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AD-A954 236

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REPORT NO. 710/261-1

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CORRELATION OF MICROSTRUCTURE AND BALLISTIC PROPERTIES OF ARMOR PLATE

PART II

FACE HARDENED PLATE

MS-13710/261-1

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UNCLASSIFIED

October 13, 1938

WATERTOWN ARSENAL
WATERTOWN, MASS.

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Report No. 710/261-1
~~Watertown Arsenal~~
~~CONFIDENTIAL~~

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CORRELATION OF MICROSTRUCTURE AND BALLISTIC PROPERTIES OF ARMOR PLATE

PART II
FACE HARDENED PLATE

Purpose

The purpose of this investigation was to correlate the microstructure and ballistic properties of all carburized armor plate on hand at Watertown Arsenal.

Conclusions

1. Laminations (elongated nonmetallic inclusions) present to an extent which would cause spalling in homogeneous plate, do not produce this result in carburized plate when tested with caliber .30 A.P. because of the protection afforded by the face.

2. Carbides (or any other constituents which may be revealed by a Murakami etch) segregated to any extent in the grain boundaries of the case are detrimental to the extent that 75% of the brittle plate had this bad carbide condition, whereas only 25% of the acceptable plate showed a similar condition, and each plate of this 25% showed slight petalling.

3. The microstructures of most carburized cases ranged from a troostite to a troostite-sorbite.

4. Martensitic structures in the core invariably caused spalling, while a uniformly distributed ferrite in sorbite was found in high ballistic nonspalling plate.

5. Plate which passed specification had an average face hardness of 542 Brinell and an average core hardness of 372 Brinell, while plate which, although ballistically ductile, failed to meet ballistic limit requirements had an average face hardness of only 465 Brinell, and an average core hardness of 363.

6. No relation could be found between the normal banding revealed by an Oberhoffer's etch and the ballistic properties.

Method of Procedure

Samples of armor plate made at Watertown Arsenal and rolled by Henry Disston & Sons, Inc., which had accumulated over the period of years from 1922 to date, and some recent Diebold and Disston 1 - 1-1/2" plate, were cut from stock. They were taken as close to the center of plate as possible.

These samples were macro-etched in Oberhoffer's reagent to study banding and also to establish the longitudinal direction from the configuration of the banding. This longitudinal section was subjected to microscopic examination; first - unetched, to determine the segregation of nonmetallic inclusions; second - a carbide study (Murakami etch); and third - a study of general microstructure (nital etch) including the condition of the rear face.

The depth of case was determined on annealed samples.

Brinell hardness determinations were made on the face and on the core at Watertown Arsenal.

Ballistic data, chemical analyses, and heat treatments, as given in Table 5, were taken from the Aberdeen Reports and letters on file at Watertown Arsenal. In the few cases where chemical analyses were missing, they were determined at Watertown Arsenal.

Experimental Results

Table 1 is a tabulation of the properties of case and core and ballistic properties of each individual plate.

Tables 2, 3 and 4, are analyses of the results of the investigation.

Macro and micro studies are shown in Figures 1 to 87, inclusive.

Discussion

As an example of high quality face hardened armor plate, plate No. 4911B is illustrated in Figures 1 - 7, inclusive, pages I and II. For comparison, see Figures 8 - 16, inclusive, pages III and IV, which show the corresponding microstructures of poor ballistic plate No. 02D238.

It will be readily observed that the structures of these plates differ in three important respects: dirt content, carbide condition, and microstructure.

A considerable amount of rounded, uniformly distributed, nonmetallic inclusions exert no influence upon the spalling characteristics. Even laminations which would cause spalling in homogeneous plate will not produce this result in carburized plate. We believe that this is due to the large amount of energy

Table 1

Relation between
Properties of Case and Core and Ballistic Properties

Plate No.	Dirt Condition	Carbide Condition in Case	Structure of Core (1)	Depth of Case	Condition (2) of Rear Face	Brinell (3) Hardness Case	Brinell (3) Hardness Core	Exceeds Ballistic Limit by AXS-54	Exceeds Ballistic Limit by 31	Calibre of Shot	Spalling Characteristics
1-1/2"											
D	O.K.	Bad	O.K.	.212		652	351	1934		37 MM. (1.85#)	Spalled on face.
1-1/4"											
A	Bad	O.K.	Ferritic + Bad Carbides	.35		512	332	1800		37 MM. (1.85#)	Badly cracked.
B	O.K.	O.K.	O.K.	.184 (4)		707/803 (4)	340	1775		37 MM. (1.85#)	Punching. (5)
1"											
F	Questionable	O.K.	Bad	.292		495	512			.50 A.P.	Cracked.
5/8"											
[illegible]	O.K.	O.K.	O.K.	.154		578	387	+130 (6)		.50 A.P.	No spalling.
[illegible]	Bad	Bad	Bad	.173		578	364	+113		.50 A.P.	Spalled.
034	Bad	Questionable	O.K.	.135		495	375	Area affected [illegible]" x 5.9"		37 MM (1.45#)	Spalled.

Table 1 (Cont.)

NOTES:

(1) The structure of the core examined with 1% Nital etch has been "Bad" only when martensitic, although the presence of large segregations of ferrite, classified as "Ferritic", indicates a structure not uniform enough to be acceptable.

(2) Symbol "C" signifies the specimen also showed a case on the rear face, the approximate depth of which is given unless it is very slight: "D" signifies a decarburization of the rear face.

(3) Brinell readings for the rear face given in the Aberdeen reports differ markedly from the above readings taken on the actual core at Watertown Arsenal. This we believe is caused by failing to grind off sufficient metal to get below carburization or decarburization on rear face. In the case of 1/4" plate, the readings are Vickers-Brinell.

(4) Since the piece examined was part of a punching, the total case is unknown. However, 0.18" remained on the punching, so the case must be greater than this. Also, the Brinell reading on face may be high because of cold-working.

(5) Termed "spalling", but due to some confusion in definition of terms it is not known whether this is serious or not.

(6) Ballistic limit taken from production plate of the same heat was used to obtain this figure.

(7) Probable amount by which the ballistic limit of this plate would exceed Specification #31, taken from average performance of such plate, see Figure 5, Watertown Arsenal Report No. 710/250

Table 1 (Cont.)

Plate No.	Dirt Condition	Carbide Condition in Case	Structure of Core(1)	Depth of Case	Condition(2) of Rear Face	Brinell(3) Hardness Case	Brinell(3) Hardness Core	Exceeds Ballistic Limit by AXS-54	Exceeds Ballistic Limit by 31	Calibre of Shot	Spalling Characteristics
1/2"											
1-445	Bad	Bad	Ferritic	.116	C 0.04"	600	351		+100(7)	.50 A.P.	Spalled.
1-1	Bad	O.K.	Ferritic	.124/.132		495	311/321	-34	+225	.30 A.P.	No spall.
1-2	Bad	O.K.	Ferritic	.088/.097		499	311/321	-97	+269	.30 A.P.	" "
444-2	Questionable	O.K.	O.K.	.147		555	364		+676	.30 A.P.	" "
3-435	O.K.	O.K.	O.K.	.123	C 0.1" and D	512	332		+338	.30 A.P. .50 A.P.	" " Petals
4-445	Bad	Bad	Ferritic	.130	D	495	302		+379	.30 A.P. .50 A.P.	Petals Spalled
5-445	Questionable	O.K.	O.K. Questionable Carbides	.134	C and D	532	364	(30° from normal)	+607	.30 A.P. .50 A.P.	No spall. Cracked
5-444	O.K.	Bad	Ferritic	.123	C 0.04" C 0.01"	600/627	351	(30° from normal)	+775	.30 A.P. .50 A.P.	Petals Badly cracked and spalled.
4-444	Bad	Bad	Ferritic	.153	D	577/600	340	(15° from normal)	+529	.30 .50	No spall. Cracked and spalled.
027	Bad	Bad	Bad	.113		575	444/495			37 MM. (1.45")	Cracked.
336	O.K.	Bad	Bad	.125		495	418			"	"

Table 1 (Cont.)

Plate No.	Dirt Condition	Carbide Condition in Case	Structure of Core(1)	Depth of Case	Condition(2) of Rear Face	Brinell(3) Hardness Case	Brinell(3) Hardness Core	Exceeds Ballistic Limit by AXS-54	Exceeds Ballistic Limit by 31	Calibre of Shot	Spalling Characteristics
3/8"											
33-7850	Questionable	Questionable	O.K.	.108	D	477	387/402	-239	+23	.30 A.P.	No spall.
34-7850	O.K.	Bad	O.K.	.104	D	477	402/418	-249	+56	.30 A.P.	Petals.
1/4"											
1-444	Bad	O.K.	O.K.	.061		477/512	418/444		+184	.30 A.P.	No spall.
442	Bad	O.K.	Questionable	.057		430/444	363	+116	+16	.30 A.P.	" "
243	Bad	O.K.	O.K.	.071		444/477	390	+120	+20	.30 A.P.	Petals.
41-7850	Bad	Bad	Ferritic	.070	C	477	373	-71	-171	.30 A.P.	Petals.
44-7850	Bad	Bad	Ferritic	.067		460/477	357/387	-221	-317	.30 A.P.	Petals.
46-7850	Bad	Bad	Ferritic	.074		460/477	351/387	-92	-186	.30 A.P.	Petals.
49-7850	O.K.	Questionable	Ferritic	.074		477	373	-211	-256	.30 A.P.	Petals
1-445	O.K.	Bad	O.K.	.064		532/555	430/444		+328	.30 A.P.	Spalled.
196	O.K.	None	Bad	.063		555	418			37 MM. (1.456)	Cracked.
1/8"											
3-1	Bad	None	Ferritic	.032	D	387	340		-527	.30 A.P.	No Spall.
3-2	Bad	O.K.	Ferritic	.034	D	418	364		-524	.30 A.P.	No Spall.

Table 2(a)

Plates	Behaviour	Ballistic specifications	No.	Dirt	Carbides	Structure	Brinells Case	Brinells Core
Out of 24 Plates (Cal. .30 and .50 impact)	16 - Ballistically Ductile	6 Pass Ballistic Specifications	3	O.K.	O.K.	O.K.	512-578	332-387
			3	Bad	O.K.	O.K.	430-512	363-444
		10 Below Ballistic Specifications	4	Bad	O.K.	Ferritic	387; 418/499	311=364
			3	Bad	Bad	Ferritic	460-477	351-387
			1	O.K.	O.K.	Ferritic	477	373
			1	O.K.	Bad	O.K.	477	402-418
			1	O.K.	O.K.	O.K.	477	387-402
	8 Brittle (Cracked or Spalled)		3	Bad	Bad	Ferritic	495-600	302-351
			1	Bad	Bad	Bad	578	364
			1	O.K.	Bad	O.K.	532-555	430-444
			1	O.K.	Bad	Ferritic	600-627	351
			1	O.K.	O.K.	Bad	495	512
			1	O.K.	O.K.*	O.K.	532	364
Out of the 7 Plates (37 MM. Impact)	1 Ballistically Ductile**		1	O.K.	O.K.	O.K.	707-803	340
	6 Brittle		1	Bad	O.K.	Ferritic	512	332
			1	Bad	Quest.	O.K.	495	375
			1	O.K.	Bad	O.K.	652	351
			1	O.K.	O.K.	Bad	555	418
			1	O.K.	Bad	Bad	495	418
			1	Bad	Bad	Bad	578	444-495

*This plate is the only one that shows any trace of carbide structure in core.
**See note (5), Table 1.

<u>Table 3</u>

Brinell Hardness of
Case and Core vs. Ballistic Properties

	Case		Core	
Plate Passing Specification	Average 542	(578	Average 372	(337
		(430/444		(363
		(566		(360
		(612		(332
		(477/512		(418/444
		(444/477		(390
		(707/803*		(340*
Plate Below Specification	Average 466	(495	Average 363	(311/321
		(499		(311/321
		(477		(387/402
		(387		(340
		(418		(364
		(477		(402/418
		(477		(373
		(460/477		(357/387
		(460/477		(351/387
		(477		(373
Brittle Plate	Average 562	(600	Average 386	(351
		(496		(302
		(577/600		(340
		(578		(364
		(532/566		(430/444
		(600/627		(351
		(495		(612
		(532		(364
		(512*		(332*
		(496*		(375*
		(652*		(351*
		(555*		(418*
		(495*		(418*
		(578*		(444/495*

*Plate struck by 37 MM. solid shot.

Table 4

Case Depth and Ballistic Properties

	Depth of Case in Inches			
	1/2" Plate		1/4" Plate	
Plate Passing Specification	Average .135	.147, .123, .127, .142	Average .063	.057, .061, .071
Plate Below Specification	Average .111	.128, .093	Average .071	.070, .067, .074, .074
Brittle Plate	Average .127	.134, .163, .130, .122, .116, .113*, .126*	Average .064	.064, .063*

*Plate struck by 37 MM. solid shot.

PLATE No	ACTUAL THICKNESS	DEPTH CASE	BRINELL CASE	BRINELL CORE	CAL. SHOT	BALLISTIC LIMIT FT. PER SEC. AXS54	BALLISTIC LIMIT FT. PER SEC. 31	DIA HOL INREA
1 1/2"								
D⊗		.212	652	351	37mm*	1934		
1 1/4"								
A●		.35	512	332	WOC * 37mm	1800		
R⊗		.18+	707/803	340	37mm*	1775		
1"								
F●		.292	495	512	.50			
5/8"								
4911B		.154	578	387	.50	2300		
620208		.173	578	364	.50	2283		
034●		.133	495	375	37mm†			
1/2"								
1-445	.510	.116	600	351	.50		2291	
1-1	.496	.124/.132	495	311/321	.30	2366	2625	
1-2	.495	.088/.097	499	311/321	.30	2353	2669	
444-2	.503	.147	555	364	ALSO [illegible] .30		3076	
G-435		.123	512	332	{ .30		2738	
[illegible]					.50		2115	

TABLE 5A

Dia. Hole Thread	Spalling Character	C	Mn	Si	Cr	Mo	V	Others
	Face Spalled	.215	.45	.205	.12	.29		Ni 4.99
	Cracked	.37	.69	.230	1.19	.60	.24	
	[illegible] Splintered	.186	.49	.175	.15	.25		Ni 5.08, Al .024, Co .22
	Cracked	.615	.56	.375	1.19	.55	.245	Al .01 Cu .04
		.275	.71	.200	1.37	.54	.27	
	Spalled	.255	.74	.170	1.34	.54	.14	
	Blown Out							
	Petals	.30/.35	.40/.60	.15/.25	1.20/1.30	.60/.70	.20/.25	
		.23	.50	.23	1.37	.77	.26	
		.23	.50	.23	1.37	.77	.26	
		.315	.53	.13	1.33	.655	.24	
		.30/.35	.40/.60	.15/.25	1.20/1.30	.60/.70	.20/.25	
	Petals							

Others	Heat To	Quench In	At °F	Draw °F	For Min.	Report No.
1.499						
.08, Al.032, Cu.22						
.01, Cb.04						
	1575	Oil		600	120	68
	1700 1535	Oil Oil		1000		79
	1700 1535	Oil Oil		1000		79
						63
	1575-1600	Oil		800	120	68

WOC = Without Cap

* = 1.85 Lbs. † = 1.45 Lbs.

⊗ Manufacturer - Diebold Safe & Lock Co.

Manufacturer - Henry Disston & Sons Co. Inc.

● All other Plates Made by Watertown Arsenal & Rolled by Henry Disston & Sons Inc.

