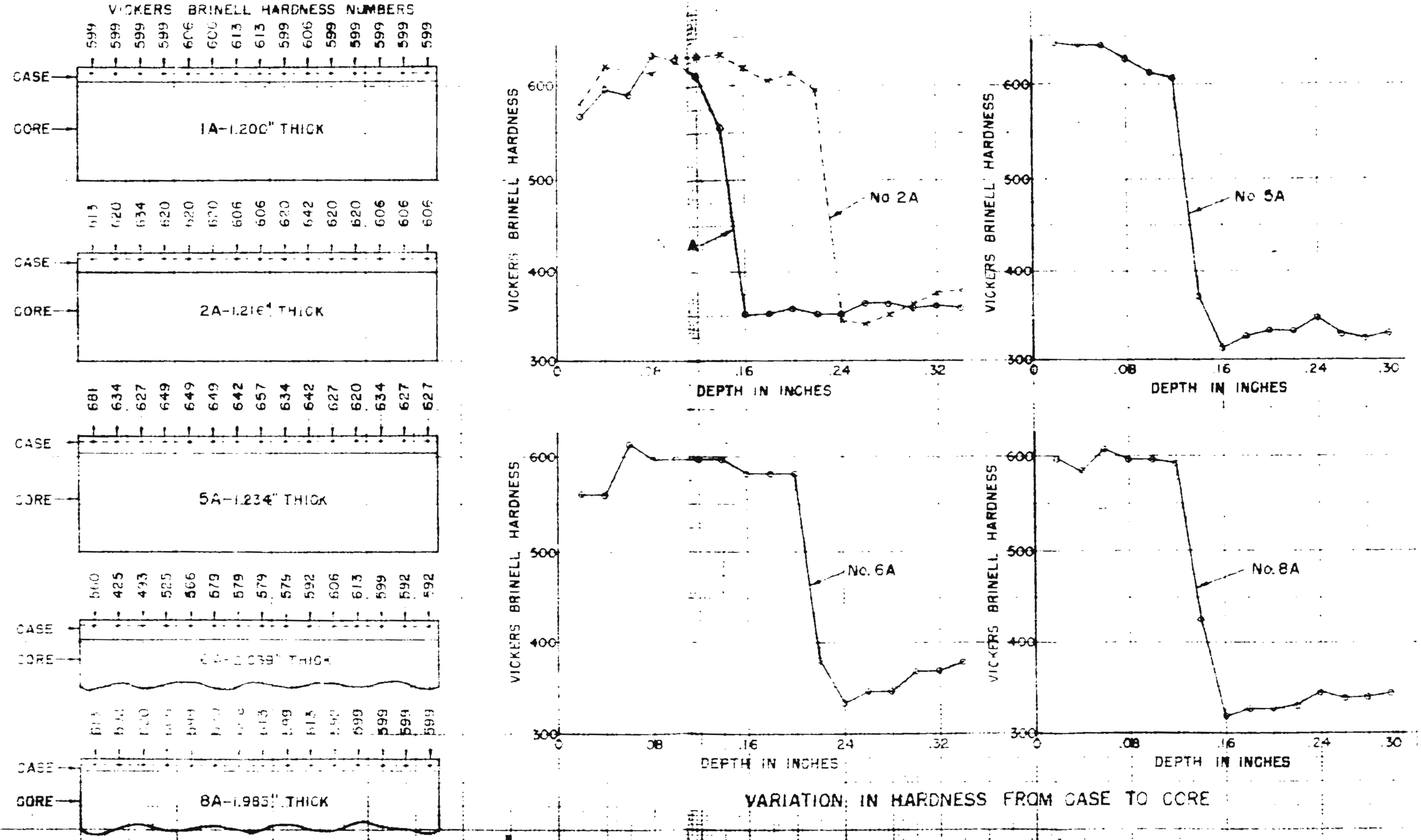


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	AL	CU	B	QUENCH TEMP.	TIME	G.S.
8-A		.39	.42	.33	.015	.011	.36	2.32	.20	.015	.12	.0006	1675°F	3 HRS.	

FIGURE 1



VARIATION IN HARDNESS FROM CASE TO CORE

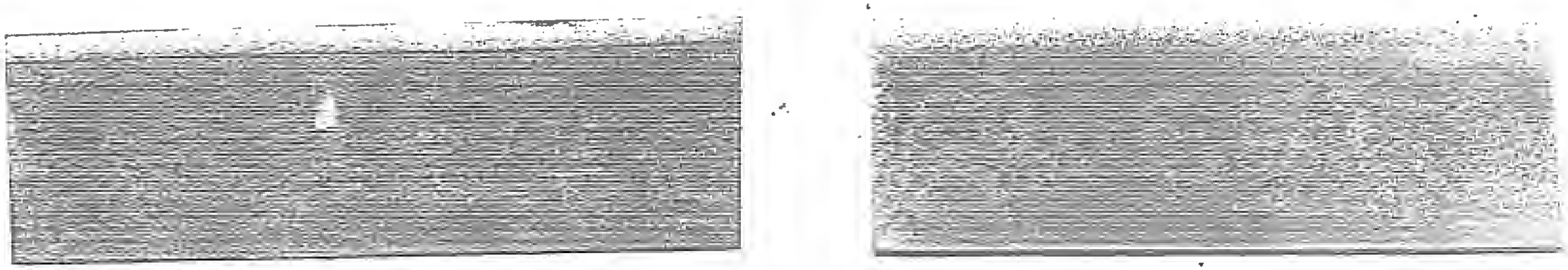
HARDNESS TESTS MADE ON CASE $\frac{1}{16}$" BELOW SURFACE

----INDICATES POSITION OF HARDNESS SURVEYS

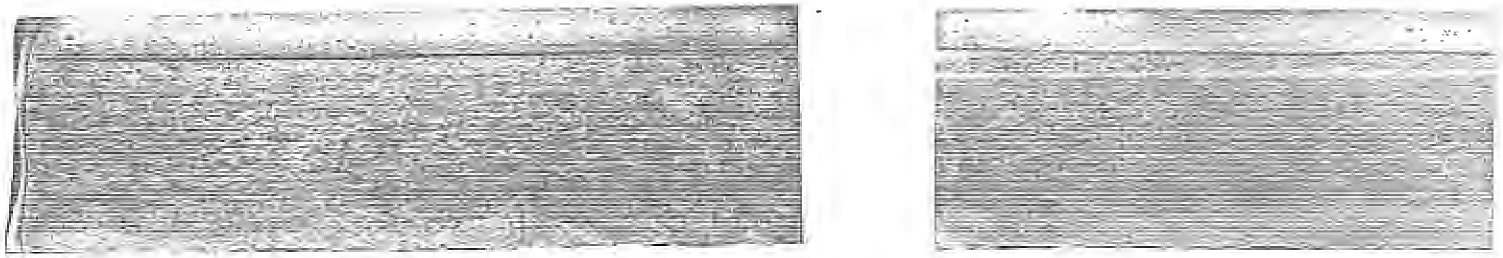
VICKERS BRINELL HARDNESS SURVEYS OF FACE HARDENED ARMOR FROM A Pz Kw-IV MODEL GF-2 GERMAN TANK