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Plate No.	Actual Thickness	Depth Case	Brinell Case	Brinell Core	Cal. Shot	Ballistic Limit Ft. per Sec. AXS54	Ballistic Limit Ft. per Sec. 31	Di… Hol… n Re…
1/2								
4-445	509	130	495	302	.30		2779	
					.50		1891	
5-445	504	134	532	364	.30		3007	
					.50		2416	30
5-444	503	128	627	351	.30		3174	
					.50		2576	30
4-444	499	153	477/600	340	.30		2929	
					.50		2184	15°
21BH		127	600	340	.30	2702		
22BH		142	600	302	.30	2683		
027°		113	578	444/495	†37mm			5.5
026°		125	495	418	†37mm			5.5
3/8"								
B37850	.378	108	477	387/402	.30	1861	2223	
B47850	.378	104	477	402/418	.30	1851	2256	
1/4"								
1-444	255	061	477/512	418/444	.30		2084	
4A2	270	057	460/444	363	.30	1916	1916	
2A3	269	071	477	390	.30	1920	1920	

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TABLE 5B

[illegible]MIT SEC [illegible]	DIA HOLE N REAR	SPALLING CHARACTER	C	MN	SI	CR	MO	V	OTHER
[illegible]779		PETALLED	30/35	40/60	15/25	1.20/1.30	60/70	20/25	
[illegible]31		SPALLED							
[illegible]07			30/35	40/60	15/25	1.20/1.30	60/70	20/25	
[illegible]	30 - 4	CRACKED							
[illegible]		PETALS	30/35	40/80	15/25	1.20/1.30	60/70	20/25	
[illegible]78	34 - 4	SPALL							
[illegible]29			30/35	40/60	15/25	1.20/1.30	60/70	20/25	
[illegible]	15 - 4	CRACKED							
			.295	.53	.188	.62		.20	W 3.36
			.325	.56	.216	.56	.44	.21	W 2.92
	5.55	CRACKED							
	5.50	CRACKED							
[illegible]23			.29	.44	.26	1.36	.71	.22	
[illegible]56		PETAL	.29	.44	.26	1.36	.71	.22	
[illegible]84			30/35	40/60		1.20/1.30	.60/.70	.20/.25	
[illegible]16			.26	.52	.20	1.21	.80	.27	
[illegible]20		PETALS	.23	.50	.23	1.37	.77	.26	

3 of 3

Mo	V	Others	Heat To	Quench In	At °F	Draw °F	For Min.	Report No
[illegible]	20/25		1575/1600	Oil			120	65466
[illegible]	20/25		1575/1600	Oil		900	120	66468
[illegible]	20/25		1575/1600	Oil		900	120	65468
[illegible]	20/25		1575/1600	Oil		900	120	65468
	.20	W 1.98	1472	H_2O		400	120	
[illegible]	.21	W 1.98	1472	H_2O		400	120	
[illegible]	.22		1700 1600	Oil Oil		1000	120	91
[illegible]	.22		1700 1550	Oil Oil		1000	120	91
[illegible]	20/25			Oil	[illegible]	900	120	66
.60	.27		1700 1535	Oil Oil		1000		79
.77	.26		1700 1535	Oil Oil		1000		79

Plate No	Actual Thickness	Depth Case	Brinell Case	Brinell Core	Cal. Shot	Ballistic Limit Ft. per Sec. AXS54	Ballistic Limit Ft. per Sec. 31	Dia Hol in Rea
2A-1	.275	06	477/495	402	.30	2034	2034	
A1 7850	.261	070	477	373	.30	1729	1729	
A4 7850		067	460/477	357/387	.30	1579	1583	
A6 7850		074	460/477	351/367	.30	1708	1714	
A9 7850		074	477	373	.30	1587	1644	
2-445	.253	.064	532/555	430/444	.30		2228	
					.50		1183	
.096"		.093	555	416	37MM			29
1/8"								
3-1	.130	.032	387	340	.30		1123	
3-2	.129	.043	418	364	.30	–	1126	

TABLE 5C

	DIA. HOLE IN REAR	SPALLING CHARACTER	C	MN	SI	CR	MO	V	OTHERS	H
			.23	.50	.23	1.37	.77	.26	Ni .10	
9		PETALS	.29	.44	.26	1.36	.71	.22		
3		PETALS	.29	.44	.26	1.36	.71	.22		
		PETALS	.29	.44	.26	1.36	.71	.22		
[illegible]		PETALS	.29	.44	.26	1.36	.71	.22		
8		SPALL }	.30/.35	.40/.60	.15/.25	1.20/1.30	.60/.70	.20/.25		[illegible]
[illegible]		SPALL }								
	295	CRACKED								
3			.26	.52	.20	1.21	.80	.27		
5			.26	.52	.20	1.21	.80	.27		

Mo.	V	Others	Heat To	Quench In	At °F	Draw °F	For Min.	Report No.
.77	.26	Ni .10						
.71	.22		1700 1550	Oil Oil		1000	120	91
.71	.22		1700 1550	Oil Oil		1000	120	91
.71	.22		1700 1550	Oil Oil		1000	120	91
.71	.22		1700 1550	Oil Oil		1000	120	91
.70	.20/.25		1575/1600	Oil		775	120	66+68
.30	.27		1700 1535	Oil Oil		1000		79
.30	.27		1700 1535	Oil Oil		1000		79

expended by the bullet in piercing the case which reduces the shock on the core. The fact that a greater tolerance in the amount of laminated dirt may be present in face hardened plate undoubtedly accounts for the fact that only 13% of the carburized plate tested in the last five years was brittle, while 45% of the homogeneous plate spalled.*

Examples of laminations in good quality carburized plate are given in Figure 17, page V, Figure 30, page IX, and Fig. 34, page X. This condition would not be acceptable in homogeneous plate, see Watertown Arsenal Report No. 710/261, Figure 2A. However, Figures 24 and 25, page VII, shows a lamination so serious that it caused spalling in carburized plate.

Carbides segregated to any extent in the grain boundaries of the case cause spalling and formation of petals. Armor plates illustrated in Figures 9 and 10, page III, Figure 39, page XI, Figure 45, page XIII, and Figures 65 and 66, page XIX, are examples of such a condition. In somearmor plates, a magnification considerably less than that utilized in specifications

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* Figures quoted from Watertown Arsenal Report 710/250

for homogeneous plate (X250 rather than X1000) reveals this carbide condition more clearly, see Figures 48 and 49, page XIV. Both plates illustrated in these figures shattered under 37 mm. impact. If Figure 49 is compared with Figure 50, page XV, it is evident that Figure 50 (X1000) gives no indication of the serious carbide condition revealed by Figure 49 (X250).

An example of ideal carbide arrangement is shown in Figures 2 and 3, page I, as well as in Figures 55 and 56, page XVI.

Plates which show some indications of carbides in the grain boundaries but not to the extent shown in Figures 9 and 10, page III, Figure 39, page IX, or even Figures 48 and 49, page XIV, are 1/2" armor plates #444-2 and #4-446. Plate No. 444-2 is classified as good ballistic plate while plate No. 4-446 is considered brittle, although both plates exhibit nearly similar structures. However, plate No. 4-446 was tested with caliber .50 A.P. and spalled, although under caliber .30 A.P. it was ballistically ductile. Since plate No. 444-2 was tested only with caliber .30 A.P., it is reasonable to assume that this also would spall under caliber .50 A.P. impact. Therefore, even a slight tendency to carbide segregation in grain boundaries must be considered undesirable.

With the exception of Plate "D", the microstructure of all carburized cases is a troostite or troostito-sorbite. In addition, a few plates show a transition zone between case and core with a decided martensitic structure, see Figures 57 to 60, inclusive, page XVII, and Figures 67 and 68, page XIX. Since both these plates spalled, this martensitic zone may be a contributing factor to their brittleness.

In Plate "D", at the extreme edge of the case, an austenito-martensitic structure was found, following which was the normal troostitic case structure, see Figures 40 to 42, inclusive, page XII.

In a good many armor plates 1/2" thick and heavier, uniformly distributed massive carbides were found on the extreme edge but no relationship between their presence and ballistic properties could be detected. Typical examples of these massive carbides are illustrated along with the structures of the case of the plate in which they occurred.

Martensitic structures in the core invariably cause spalling, see Plate "F", Figure 73, page XX, Plate 096, Figure 76, page XXI, Plate 027, Figure 53, page XV.

The core Brinell hardness of Plates "F", 096 and 027, was reported as 512, 418 and 444/495, respectively.

An example of good sorbitic core structure (Brinell 387) in a high ballistic plate is shown in Figure 7, page II, while a sorbito-troostitic structure (Brinell 430/444) of a similar appearance occurs in brittle plate, see Figure 47, page XIII.

Varying amounts of ferrite uniformly distributed in sorbite are permissible. For example, high ballistic plate No. 444-2 has a small amount of ferrite very uniformly distributed, see Figure 18, page V. Plate No. "R" exhibits the same type of structure only with larger ferritic areas, see Figure 60, page XVII. When, however, the ferrite areas become the size of those shown in Figure 33, page IX, a degree of softness is reached which is not desirable, a condition which we classify as ferritic, see note 1, Table 1.

Also, ferrite segregations of the type illustrated in Figure 29, page VIII, and Figure 63, page XVIII, are not found in high ballistic plate.

Typical macrostructures of good and poor face hardened plate are given on page XXII.

It was found that in all cases carburization of the rear face promoted spalling. An example of carburization of the rear face is shown in Figure 68, page XIX.

In Table 3 a classification is made of Brinell hardnesses according to whether the plate passed specifications, failed to meet the ballistic limit, or was brittle. As a rule, when the Brinell hardness of the case is below 500, the plate is not able to meet the ballistic requirements.

In Table 4 is given an analysis of case depth to ballistic properties of 1/2" and 1/4" plate of the following classification: passing specifications; failing to meet specifications; and brittle plate. No relationship between case depth and ballistic properties can be deduced from the results in Table 4.

In connection with the microscopic examination of face hardened plate, a microscopic study was made on partial penetrations of face hardened 1/4" plate subjected to impact with caliber .30 A.P. bullets.

Figures 81 and 82, page XXIII, illustrate the macrostructure of sections cut through the partial penetrations. The irregular light colored areas are portions of fused bullet cores. The case is deformed as well as the core in the area of impact.

Figure 83, page XXIII, illustrates a crack in the case which was subjected to impact.

*White layer, which was previously revealed in the vicinity of penetrations of homogeneous armor plate (see W.A. Report No. 710/197), was readily detected at the junction of the bullet core and carburized case and also in the fused bullet core, see Figure 83, page XXIII, and Figures 84, 85, 86, and 87, page XXIV.

In the study of homogeneous plate, the white layer was not found in the core of the penetrating bullet. This is indicative of the greater amount of work done on the bullet core by the case of carburized plate in comparison to a homogeneous plate.

Proof that the nose of the bullet and that some areas along the junction of bullet core and outer case melted under impact is indicated by the presence of tiny dendritic structures shown in Figures 84 and 85, page XXIV. It is well known that dendritic structures result from solidification of metals from liquid state.

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*Sufficient heat has been generated to raise the temperature of these localized slip areas above the critical, or in some cases, even to the melting point; The sudden chilling of these areas forms layers which are referred to as "white layers".

Respectfully submitted,

E. L. Reed,
Research Metallurgist.

S. L. Kruegel,
Jr. Phys. Science Aide.

5/8" Plate #4911B

Brinell Hardness (Case 578
Core 387   Case Depth .154"

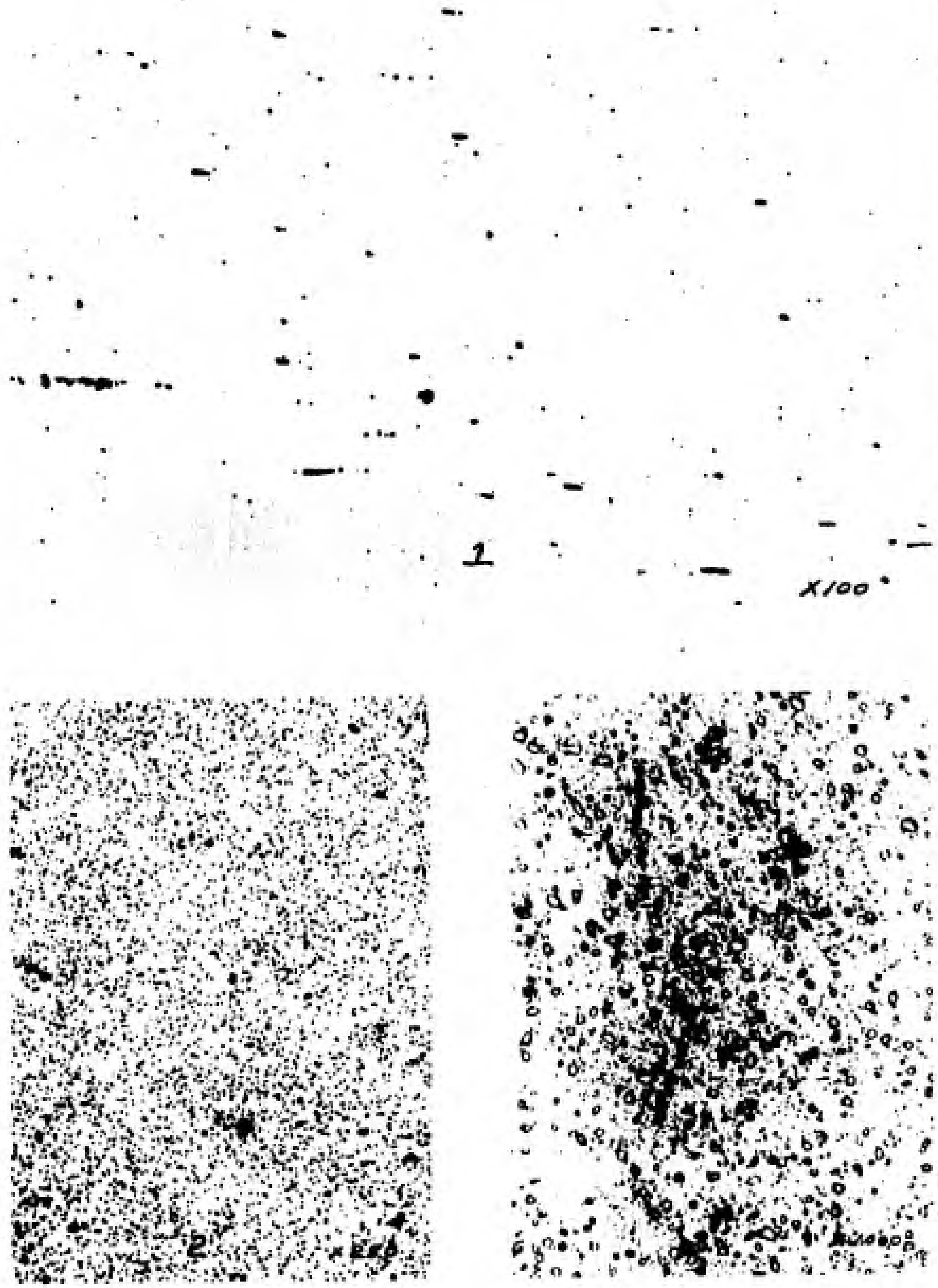
No Spall; Ballistic Limit 2300 ft/sec. (estimated)
Caliber .50 A.P., Specification AX954-2

(1) Uniform distribution of rounded nonmetallic inclusions.
Unetched, X100   MA1307

(2) Uniform carbide distribution in case.
Murakami Etch, X250   MA1339

(3) Greater magnification of carbides again shows even distribution.
Murakami Etch, X1000   MA1309

I



W.A. 639-1521

5/8" Plate #4911B (Cont.)

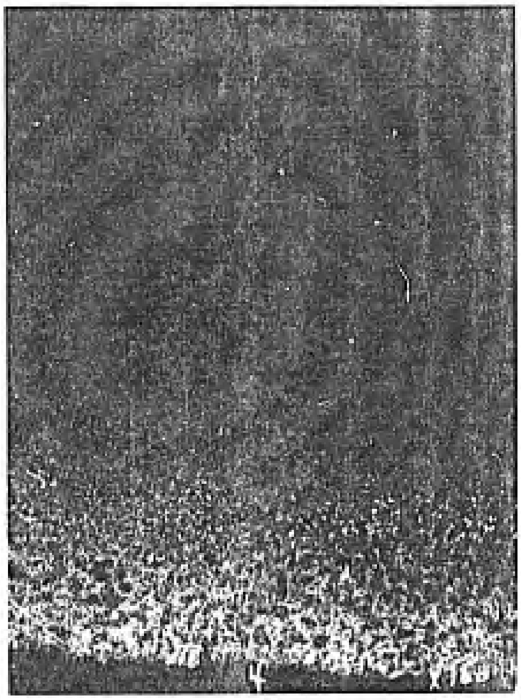
(4) Slight decarburization of case with remnants of massive carbides at edge.
X100 MA724

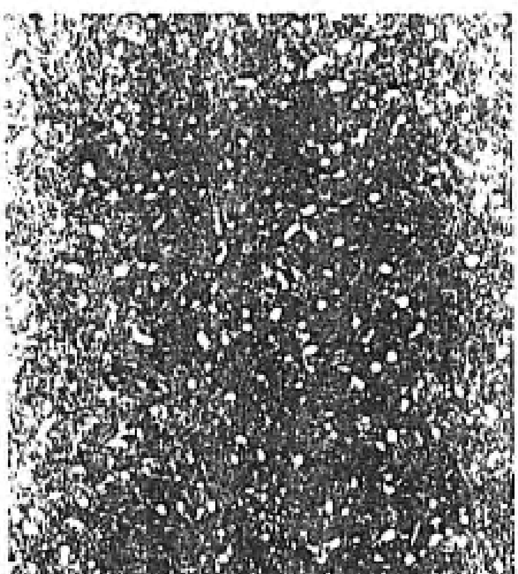
(5) Shows structure of massive carbides at outer edge of case, resembling ledeburite.
X1000 MA727

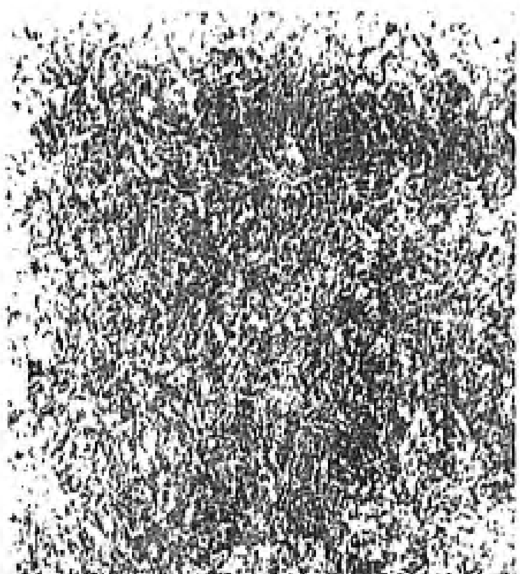
(6) Uniform distribution of medium sized carbides in sorbito-troostite, constitutes main portion of case.
X1000 MA729

(7) Uniform sorbitic core structure.
X1000 MA728

1% Nital etch in all figures.







W.A. 639-1522

5/8" Plate #C2D238

Brinell Hardness (Case 578 / Core 364) Case Depth .173"

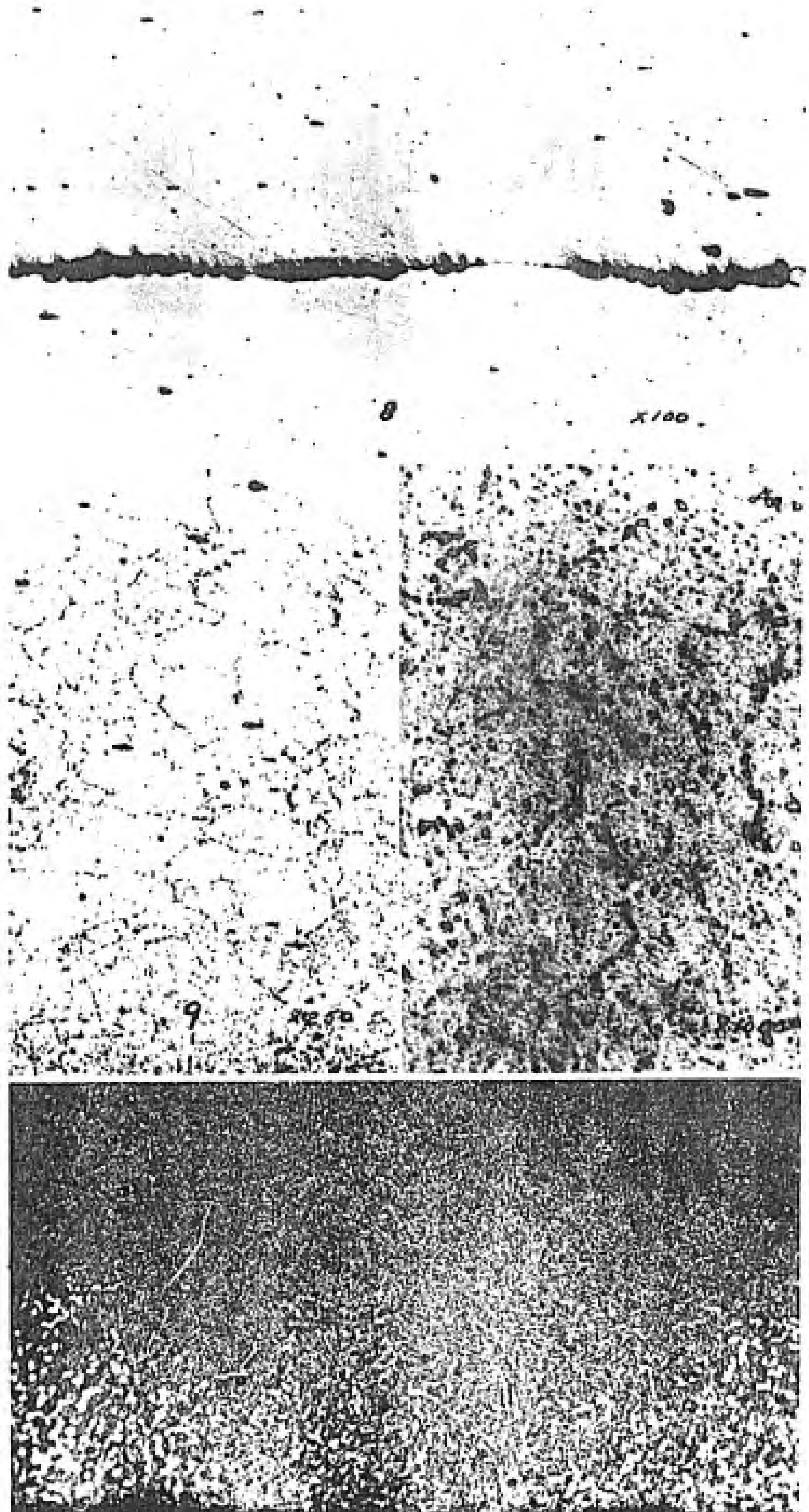
Spalled; Ballistic Limit 2283 ft/sec. with Caliber .50 A.P., Specification AXS64-2

(8) Very large elongated nonmetallic inclusion.
Unetched, X100 MA1306

(9) Nearly continuous carbide chains outlining grain boundaries in case.
Murakami etch, X250 MA1338

(10) Same condition as (9) shown for X1000.
Murakami etch. MA1308

(11) Massive carbides at outer edge of case.
1% Nital etch, X100 MA722



W.A. 639-1523

3/8" Plate #C2D238 (Cont.)

(12) Ferritic streak which runs through core.
X100 MA723

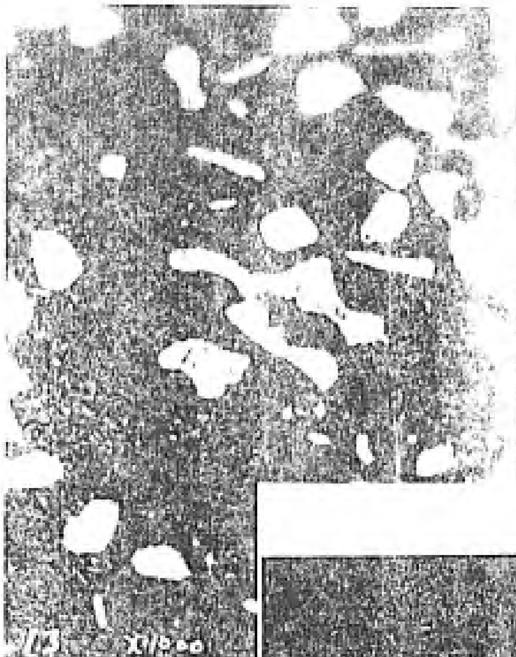
(13) Structure of massive carbides in Figure (11) resembles ledeburite.
X1000 MA730

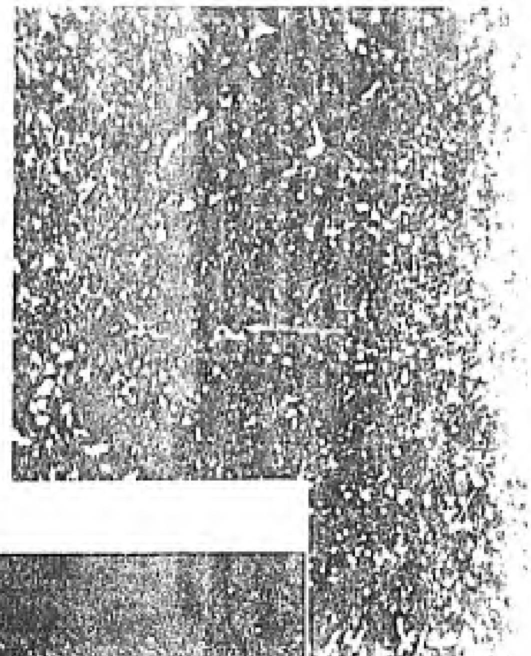
(14) Troostito-sorbite in central portion of case shows many carbides, the larger sized ones being segregated at the grain boundaries.
X1000 MA731

(15) Tempered martensite found in major portion of core.
X1000 MA733

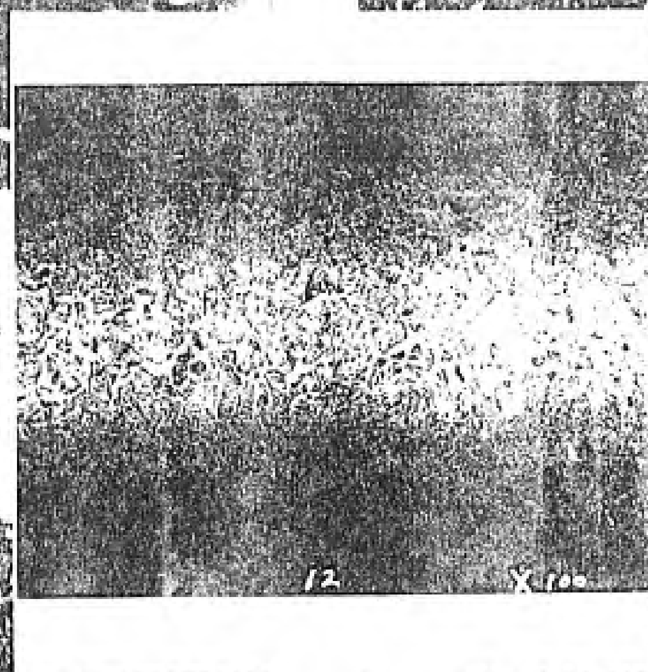
(16) Higher magnification of ferritic streak where it joins the normal core structure. Slag appears at the sharp demarcation between ferrite and tempered martensite.
X1000 MA732

All etched in 1% Nital.





W.A. 639-1524



1/2" Plate #444-2

Brinell Hardness (Case 555 Core 364) Case Depth .147"

No spall; Ballistic Limit 3076 ft/sec. with Caliber .30 A.P.; Specification 31.

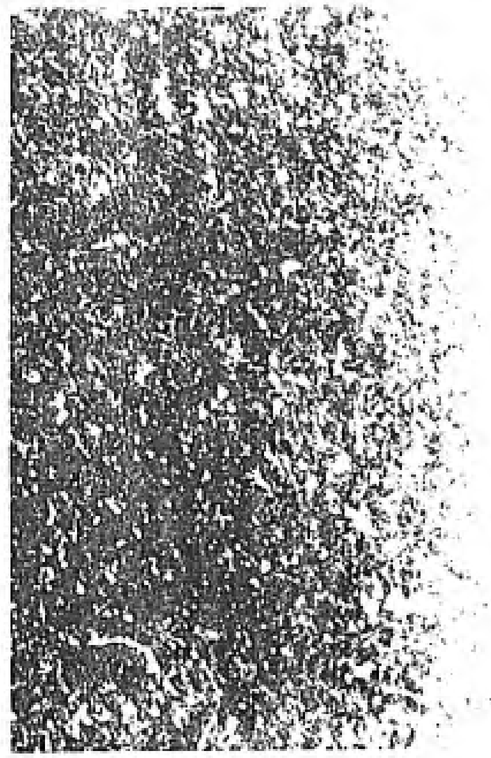
No spall, Machine Gun Fire Caliber .30.

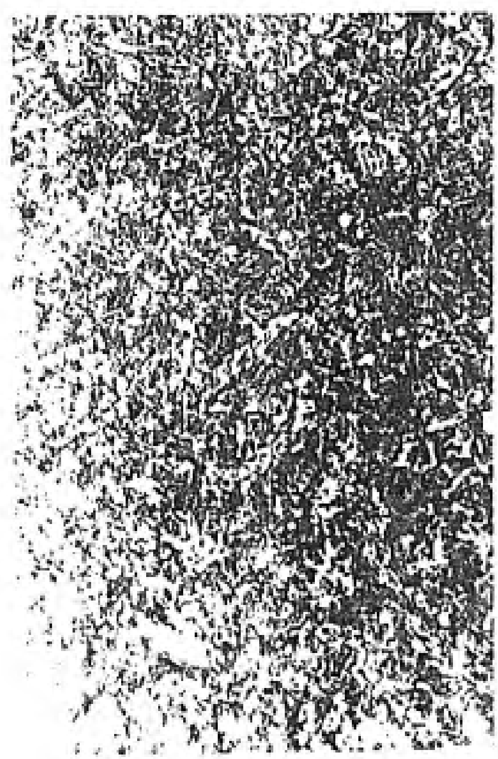
(17) With this degree of laminations, it is doubtful whether it would pass Specification AX504-K. This amount would certainly cause spalling in homogeneous plate.
Unetched, X100 MA1240A & B

(18) Troostite-sorbite case structure shows slight tendency to form carbide chains in boundaries.
1% Nital etch, X1000 MA1241