FIG. 2

LONGITUDINAL TRANSVERSE



1A RIGHT SPONSON SIDE PLATE

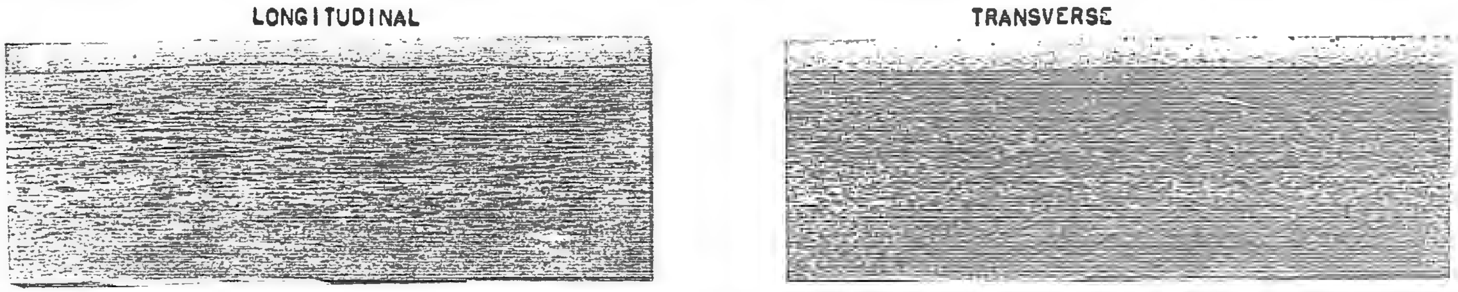


2A HULL RIGHT SIDE PLATE

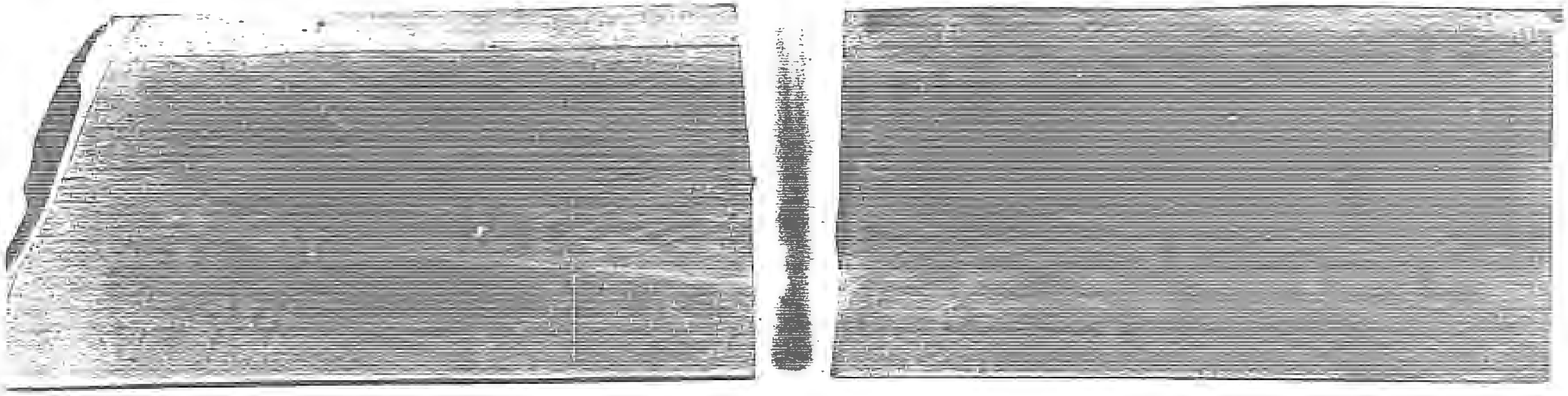
3A HULL ROOF PLATE

MACROSTRUCTURE OF SAMPLES FROM PZKW IV MODEL GF-2 GERMAN TANK
12 FEB 1944 MAG. X 1 WTN.710-2277

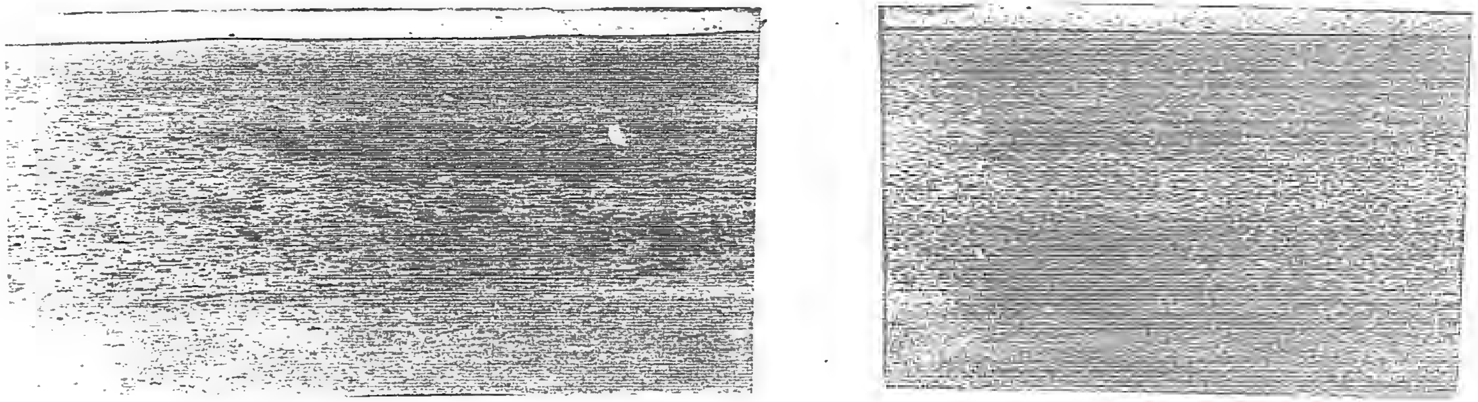
FIGURE 3



5A TURRET REAR PLATE



6A DRIVER'S FRONT PLATE



8A FINAL DRIVE FRONT PLATE

MACROSTRUCTURE OF SAMPLES FROM PZKW IV MODEL GF–2 GERMAN TANK

FIGURE

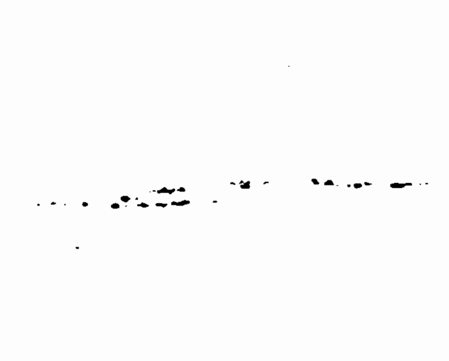
Nonmetallic Inclusions in Samples from PZKW 1V Model G F-2 German Tank

Photomicrographs were taken on unetched longitudinal sections at magnification of 100 diameters.