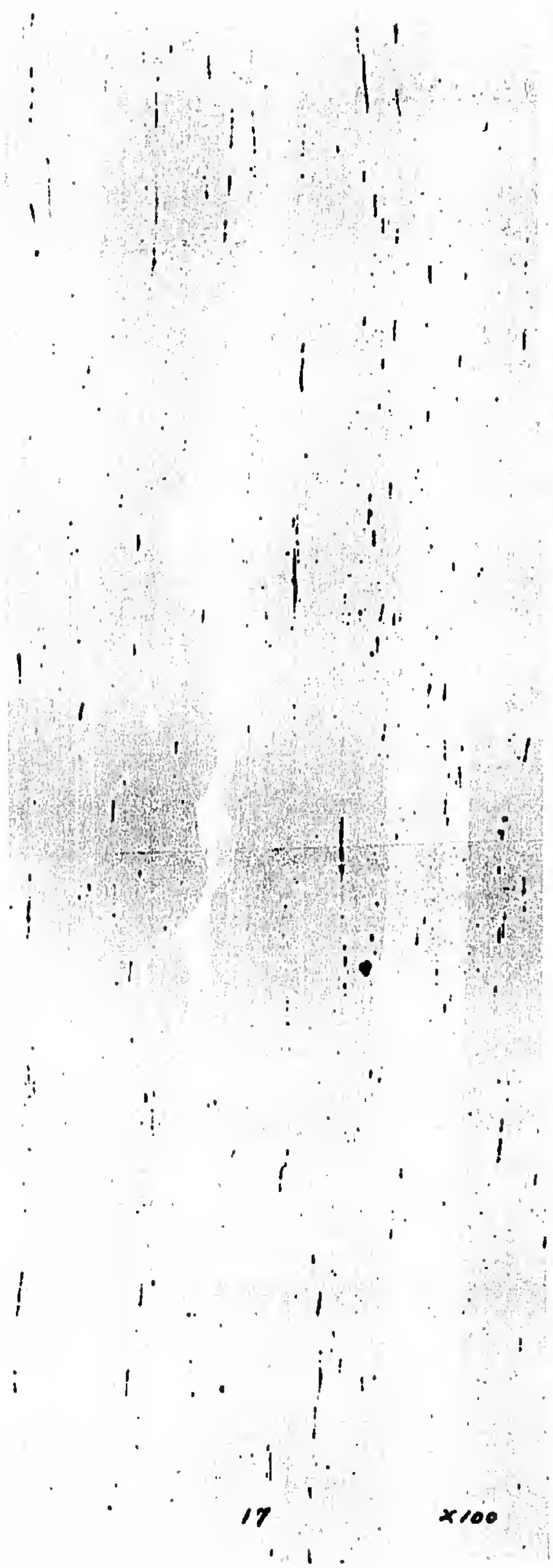
(19) Uniform ferrite distributed equally throughout sorbitic core.
1% Nital etch, X1000 MA1242

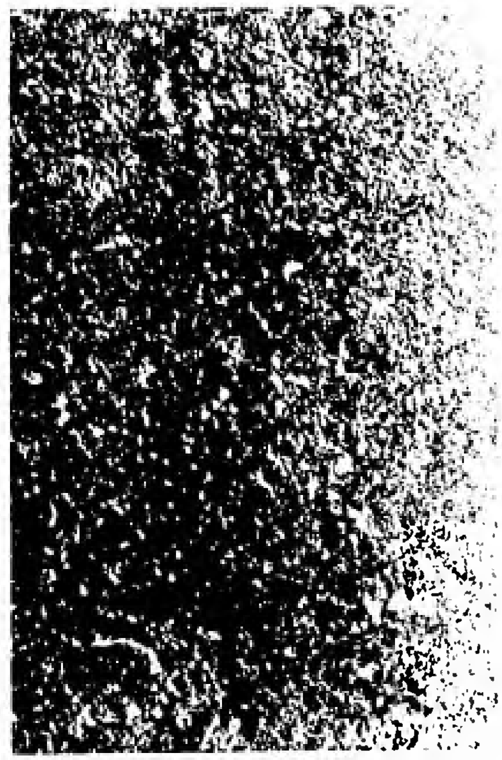
IV

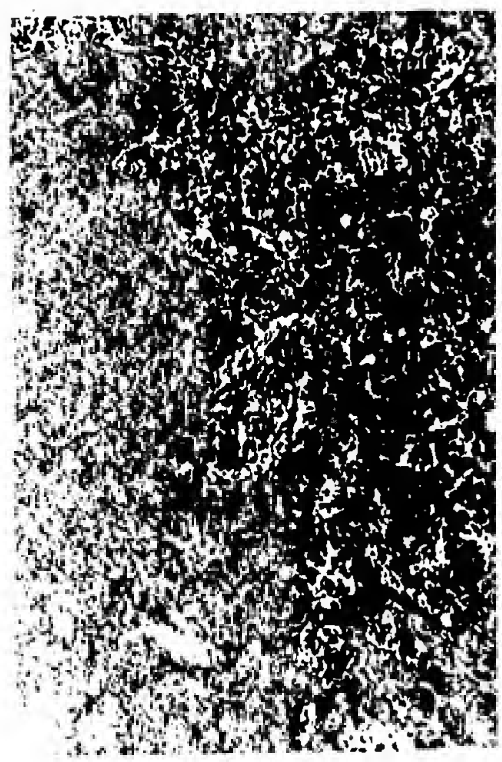




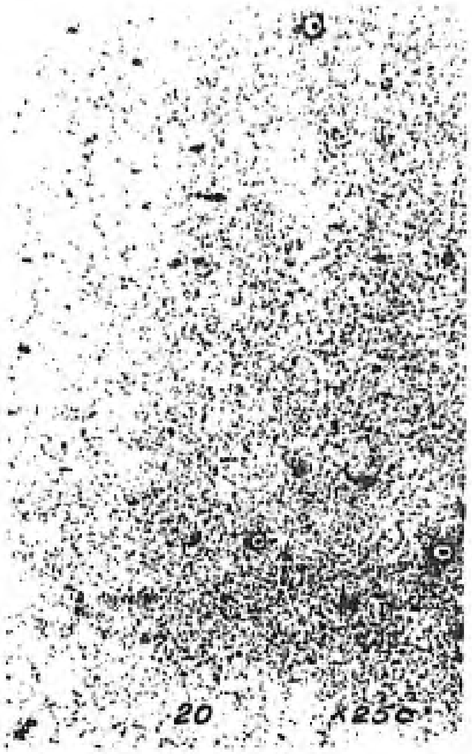
W.A. 639-1525







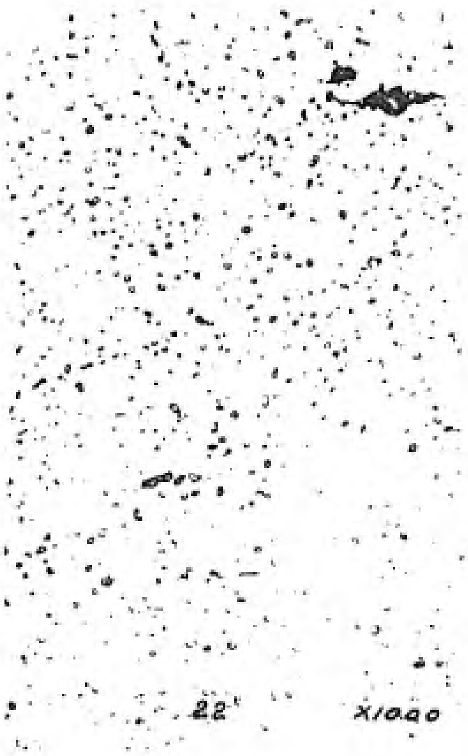
W.A. 639-1525



20 x250

21 x1000

W.A. 639-1526



22 x1000

23 x1000

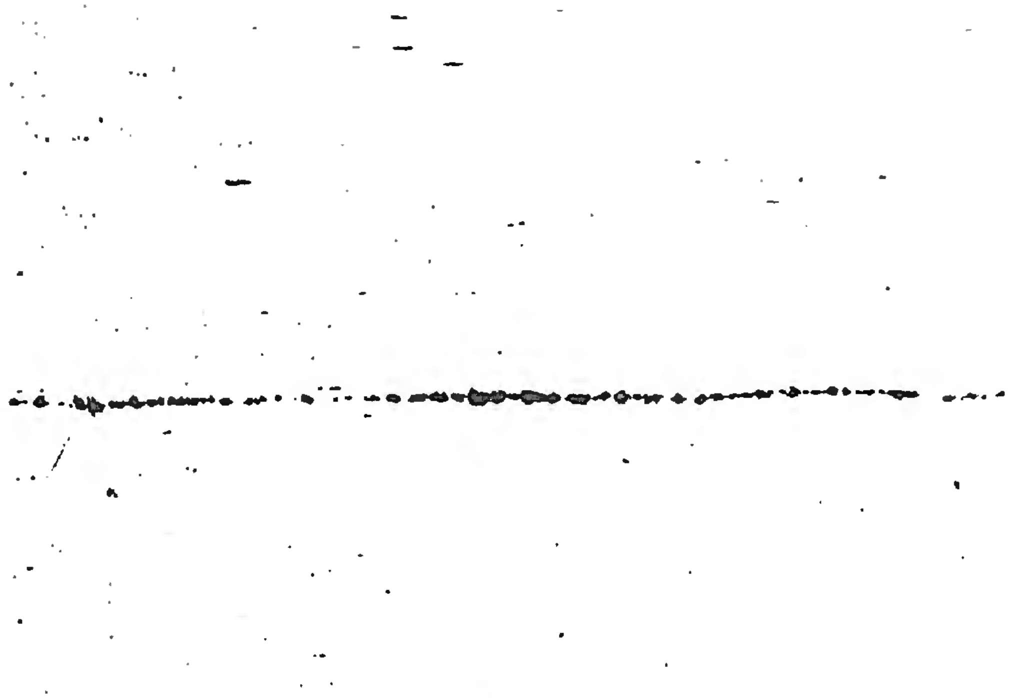
1/2" Plate #4-444

Brinell Hardness (Case 577/600, Core 340)   Case Depth .153"

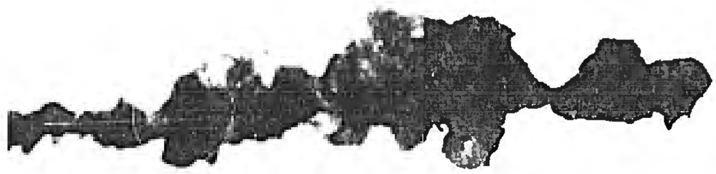
No Spall; Ballistic Limit 2929 ft/sec. with Caliber .30 A.P., Specification 31.
Cracked, 2164 ft/sec. at 15° angle, caliber .50 .P.

(24) Bad stringer of nonmetallic inclusions.
Unetched, X100   MA1167

(25) High magnification of stringer shown above.
Unetched, X1000   MA1170

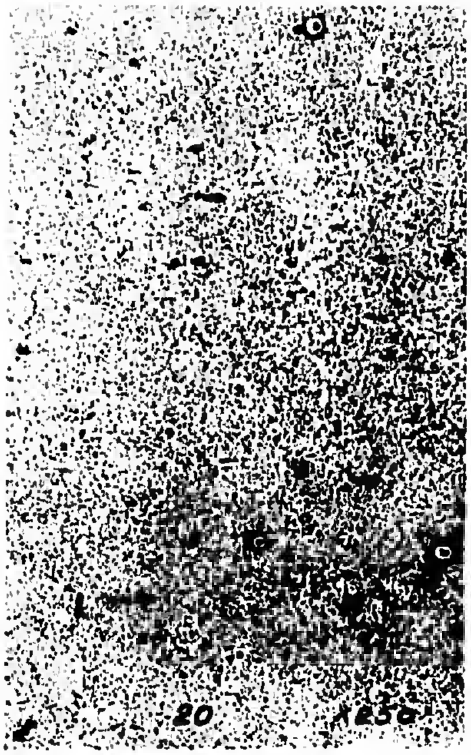


24 x100



25 x1000

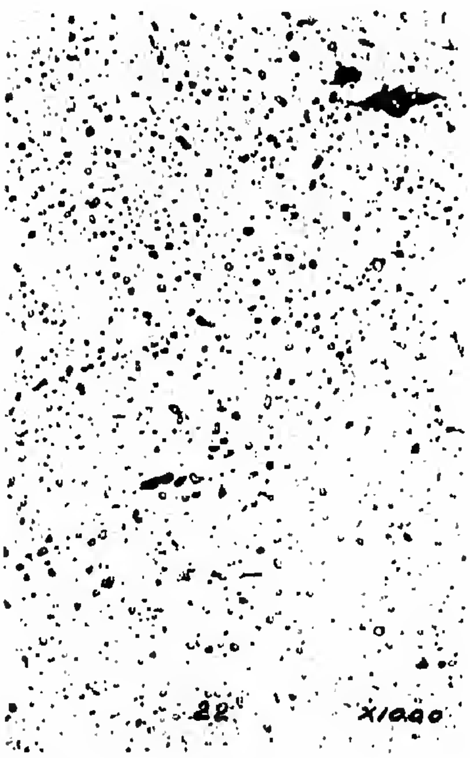
W.A. 63 1527



20 X250

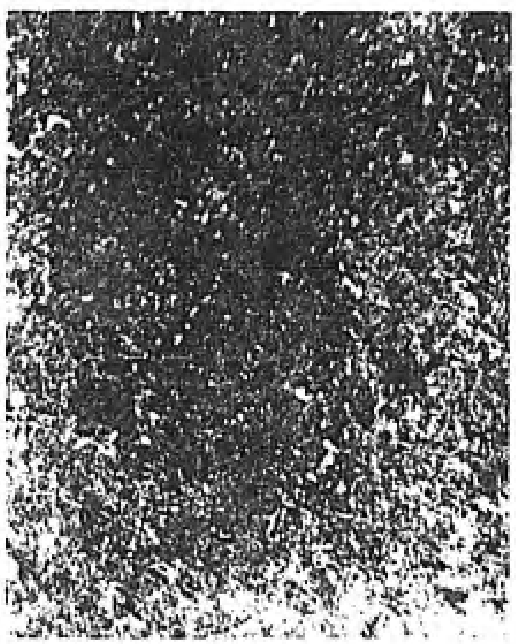
21 X1000

W.A. 639-1526



22 X1000

23 X1000



W.A. 633-1[illegible]

1/2" Plate #1-1

Brinell Hardness (Case 495 / Core 311/321 : Case Depth = .124"/.132"

No Spall; Ballistic Limit 2366 ft/sec., Spec. AX354-2 with Caliber .30 A.P.; Ballistic Limit 2626 ft/sec., Spec. 31

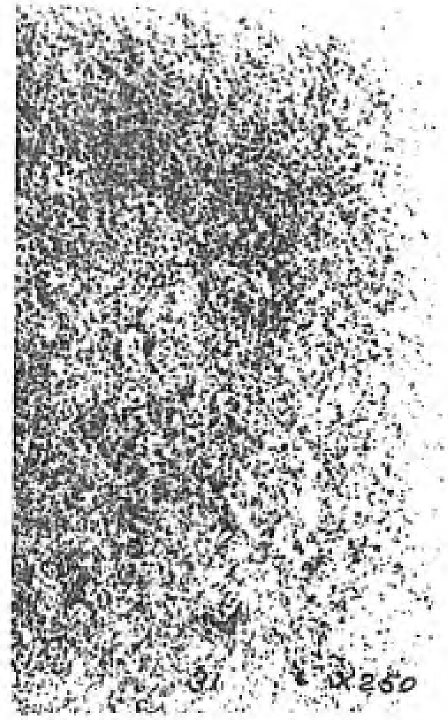
(30) Bad laminations of nonmetallics.
Unetched, X100 MA1343

(31) Uniform carbide distribution in case.
Murakami etch, X1000 MA1347

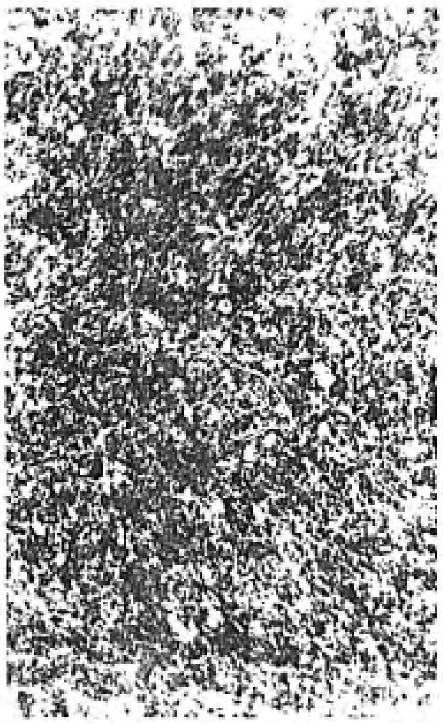
(32) Troostite-sorbite case structure.
1% Nital etch, X1000 MA1355