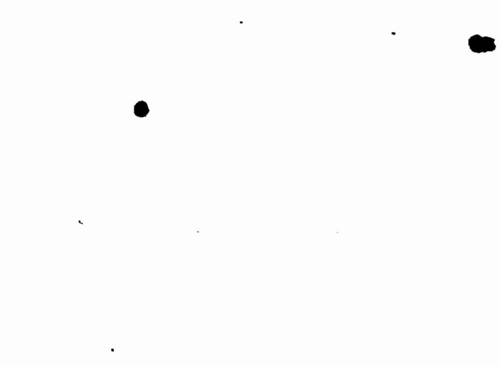
No. 1A
Typical complex oxides(dark) and fine elongated nonmetallics(light)present in section.

No. 1A
Typical segregation of fine complex oxides in center of section.

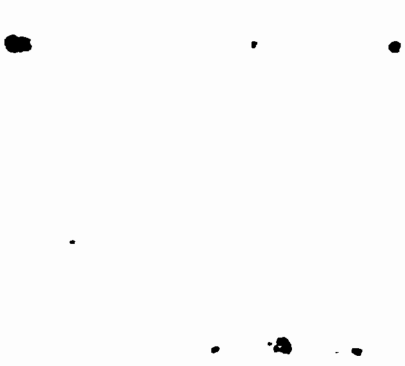
No. 2A
Typical angular complex oxides present in section.



No. 2A
Typical segregation of fine complex oxides in center of section.

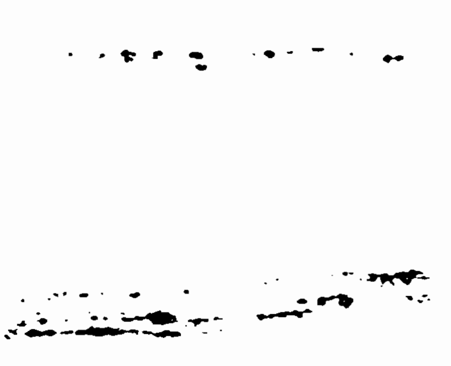


No. 3A
Typical scattered small complex oxides.



No. 5A
Typical angular complex oxides in center section.

No. 6A
Typical segregation of small angular complex oxides.



No. 8A
Segregation of nonmetallics near edge of plate. Fine angular oxides were present throughout section.

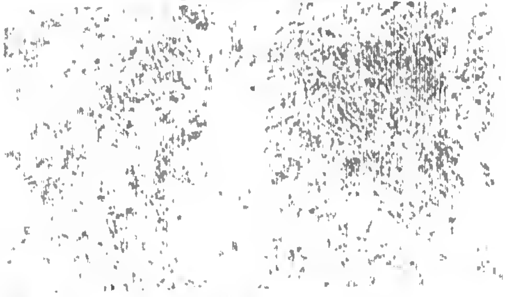
Microstructure of Samples from PZKW lV Model G F-2 German Tank

All Photomicrographs X1000 - Picral

No. 1A
1.200" Thick

No. 2A
1.215" Thick

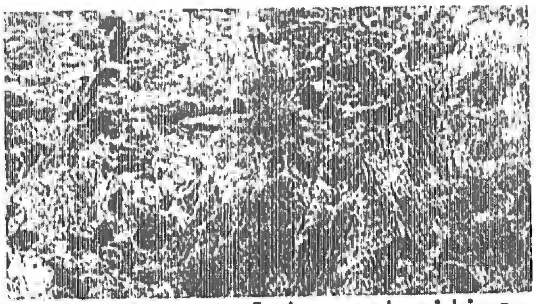
OUTER CASE



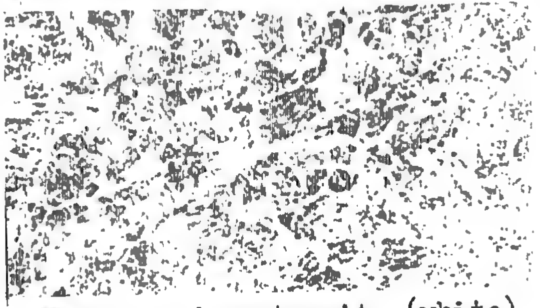
Fine martensite.

Fine martensite.

CENTER CASE



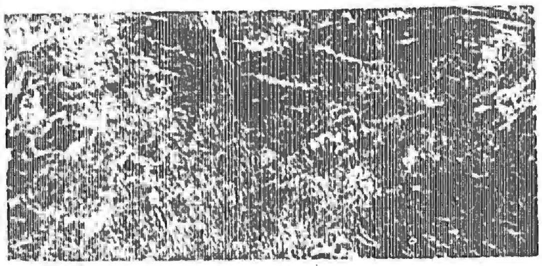
Zone of incomplete austenitization.



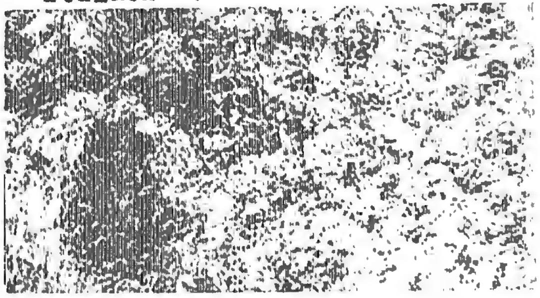
Untempered martensite (white) and zone of incomplete austenitization.

JUNCTION

CASE & CORE



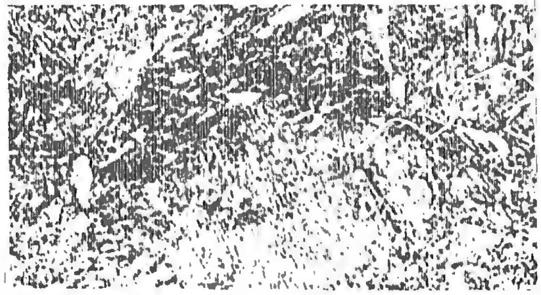
Patches of slightly tempered martensite (light gray) and tempered martensite (dark).



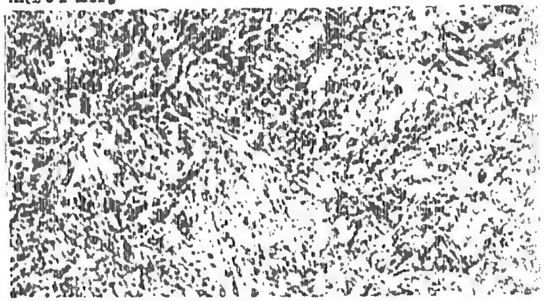
Rejection of fine carbide in slightly tempered martensitic matrix.

CORE

WTN.639-6488



Tempered martensite and occasional areas of tempered upper bainite.



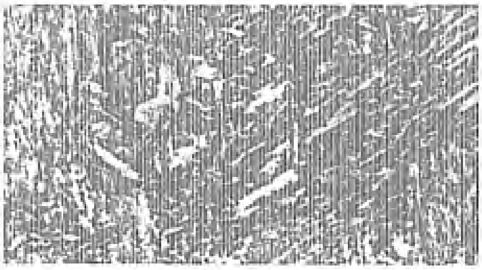
Tempered martensite and occasional areas of tempered upper bainite. Fairly uniform distribution of fine carbide.

FIGURE 6

Microstructure of Samples from PZKW 1V Model G F-2 German Tank

All photomicrographs X1000 - Picral etch, nos. 8A-1 & 8A-2 were taken at X100 - Oberhoffer etch.

No. 3A
.482" Thick



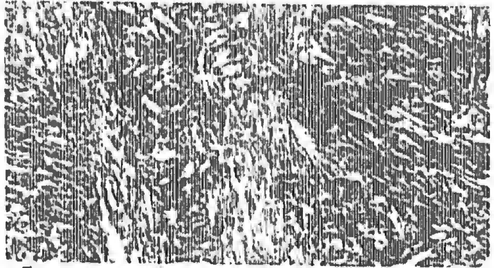
Coarse acicular tempered martensite.

OUTER CASE →

No. 5A
1.234" Thick

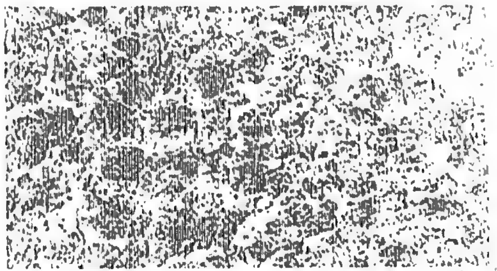
Fine martensite.

No. 3A
.482" Thick



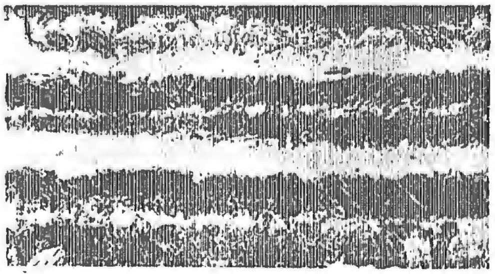
Coarse acicular tempered martensite and tempered upper bainite.

CENTER CASE →



Untempered martensite (white) and zone of incomplete austenitization (gray).

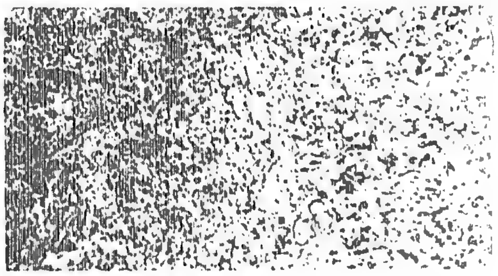
No. 8A-1
1.985" Thick



Typical banding revealed in the center of plates 2A, 5A, 8A.

JUNCTION

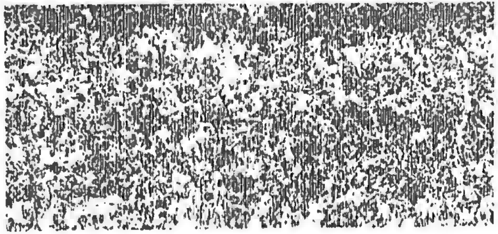
CASE & CORE →



Rejection of fine carbide in slightly tempered martensite.

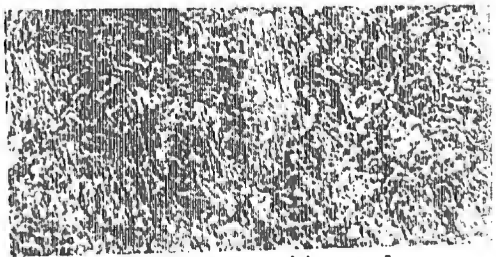
No. 8A-2
1.985" Thick

WTN.639-6489



Typical structure near surface of plates 2A, 5A, 8A (absence of banding).

CORE →



Tempered martensite and evidence of small areas of tempered upper bainite.

FIGURE 7

All photomicrographs X1000 - Picral Etch

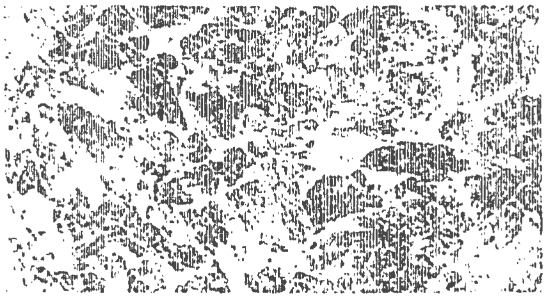
No. 6A
2.039" Thick

No. 8A
1.985" Thick

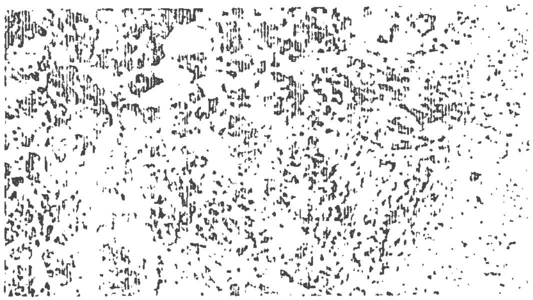
OUTER

CASE

Fine martensite.

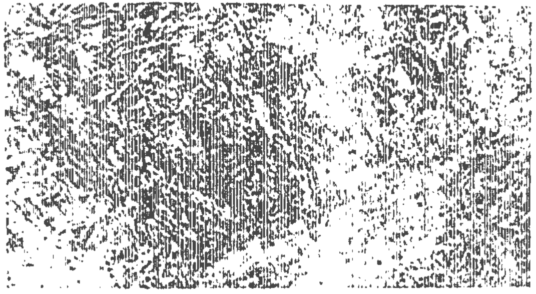


Fine martensite.

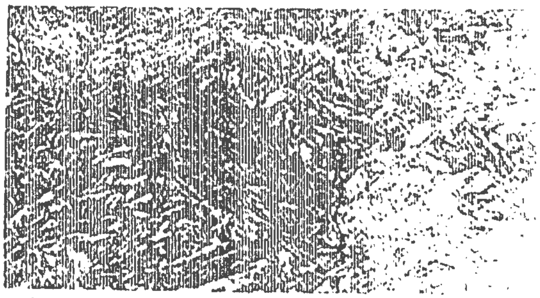


CENTER CASE

Some untempered martensite (white) and zone of incomplete austenitization (gray).



Some untempered martensite (white) and zone of incomplete austenitization (gray).



JUNCTION

CASE & CORE

Patches of slightly tempered martensite (gray) and tempered martensite (dark).

Patches of slightly tempered martensite (gray) and tempered martensite (dark).

CORE

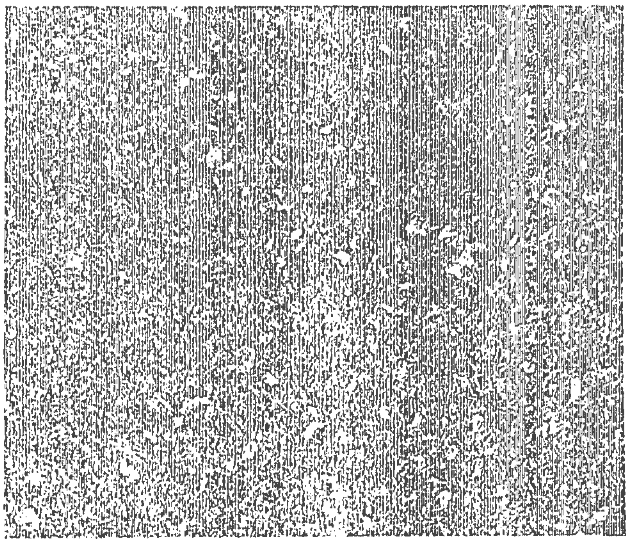
Tempered martensite and area of tempered upper bainite.