(33) Large patches of ferrite uniformly distributed throughout the sorbitic core.
1% Nital etch, X1000 MA1368

30 X100



31 X250



W.A. 639-1599

1/4" Plate #4A2

Brinell Hardness (Case 430/444 Core 364   Case Depth .057"

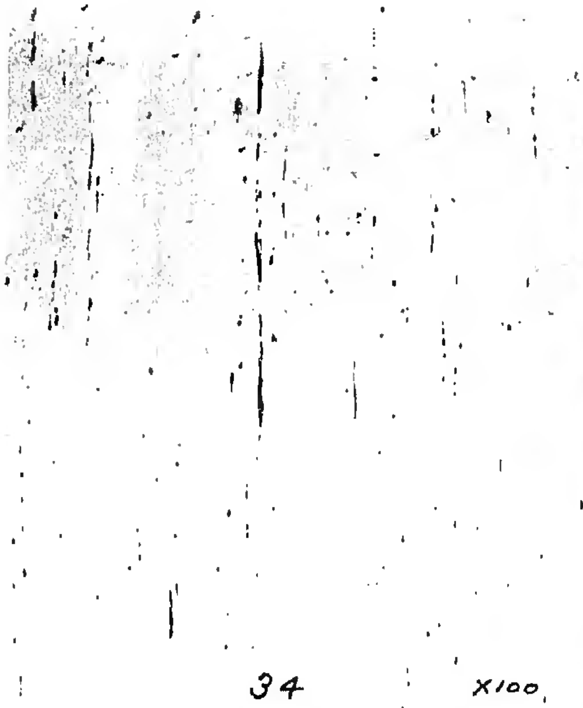
No Spall; Ballistic Limit 1916 ft/sec. with Caliber .30 A.P., Specifications AX554-1 and 51

(34) Bad laminations of nonmetallics.
Unetched, X100   MA1348

(35) Uniform carbide distribution in case.
Murakami etch, X1000   MA-1352

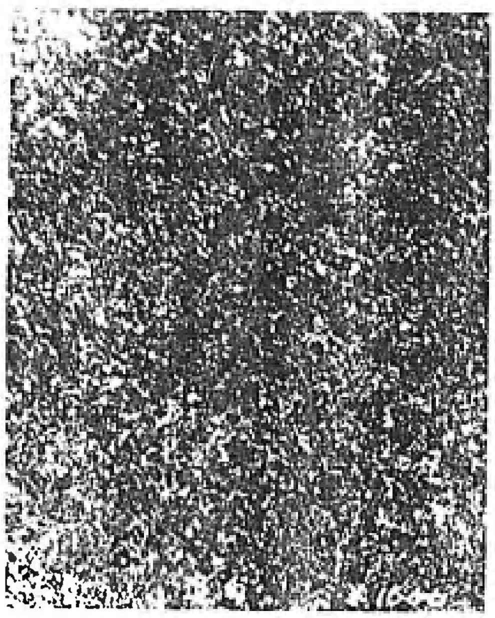
(36) Troostito-sorbitic case structure.
1% Nital etch, X1000   MA-1356

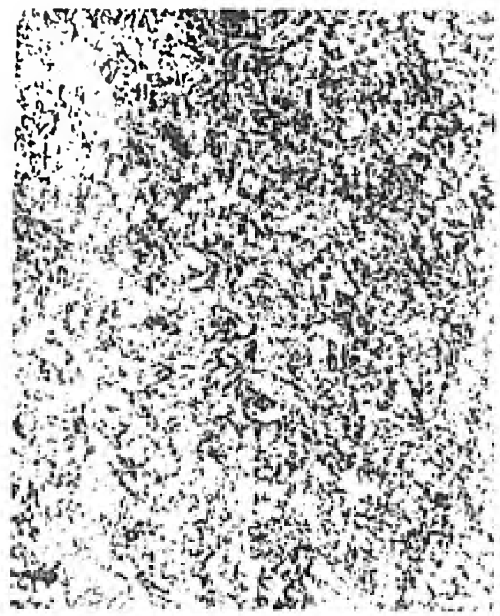
(37) Uniform ferrite distribution in sorbitic matrix.
1% Nital etch, X1000   MA-1359



34 X100

35 X1000





W.A. 65[illegible]-1530

1-1/2" Plate #D

Brinell Hardness (Case 662 / Core 351)   Case Depth .212"

Spalled on face; Ballistic Limit 1934 ft/sec. with 37 mm. 1.86 lb. A.P. solid shot.

(38) Average quantities of rounded nonmetallics are not "strung out" in any way.
Unetched, X100   MA1257

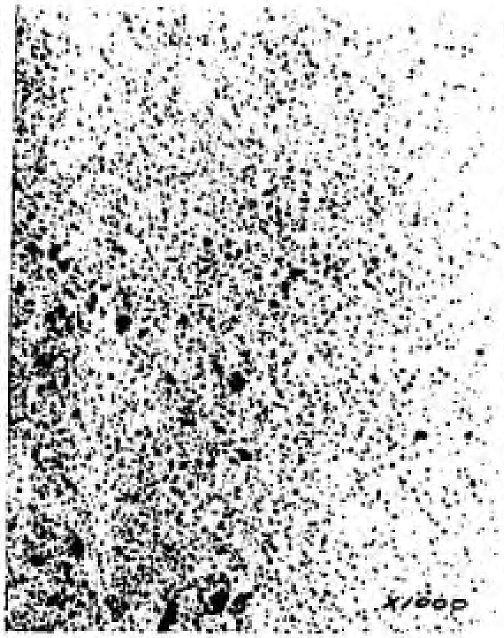
(39) Distinct chains of carbides outline grain boundaries in case.
Murakami etch, X1000   MA1273

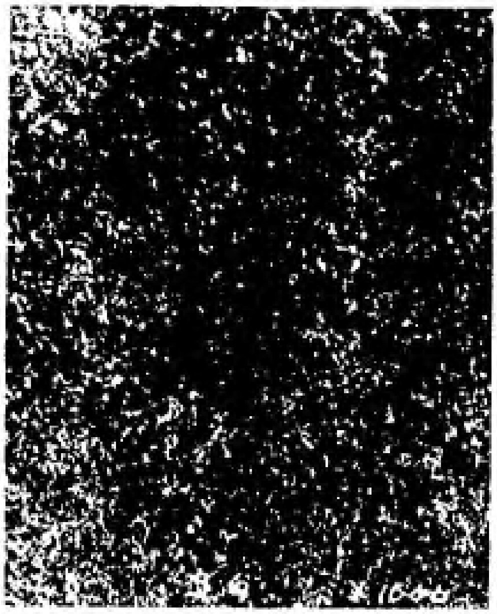
XI

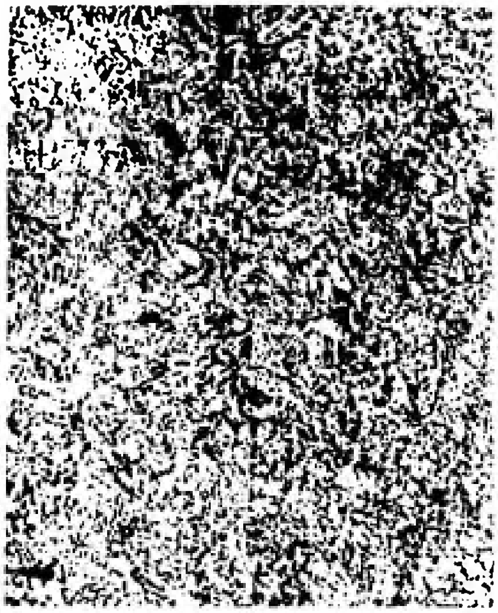
38 X100

39 X1000

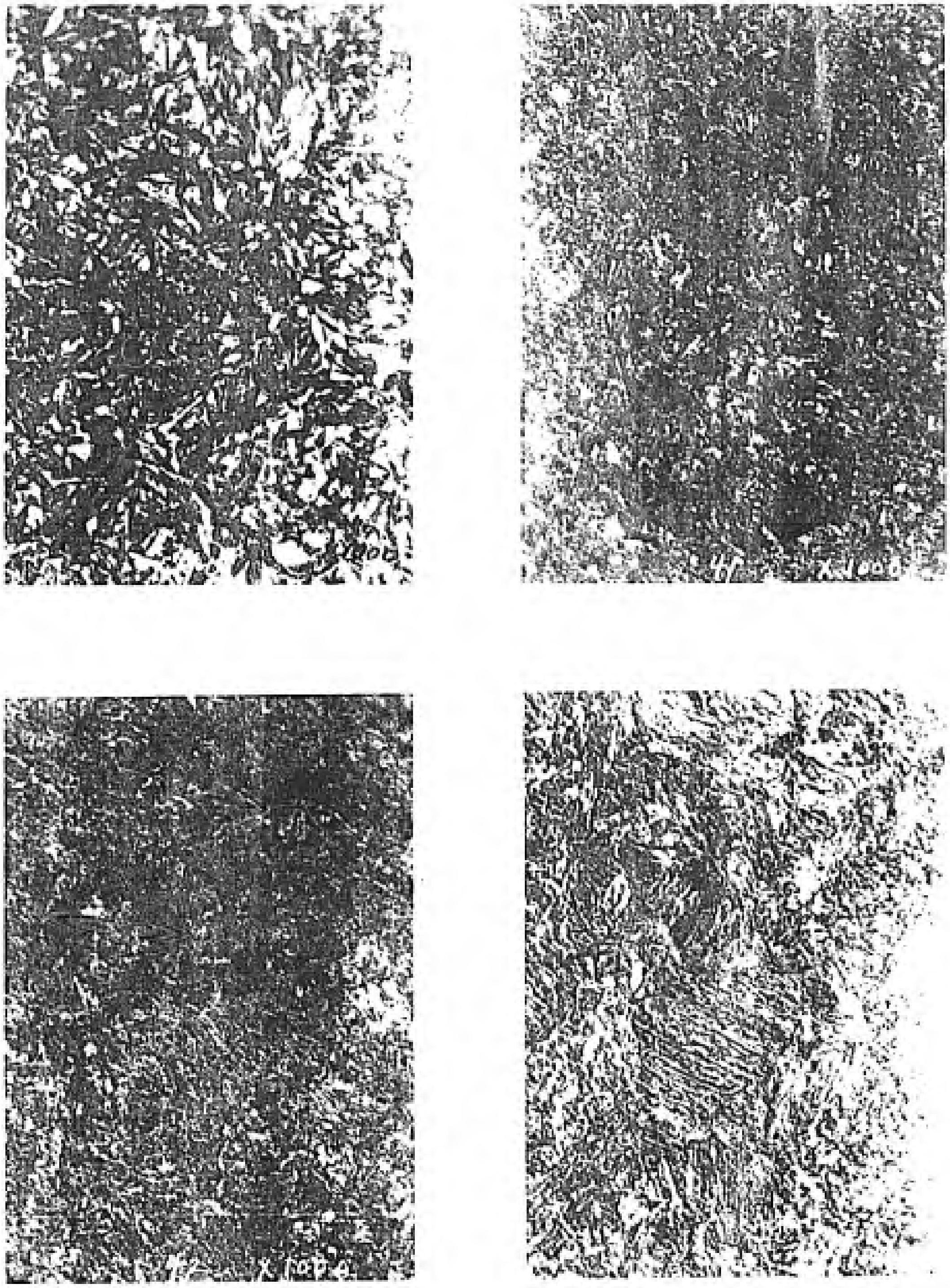
W.A. 639-1531







W.A. 639-1550



W.A. 634-1537

1/4" Plate #2-448

Brinell Hardness (Case 532/555 Core 430/444 Case Depth .064"

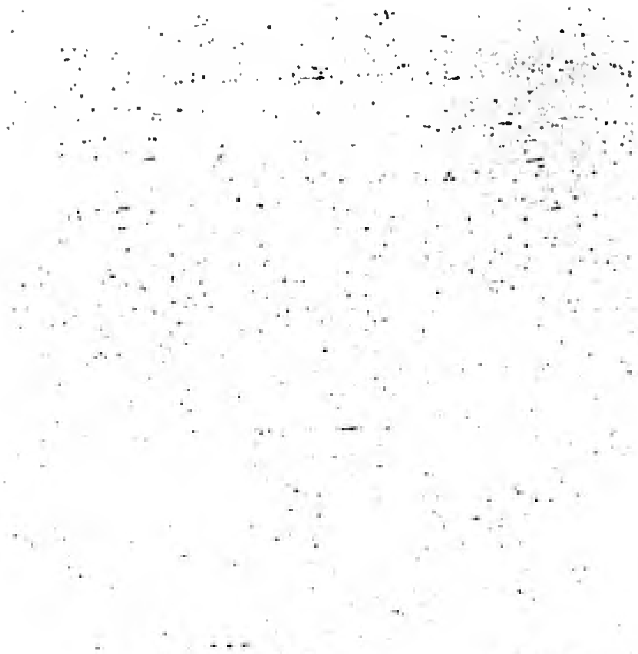
Spalled; Ballistic Limit 2228 ft/sec. with Caliber .30 A.P., Specification 31.
Spalled; 1183 ft/sec., Caliber .50 A.P.

(44) Dirt shows short laminations but not as long as usual.
Unetched, X100 MA1290

(45) Grain boundary carbides in case.
Murakami etch, X1000 MA1247

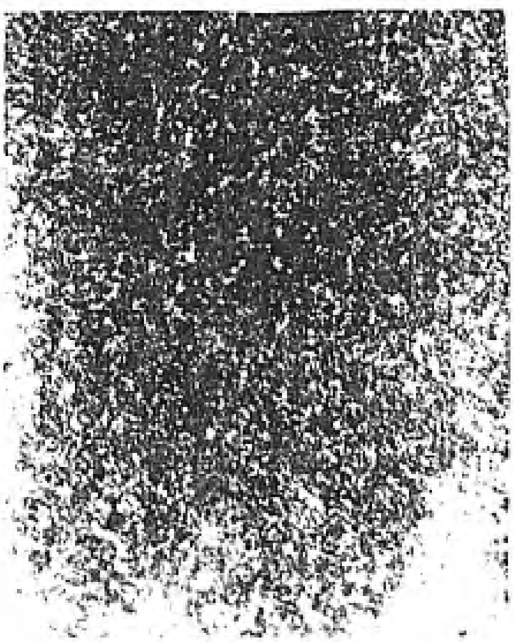
(46) Troostite-sorbite in case.
1% Nital etch, X1000 MA1250

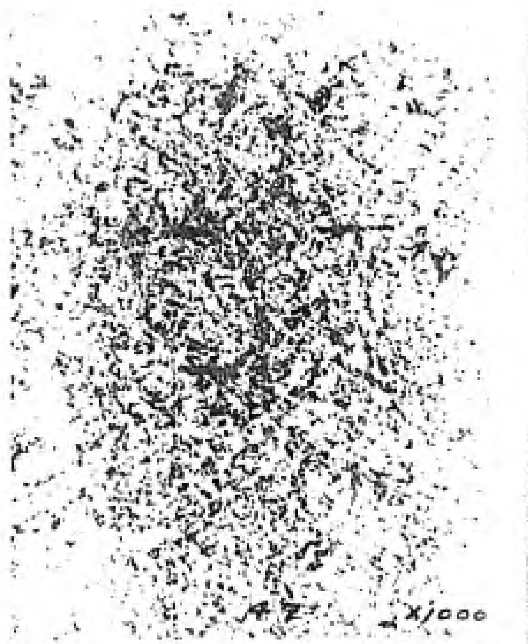
(47) Uniform sorbite and troostite in core.
1% Nital etch, X1000 MA1251



44 x100

45 x1000





47 x1000

W.A. 632-1533

1/2" Plates #026 and #027

Plate #026

Brinell Hardness (Case 495
Core 418   Case Depth .125"

Cracked. Diameter of hole in rear 5.50" blown out 37 mm. 1.45 lb. solid shot.

(48) Grain boundary carbides in case.
X250   RA1316

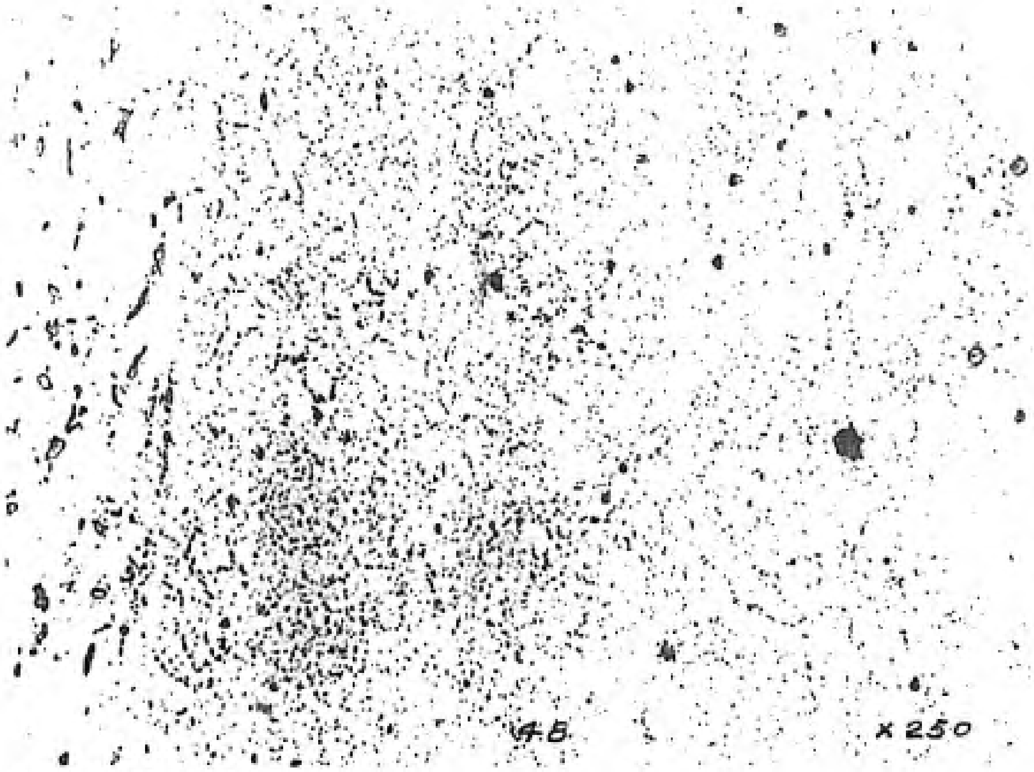
Plate #027

Brinell Hardness (Case 578
Core 444/495   Case Depth .113"

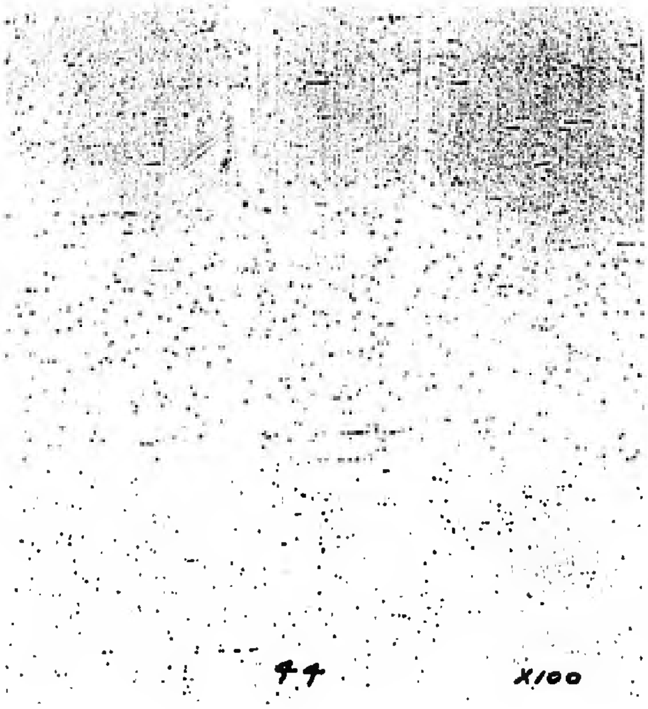
Cracked. Diameter of hole in rear 5.55" blown out 37 mm. 1.45 lb. solid shot.

(49) Grain boundary carbides in case.
X250   RA1317

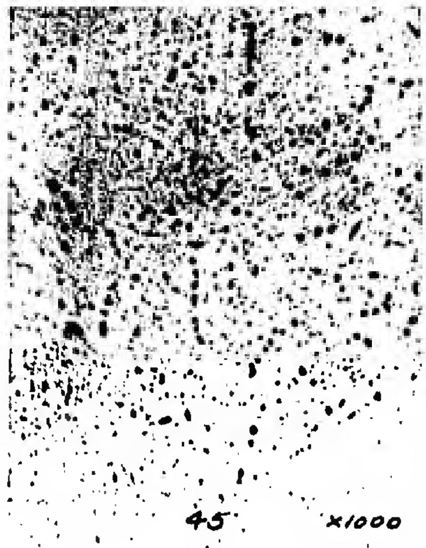
Both figures had Murakami etch.



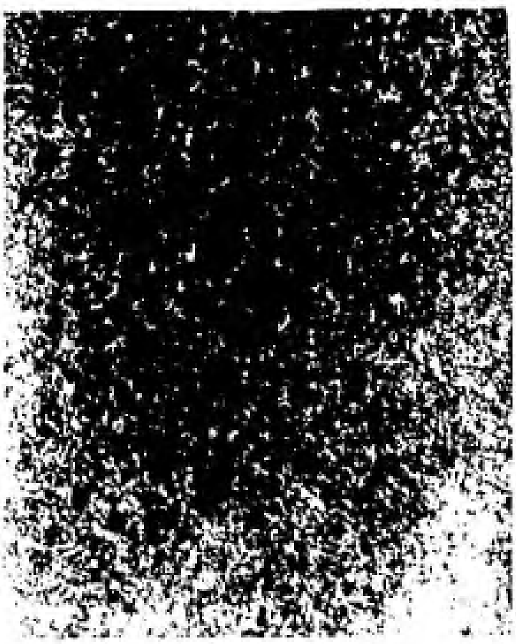
W.A. 639-1534

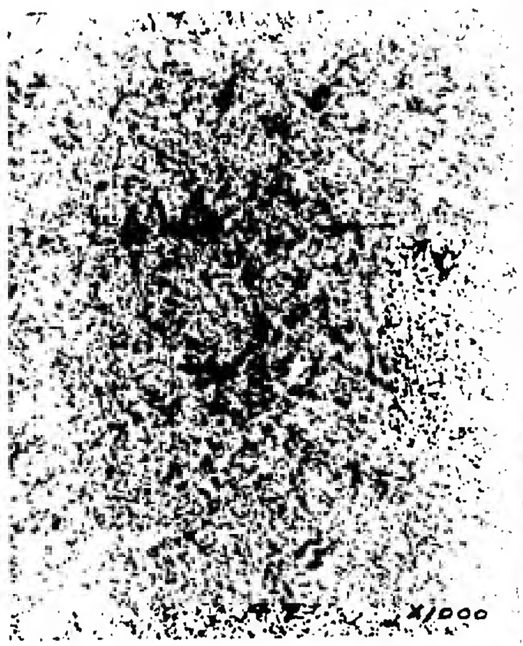


44 X100



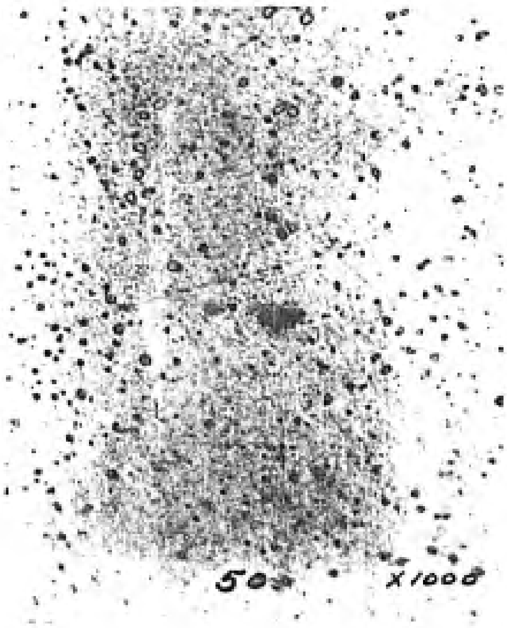
45 X1000

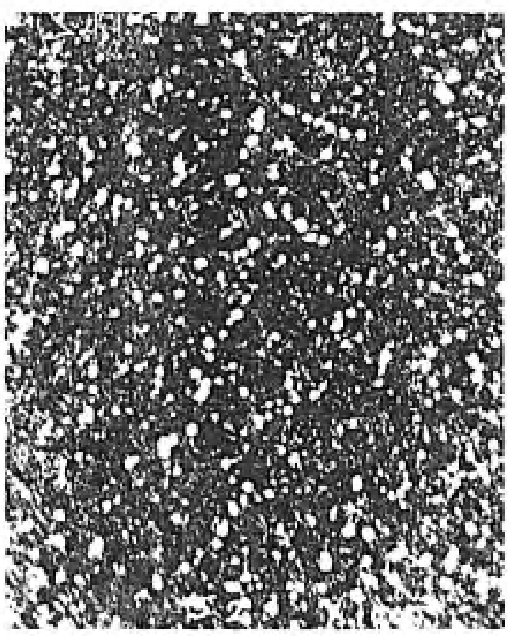




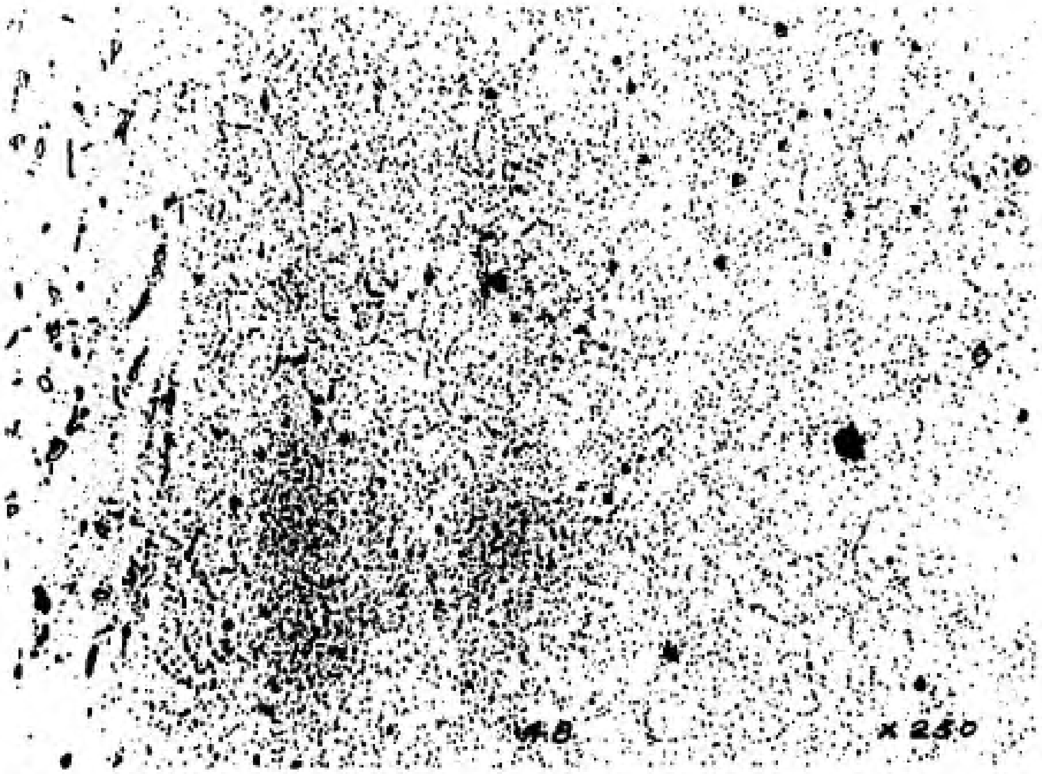
47 X1000

W.A. 639-1533

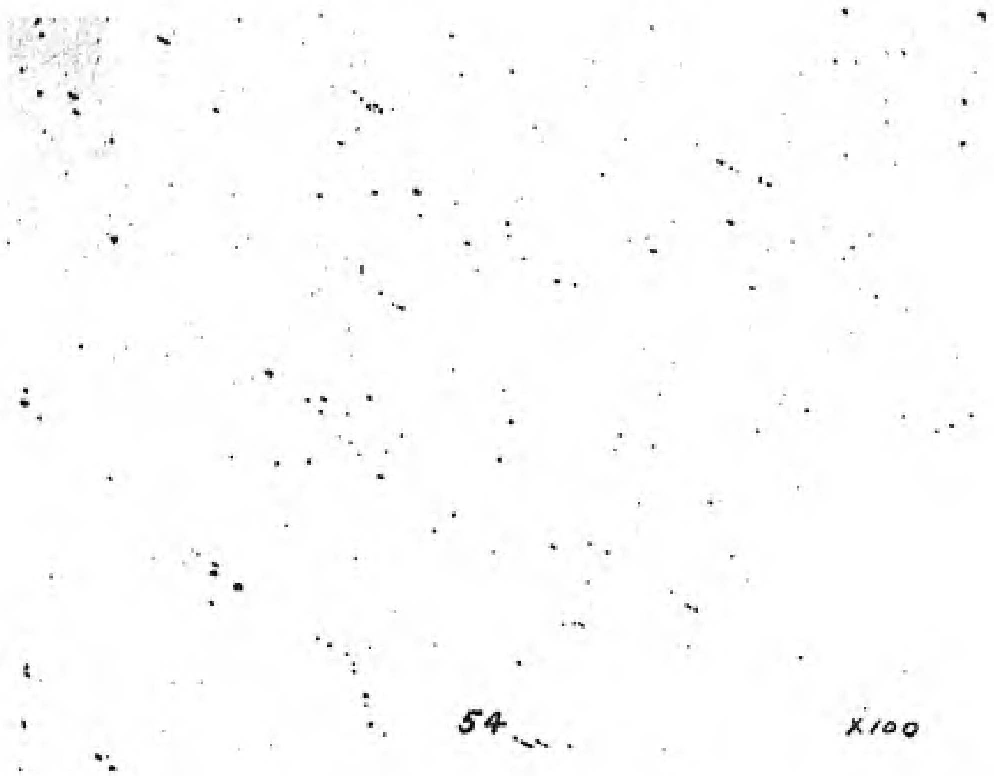




W.A. 639-1535



W.A. 639-1534



W.A. 639-1536

1-1/4" Plate #A (Cont.)