Tempered martensite and area of tempered upper bainite.

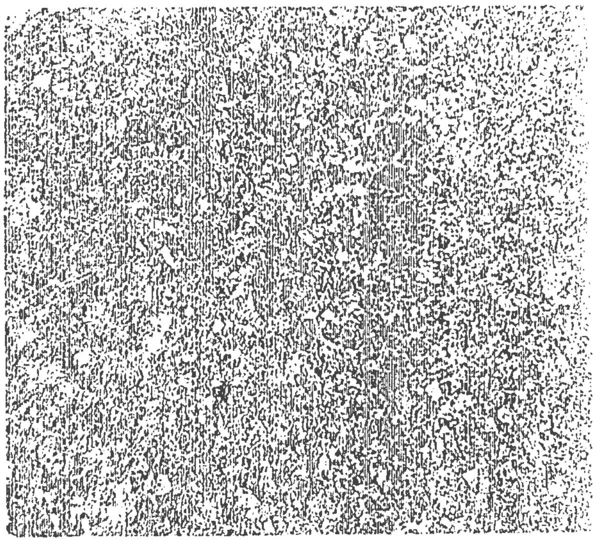
WTN.639-6490

FIGURE 8

Typical Grain Size Observed in Samples
From PzKw IV Model G F-2 German Tank

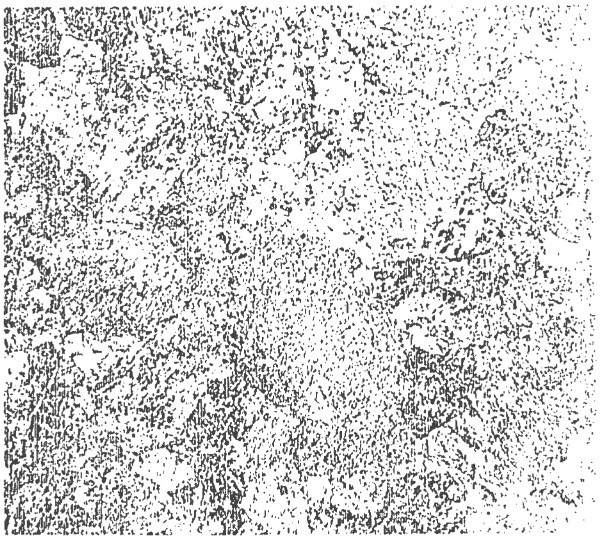


No. 2A - Core
ASTM grain size No. 8



No. 2A - Case
ASTM grain size No. 7-8.

No. 1A
ASTM grain size No. 4-6.



No. 6A.
ASTM grain size No. 1-5.

All Photomicrographs X100 - Vilella Etch.

WTN.639-6479

FIGURE [illegible]

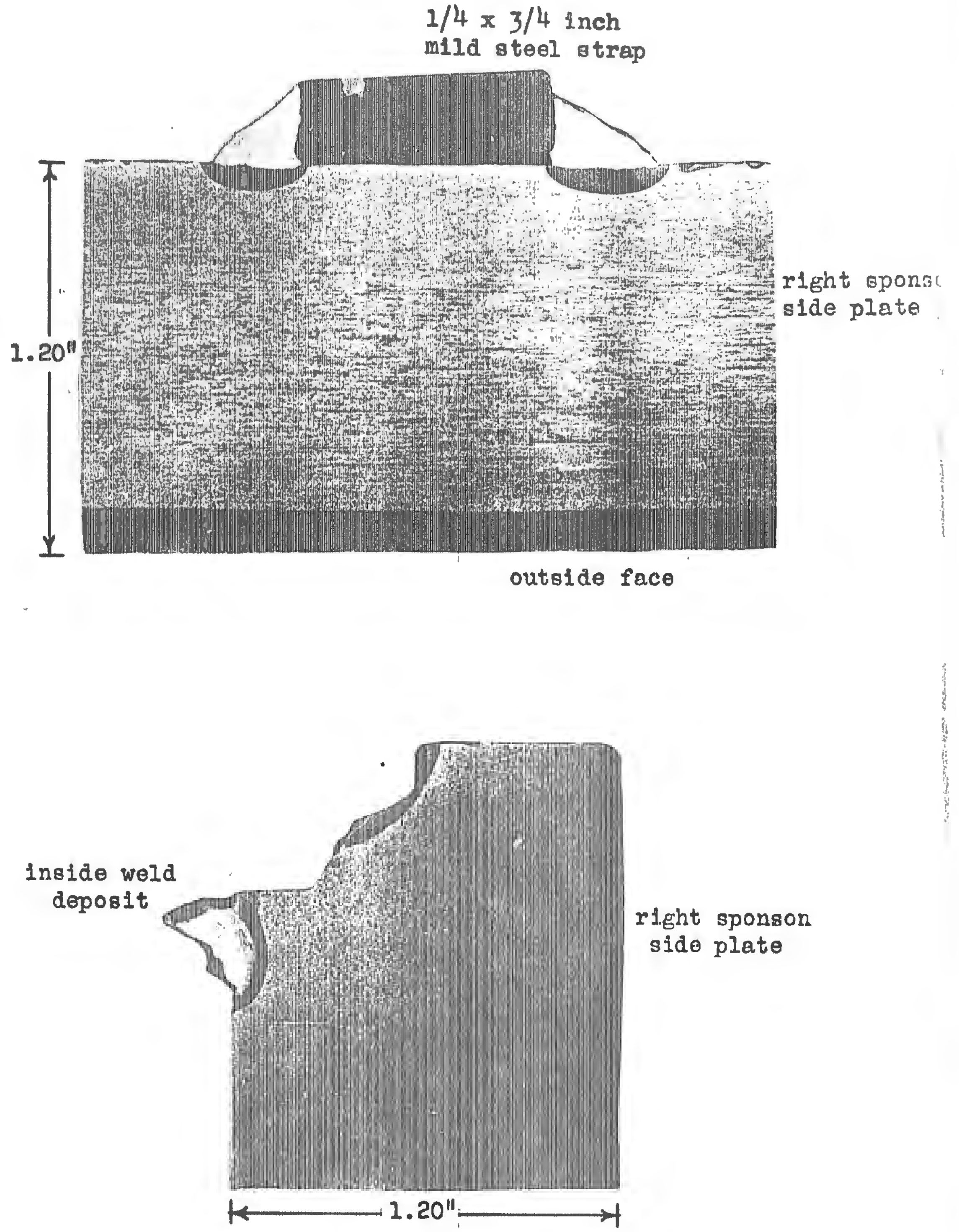


Figure 10. Macroetched Transverse Sections Through Attachment Weld and Broken Weld Joint of Sample No. 1.

German PzKw IV Tank

WTN.639-6465

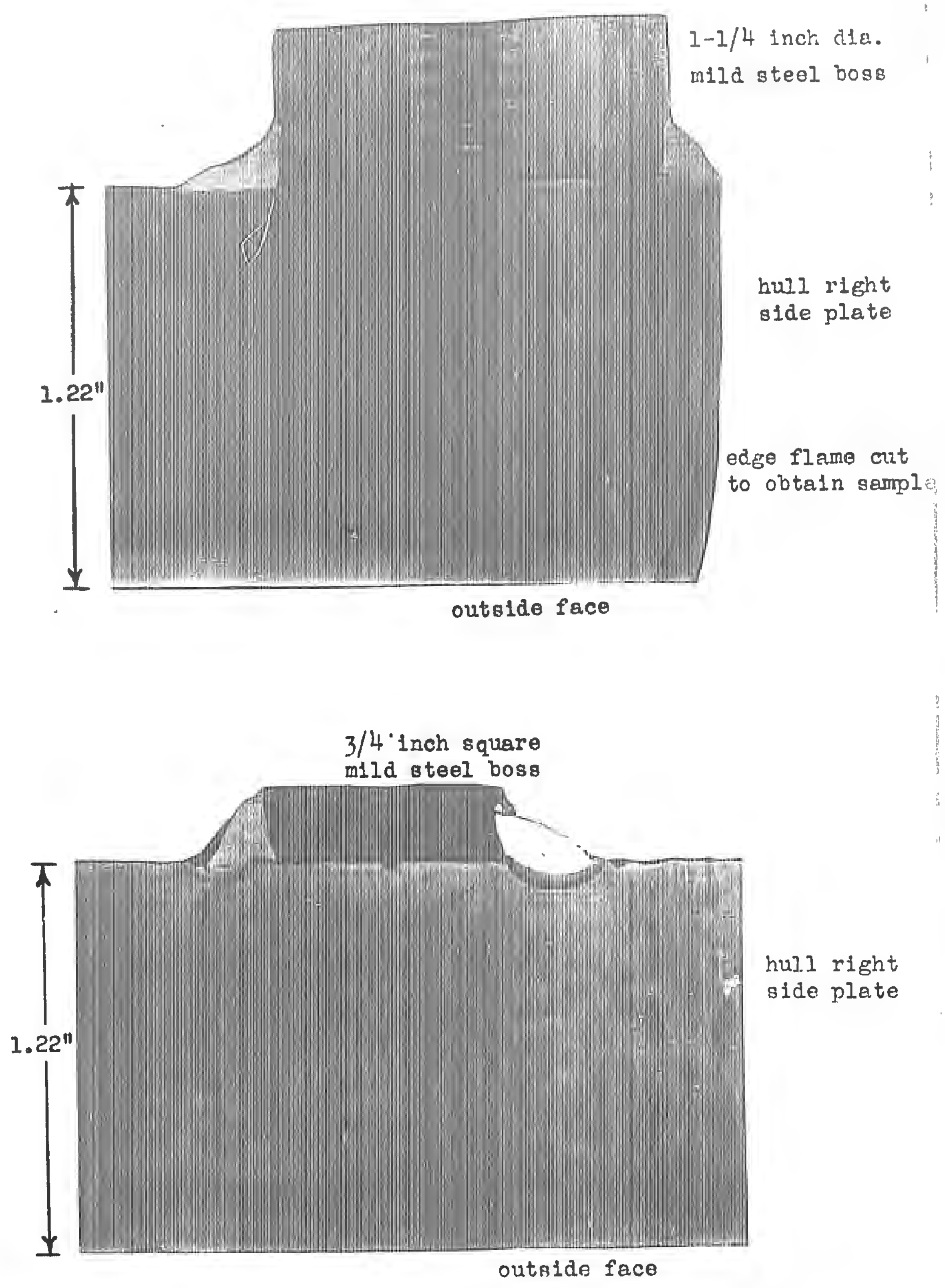
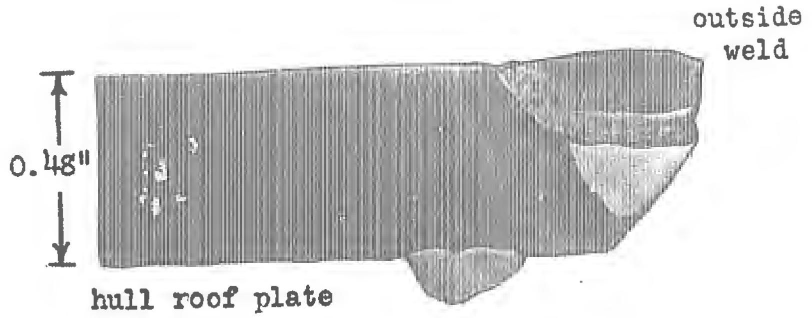


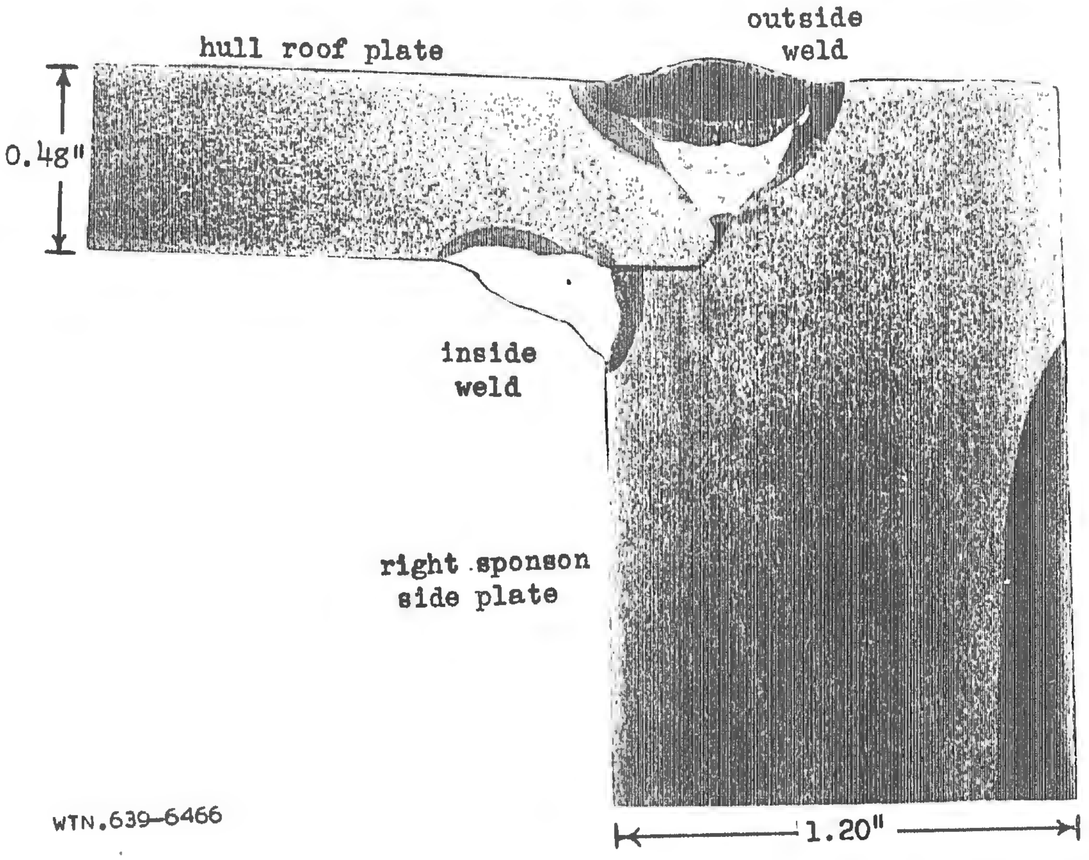
Figure 11. Macroetched Transverse Sections Through Welded Attachment Joints of Sample No.2.