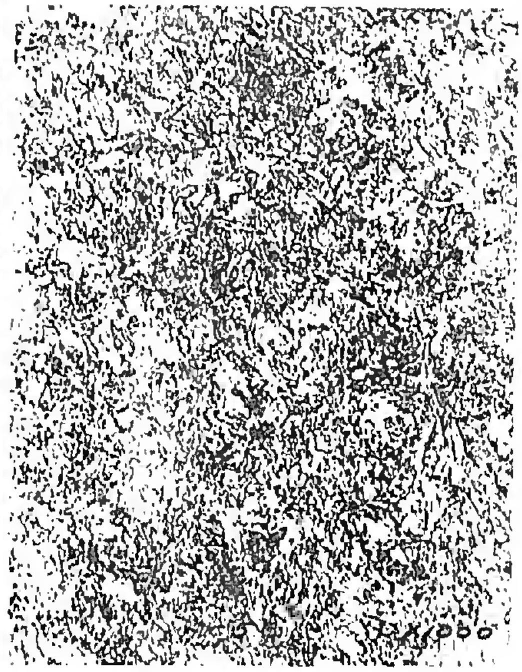
(57) Structure of outer case.
X1000 MA1158

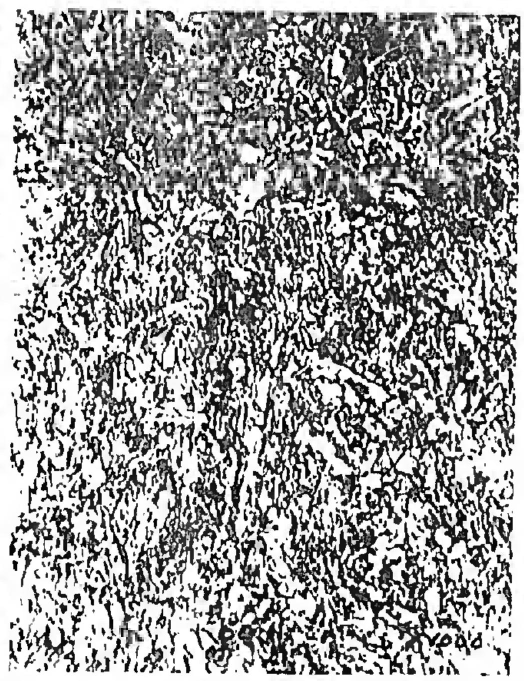
(58) Fine martensito-troostite in center case.
X1000 MA1161

(59) Coarse tempered martensite of rear case.
X1000 MA1160

(60) Fairly uniform distribution of ferrite patches in sorbitic core.
X1000 MA1159

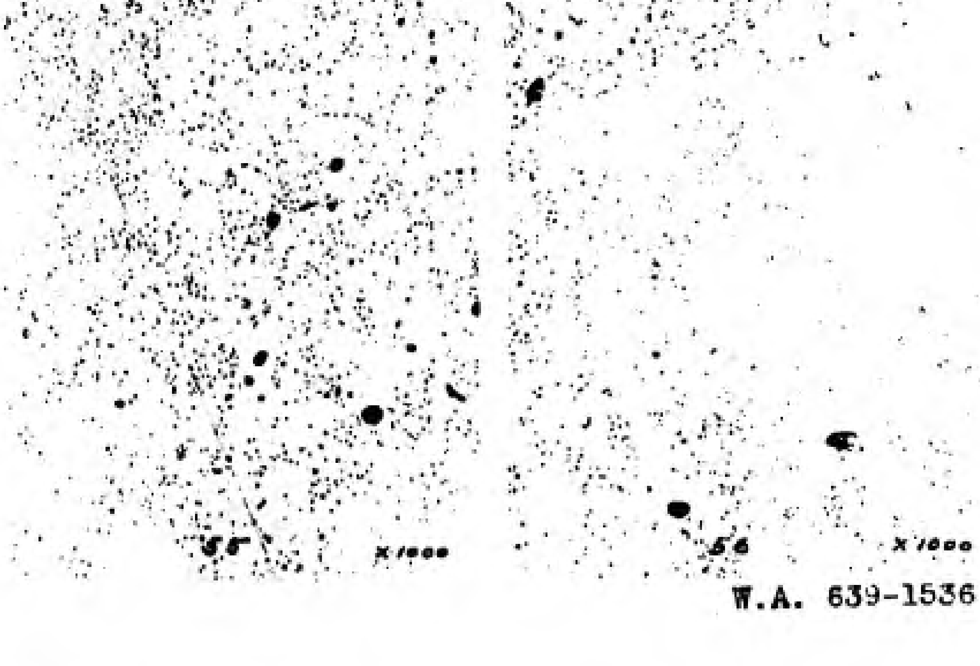
All figures etched in 1% Nital.



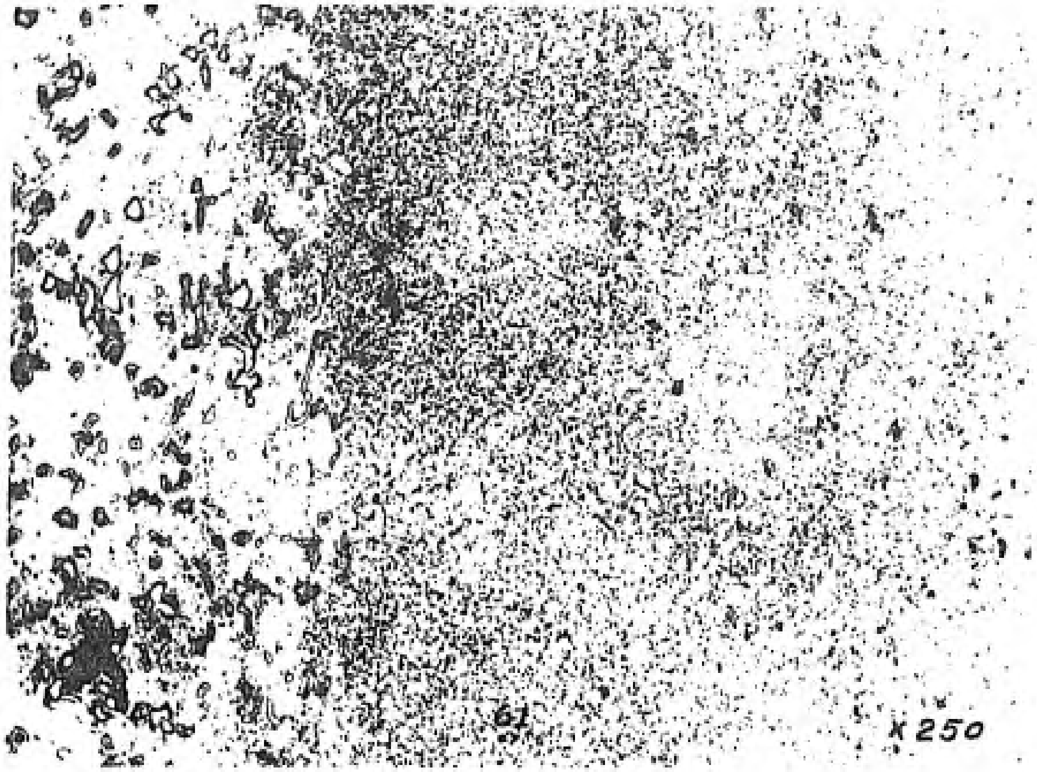


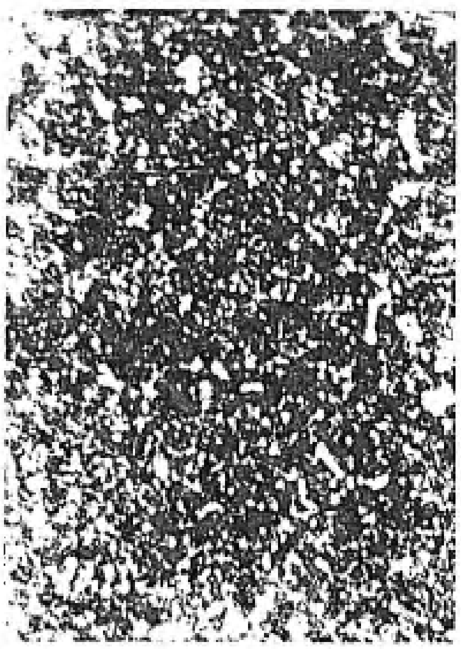
W.A. 639-1537

X



W.A. 639-1536





W.A. 639-1538

1/2" Plate #6-444

Brinell Hardness (Case 627 / Core 381)   Case Depth .128"

Petals; Ballistic Limit 3174 ft/sec., Cal. .30 A.P., Specification 31.
Spalled; Ballistic Limit 2676 ft/sec. at 30° angle, Caliber .50 A.P.

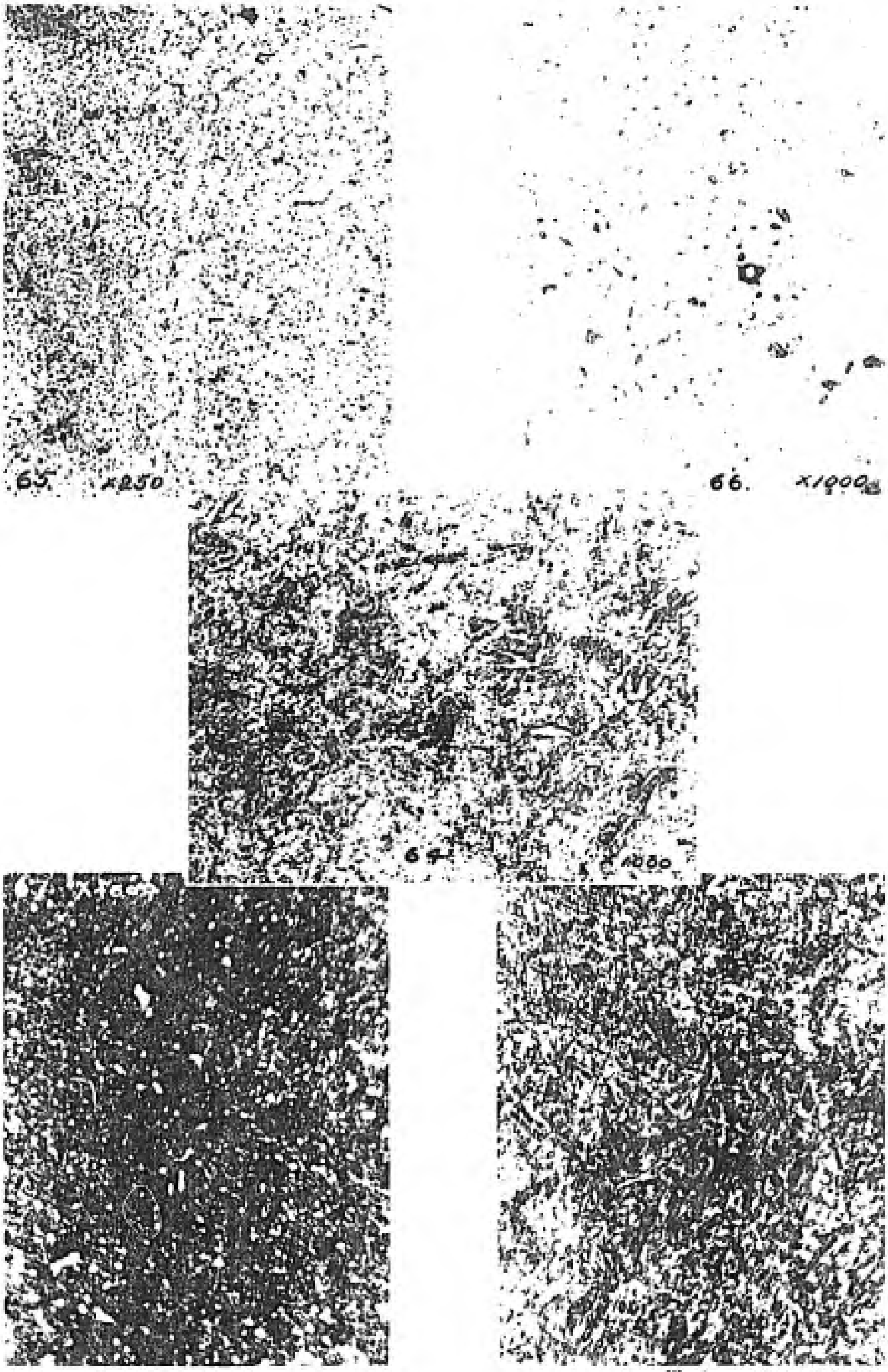
(64) Ferritic segregations in sorbitic core.
1% Nital etch, X1000   MA1245

(65) Grain boundary carbides in case.
Murakami etch, X250   MA1384

(66) Higher magnification of Figure (65). Still shows chains of carbides around grain boundaries.
Murakami etch, X1000   MA1178

(67) Troostite-sorbite in case.
1% Nital etch, X1000   MA1[illegible]43

(68) Troostite-sorbite with traces of tempered martensite found on rear face (not supposed to be carburized).
1% Nital etch, X1000   MA1244



W.A. 639-1539

1" Plate #F

Brinell Hardness (Case 495 / Core 512)   Case Depth .292"

Cracked. No ballistic data available, Caliber .50 A.P.

(69) Some large inclusions are scattered through a fairly clean background.
Unetched, X100   MA1228

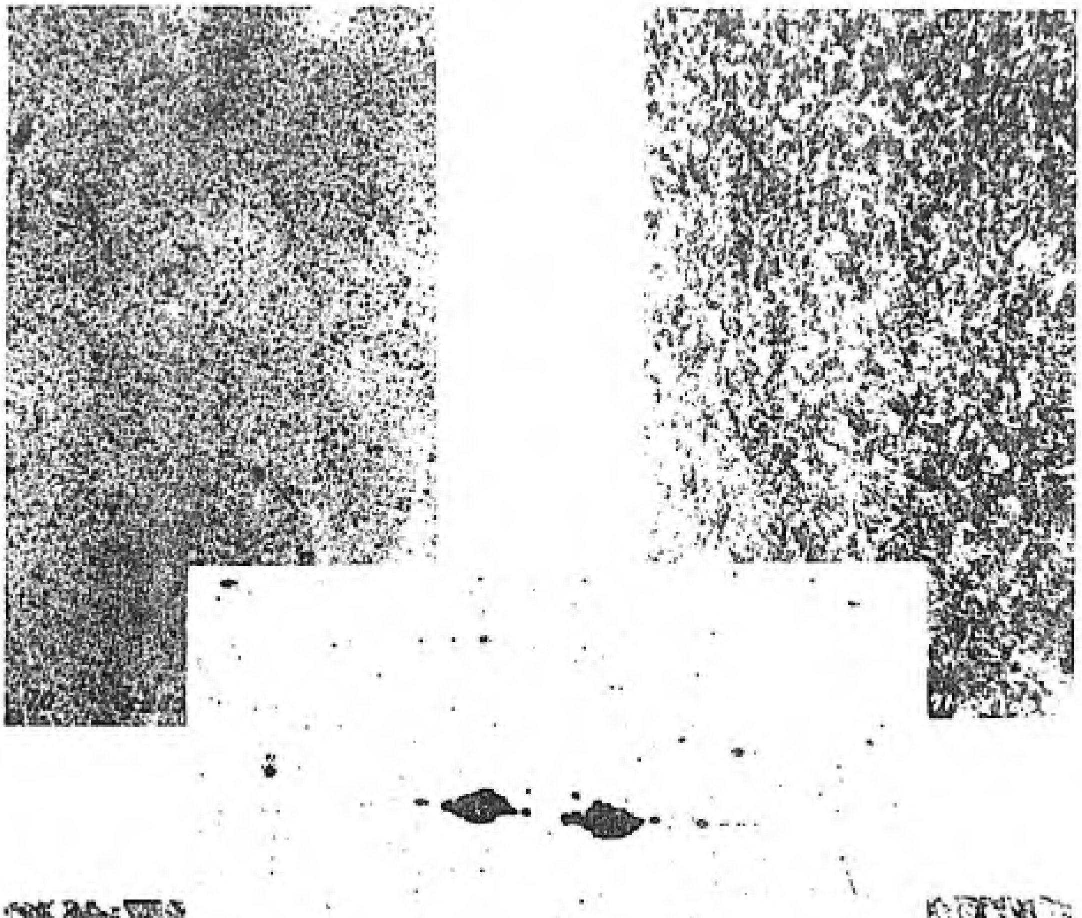
(70) Carbides scattered throughout case.
Murakami etch, X250   MA1322

(71) Structure of extreme outer case.
1% Nital etch, X1000   MA1234

(72) Troostite-sorbite in body of case.
1% Nital etch, X1000   MA1235

(73) Coarse tempered martensite in core.
1% Nital etch, X1000   MA1233

XX



1/4" Plate #096

Brinell Hardness (Case 555 Core 418)   Case Depth .093"

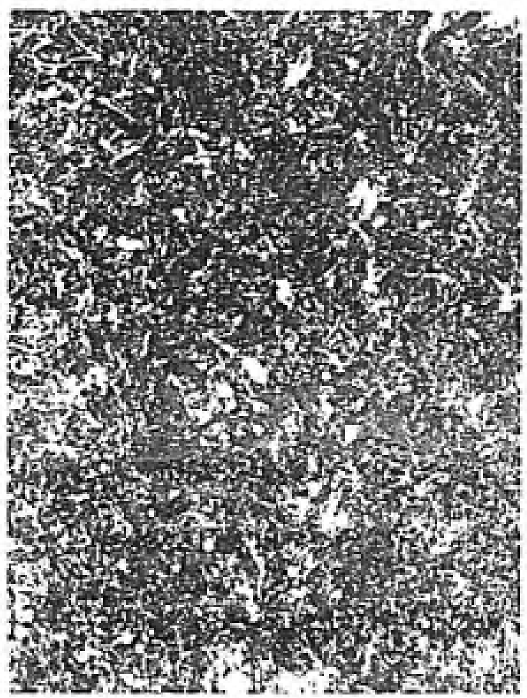
Cracked; Diameter of hole in rear 2.95" blown out 37 mm. 1.45 lb. solid shot.