German PzKw IV Tank

WTN.639-6470



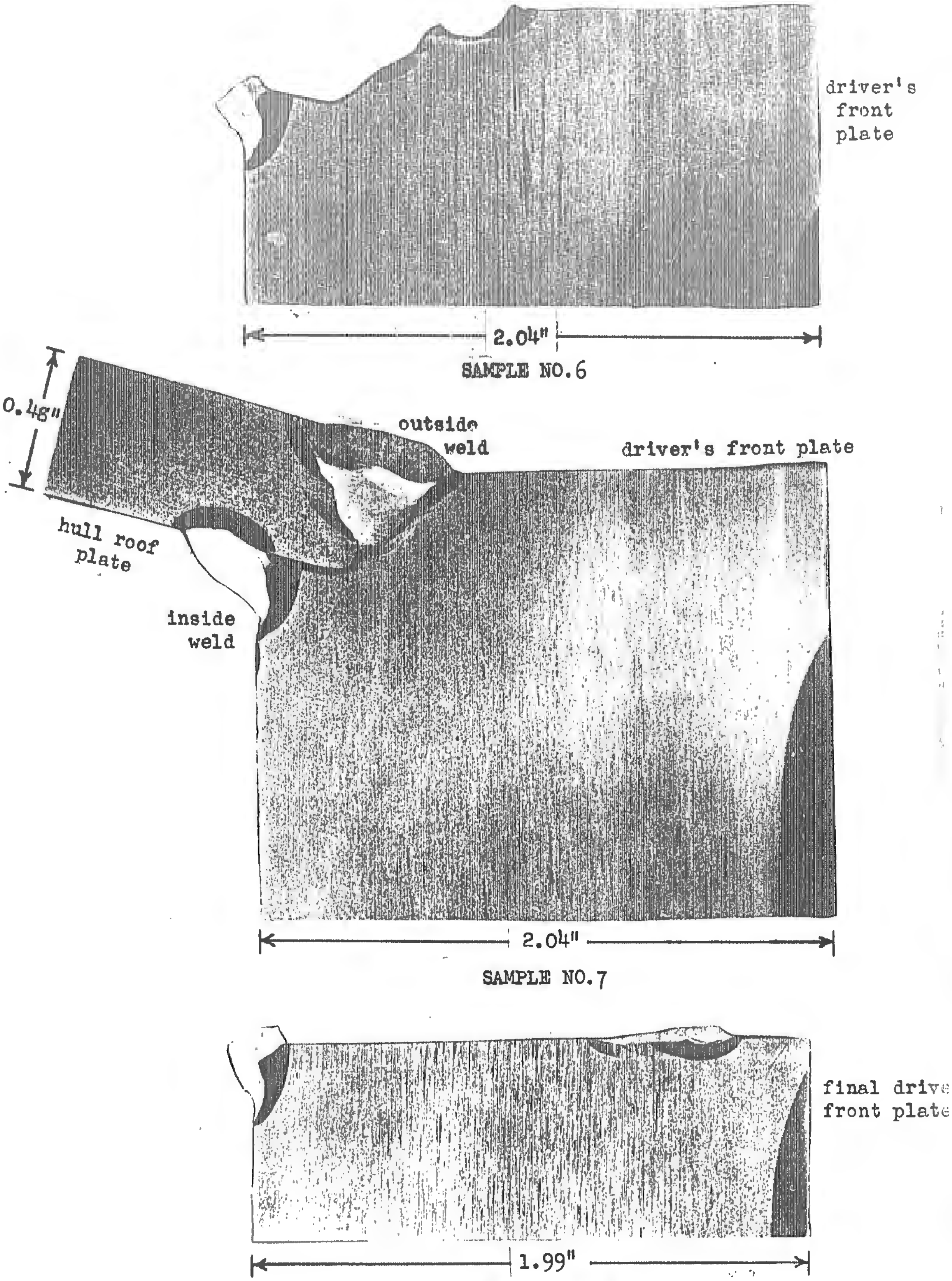
SAMPLE NO. 3



WTN.639-6466

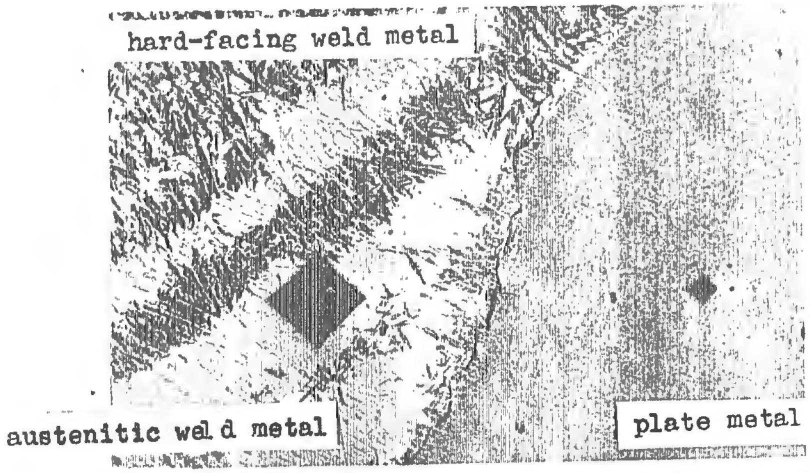
SAMPLE NO. 4

Figure 12. Macroetched Transverse Sections Through Weld Joints in German PzKw IV Tank.