(74) Structure of case at outer edge.
X1000   MA1076

(75) Troostito-sorbite in case.
X1000   MA1077

(76) Coarse tempered martensite in core.
X1000   MA1078

All figures etched in 1% Nital.



W.A. 639-1541

XXI

Macro Structures of -

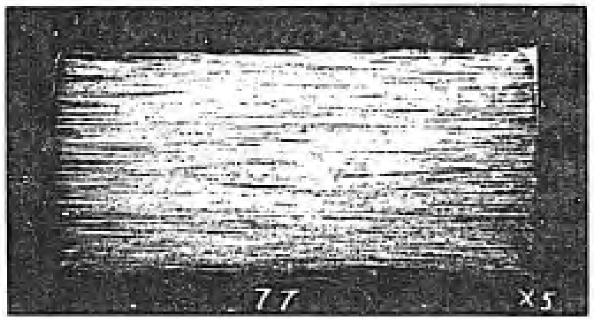
(77) 1/4" Plate #2A3 - Good Ballistic Plate.
MA1301

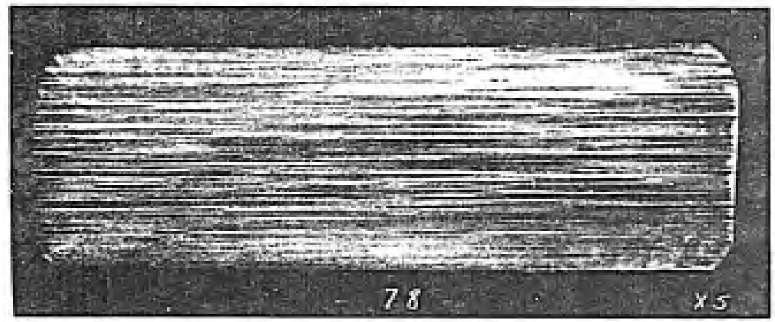
(78) 1/4" Plate #2-446 - Poor Ballistic Plate.
MA1300

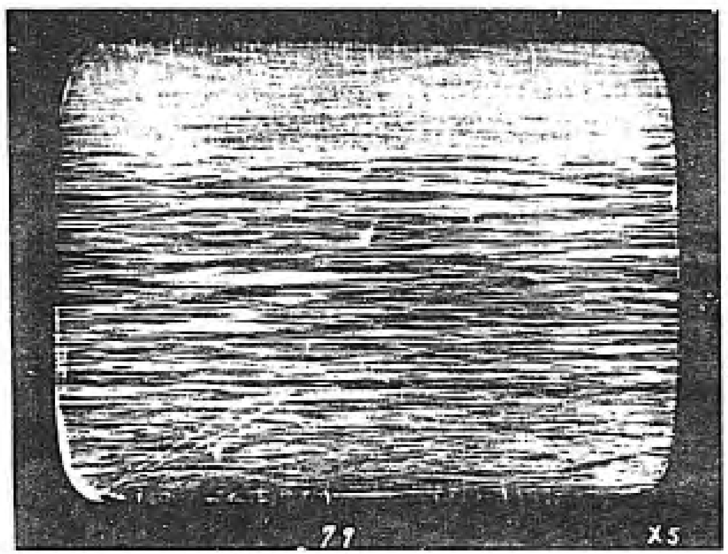
(79) 1/2" Plate #444-2 - Good Ballistic Plate.
MA1263

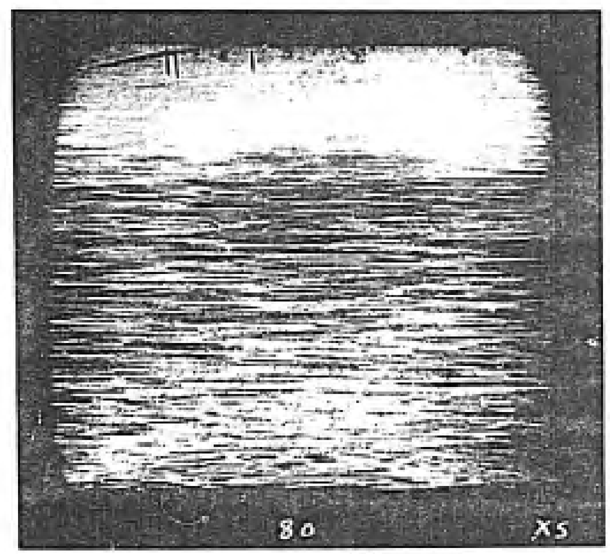
(80) 1/2" Plate #6-446 - Poor Ballistic Plate.
MA1165

All figures etched in Oberhoffer's reagent and had magnifications of X5.









W.A. 63J-1542

XXII

1/4" Plate #2A1

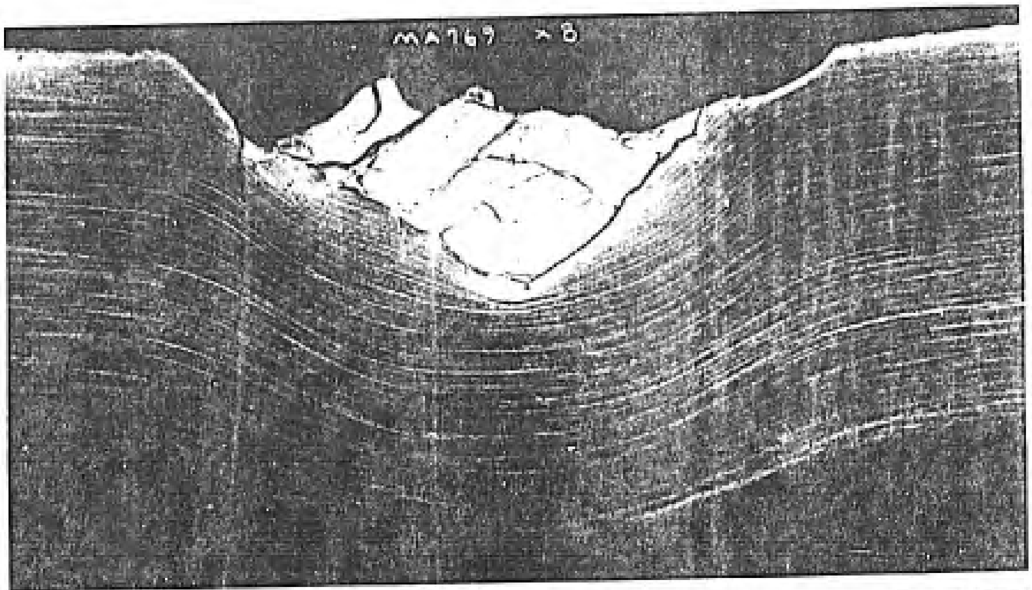
Brinell Hardness {Case 477/495, Core 402}   Case Depth .06"

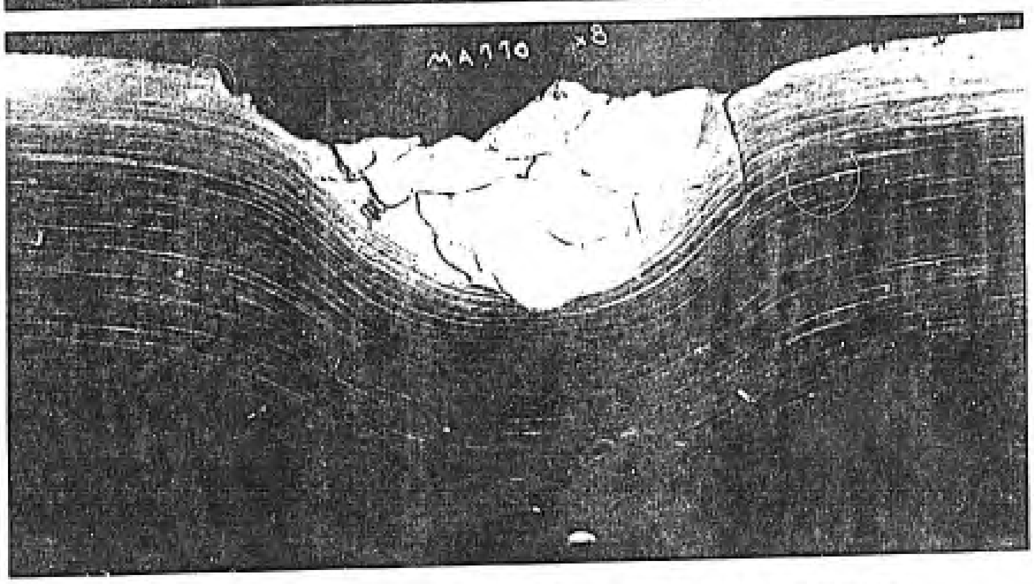
Ballistic Limit 2034 ft/sec., Caliber .30 A.P., Specification AX854-1

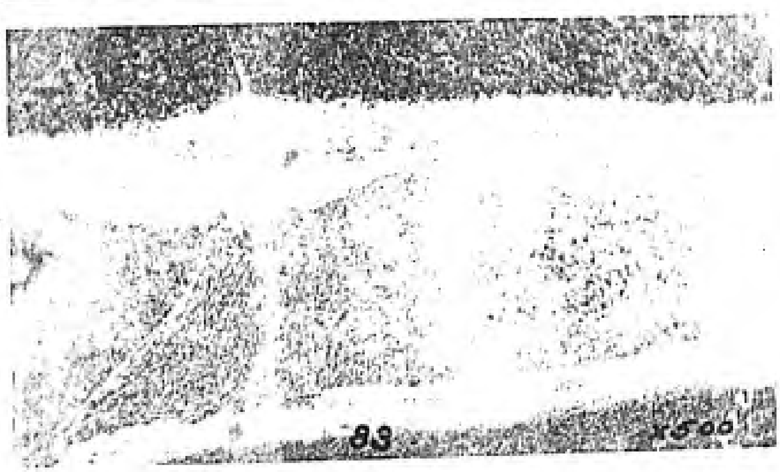
(81) Shows the fused bullet core adhering to the armor plate, and arrangement of white layer in bullet core. Round 2, striking velocity 2025, caliber .30 A.P., Specification AX854-1, bulge in back .08".
Oberhoffer's etch, X8   MA769

(82) Round 6.
Oberhoffer's etch, X8   MA776

(83) Junction of case and core of bullet shows white layer.
1% Nital etch, X500   MA783







W.A. 639-1543

1/4" Plate #2A1 (Cont.)

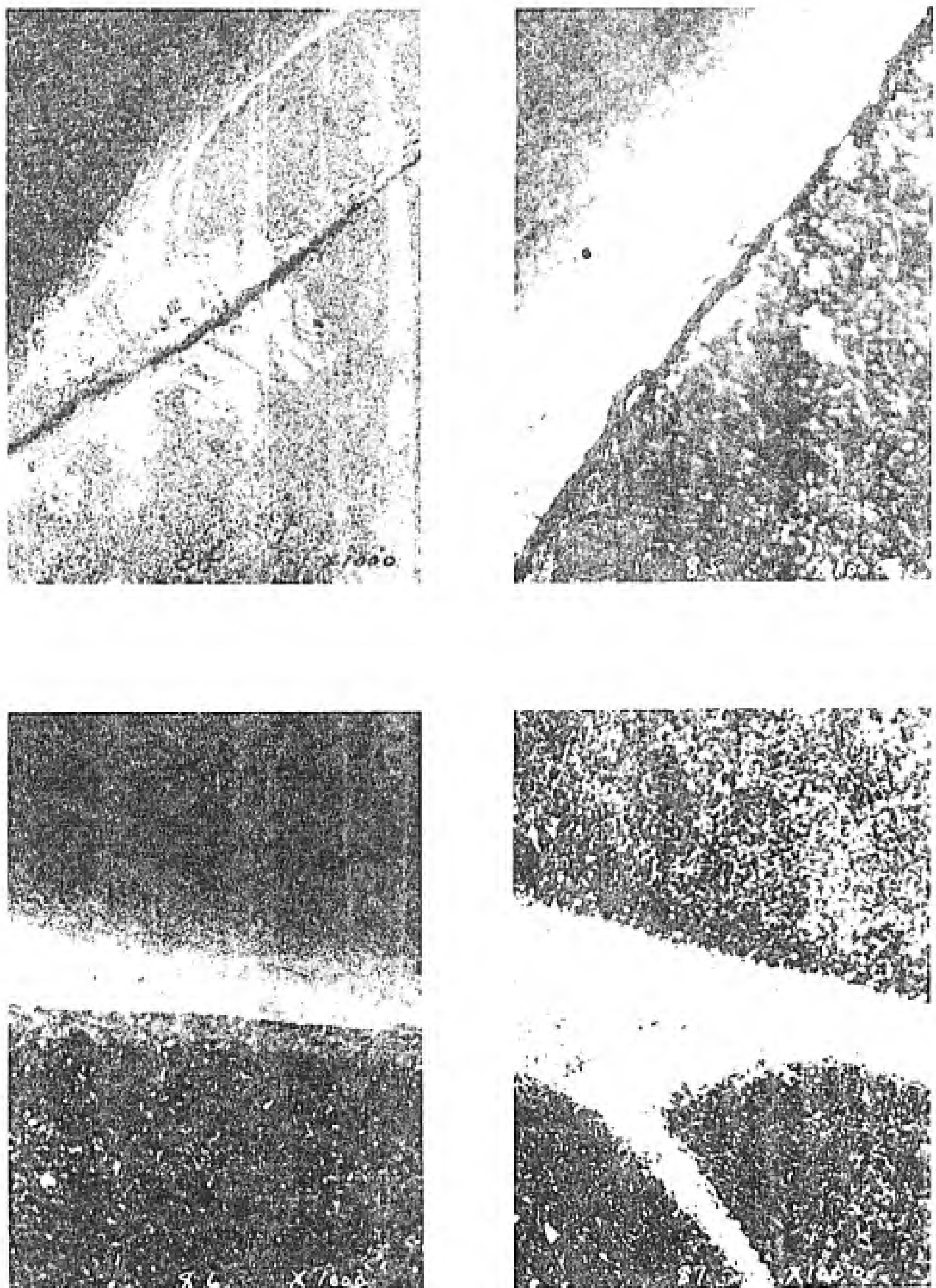
(84) Zone of fusion (fine dendritic structure) in white layer found in carburized case.
X1000 MA762

(85) More dendrites at junction of case and bullet core.
X1000 MA761

(86) Junction of bullet core and case shows a more narrow white layer than Figure (83) but there is here evidence of fusion.
X1000 MA767

(87) Typical white layer found entirely with the core of the bullet.
X1000 MA763

All figures etched in 1% Nital.



W.A. 639-1544