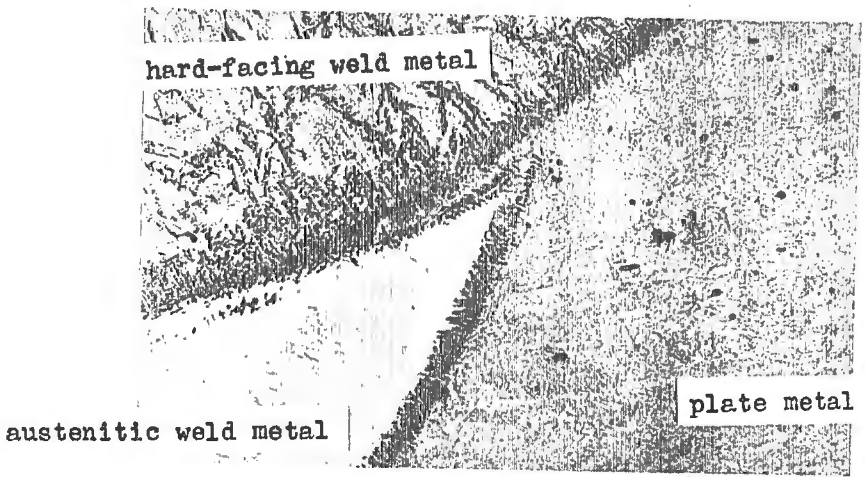


WTN.639-6467

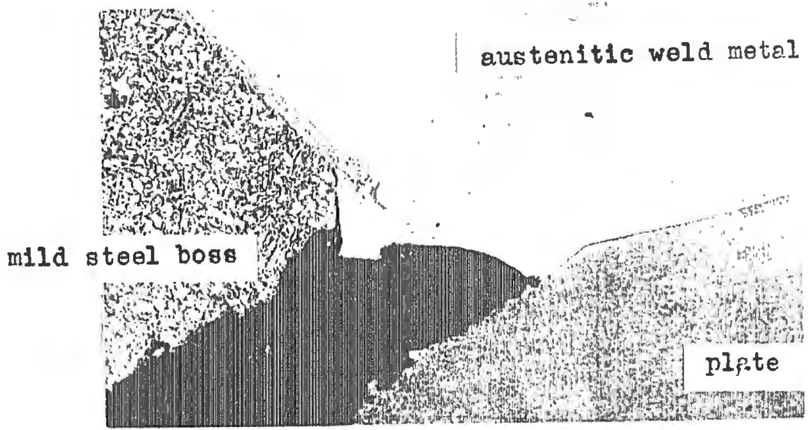
Figure 13. Macroetched Transverse Sections Through Weld Joints in German PzKw IV Tank



X100 Picral etch
Junction of hard-facing crown, austenitic body, and plate. Sample No. 4.

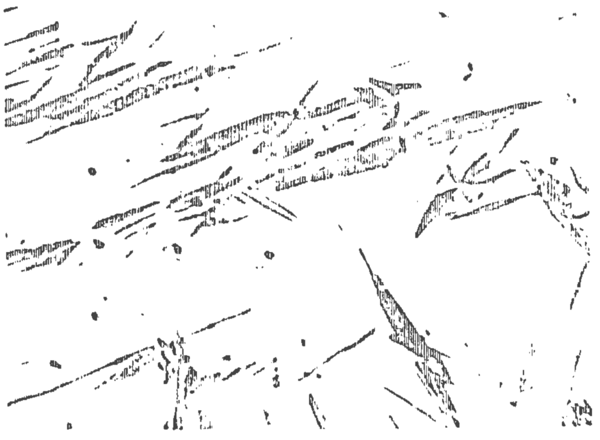


X100 Picral etch
Junction of hard-facing crown, austenitic body, and plate. Sample No. 7.



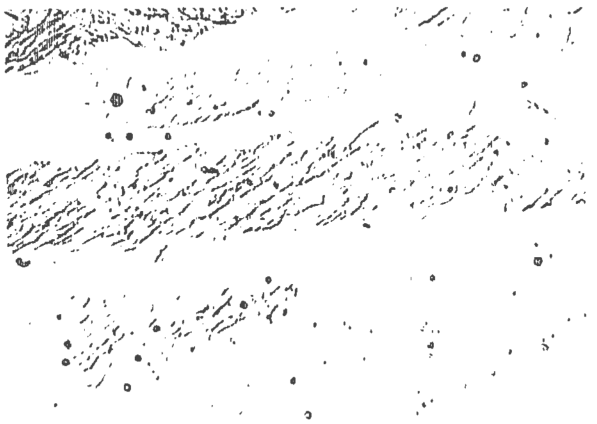
X100 Picral etch
Junction of 1 1/4" diameter mild steel boss, plate, and weld. Sample No. 2.

Figure 14. Photomicrographs of Fusion Zone of Welds in German PzKw IV Tank



X1000 Picral etch
Microstructure at crown of outside weld. Sample No. 4.

X1000 aqua regia glycerol
Microstructure in body of outside weld. Sample No. 7.



WTN.639-6469

X1000 aqua regia glycerol
Microstructure of inside weld. Sample No. 7.

Figure 15. Photomicrographs of Weld Metal Structure in German PzKw IV Tank

APPENDIX A

Basic Correspondence

COPY - 17 April 1944 - ahk

WAR DEPARTMENT
OFFICE OF THE CHIEF OF ORDNANCE
WASHINGTON, D. C.

O.O. 400.112/4800
Attn: SPOTM
Wtn. 350.05/530

30 November 1943

Subject: Metallurgical Examination of PzKw IV, Model GF-2, German Tank

To: Commanding Officer
Watertown Arsenal
Watertown 72, Mass.

Attn: Colonel H.H. Zornig

1. A German PzKw IV tank is being ballistically tested at Aberdeen Proving Ground. Preliminary ballistic results have been obtained and indicate that metallurgical data on the armor and welding should be obtained prior to completion of ballistic test.

2. Samples of the main types of basic armor and welded joints are being forwarded to Watertown Arsenal from Aberdeen Proving Ground. All samples will be identified, and Aberdeen will advise his arsenal as to the location in the vehicle from which all samples were removed.

3. It is requested that metallurgical examination be conducted on both the basic armor and the weldments, and the preliminary reports be submitted to this office as soon as possible so that the remainder of the ballistic program can be arranged.

By order of the Chief of Ordnance:

(s/t) G. Elkins Knable
Colonel, Ord. Dept.
Assistant

cc: Aberdeen Proving Ground

WAR DEPARTMENT
ABERDEEN PROVING GROUND
MARYLAND

A.P.G. 386.3/947
McCurry/dlf
2225
Wtn. 386.3/128(r)

RESTRICTED

16 December 1943

Subject: Identification of Samples from German Tank, PzKw IV.

To: Commanding Officer
Watertown Arsenal
Watertown 72, Mass.

1. Reference is made to a letter from the Ordnance Office (SPOTB - 400.112/4800 dated 30 November 1943) to your office which requests a metallurgical examination of samples from a German PzKw IV tank which is being ballistically tested at this station.

2. The following samples have been removed from the hull and have been forwarded to your station:

Number	Size	Location
1	5" x 10"	Right sponson side plate
2	5" x 10"	Hull right side plate
3	5" x 10"	Hull roof plate
4	4" x 4"	Joint between right sponson side plate and hull roof plate
5	5" x 10"	Turret rear plate
6	5" x 10"	Driver's front plate
7	4" x 4"	Joint between driver's front plate and hull roof plate
8	5" x 10"	Final drive front plate.

The samples may be oriented with respect to the hull by arrows which are stenciled on each sample; the arrows on samples 1, 2, 3 and 4 point toward the front of the hull, those on samples 6, 7 and 8 point toward the left side of the hull, the left side of the hull being to the driver's left, and that on sample 5 points towards the right side of the turret.

For the Commanding General:

(s/t) John W. Cave
Lt. Col., Ord. Dept.
Chief, Arms & Ammn. Div.

cc: Tech. Sub-Office, Aberdeen, Lt. H. F. Brown
Foreign Materiel Branch, Capt. Klima