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CORRELATION OF MICROSTRUCTURE AND BALLISTIC PROPERTIES OF ARMOR PLATE

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JULY 11, 1938

WATERTOWN ARSENAL
WATERTOWN, MASS.

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Report No. 710/261
Watertown Arsenal

July 11, 1938

CORRELATION OF MICROSTRUCTURE AND BALLISTIC PROPERTIES OF ARMOR PLATE

I. HOMOGENEOUS PLATE

Purpose

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

Conclusions

Results are based on normal impact of caliber .30 armor piercing ammunition upon plate, 1/2" and lighter, shock test data not being available. Heavier plate was tested only with caliber .50 A.P., with the exception of two Watertown Arsenal experimental 1" plates which were tested with 37 mm. M59 solid shot.

1. Laminations of any considerable extent are a primary cause of spalling in plate of passable ballistic limit.

2. Carbides (or any other segregates which may be revealed by a Murakami etch) in definite chains in grain boundaries produce spalling. Segregations of these constituents into bands or patches contribute to spalling, but do not of themselves produce it under tests made with caliber .30 armor piercing single shot.

3. Martensitic structure invariably caused spalling, while a fairly uniform troostito-sorbitic structure was found in the majority of high ballistic nonspalling plate.

4. Eliminating all plate with laminations, bad carbide conditions and nonuniform nital structure, Brinell hardnesses from 418 to as high as 444 were found to produce the highest ballistic plate which did not spall under the caliber .30 A.P. tests to which they were subjected.

5. Macro segregations in the form of banding (in the absence of elongated nonmetallic inclusions) were found in both high and low ballistic plate.

Method of Procedure

Samples of armor plate accumulated over the period of years from 1922 to date were cut from stock. They were taken as close to the center of plate as possible.

TABLE 1

Relation between
Microstructure and Ballistic Properties

Plate #	Unetched	Murakami	(1) Nital	Brinell	Spalling Characteristic	Ballistic Limit Foot Seconds Spec. K-1	Spec. 31 (1932-33)
				CALIBER .50 A.P.			
1"							
B	Bad	Bad	O.K.	430/444	Spall	+210	
D	Bad	O.K.	O.K.	477	Spall	+209	
29	O.K.	O.K.	O.K.	418			
W-10	Bad streak center.	Questionable	Ferritic	352/365		-255	+150(H.P.) +310
7/8"							
37	O.K.	O.K.	O.K.	418			+323(H.P.)
3/4"							
W-9	O.K.	Bad	Ferritic	352/365	Spall	-452	+195
35 }	O.K.	Bad	O.K.	436	Petals	M. G. Fire	
36 }	O.K.	Bad	O.K.	418/444	Petals	" "	" +644
				CALIBER .30 A.P.			
1/2"							
EX-28	Questionable	Bad	Ferritic	340/364		-290	+76
EX-29	O.K.	O.K.	O.K.	364/376		-229	+77
A	O.K.	O.K.	Ferritic	387		M. G. Fire	+111
22 }	O.K.	O.K.	O.K.	418			+143
26 }	O.K.	O.K.	O.K.	418			+252
28 }	O.K.	O.K.	O.K.	418		.50 cal. A.P.	

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, see Figures 19a and b. 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).

Brinell hardness data were taken from the Aberdeen Reports as well as ballistic limits. Chemical analyses and those heat treatments reported are given in Table 3. In the few cases where chemical analyses or Brinell hardness figures were missing, they were determined at Watertown Arsenal.

---

*Murakami's Reagent -
10 gm Potassium Ferricyanide
10 gm Potassium Hydroxide
100 cc Water
(Etched in simmering solution from 10 to 30 minutes)

TABLE 1 (Cont.)

Plate #	Unetched	Murakami	(1) Nital	Brinell	Spalling Characteristic	Ballistic Limit Foot Seconds Spec. K-1	Ballistic Limit Foot Seconds Spec. 31 (1932-33)
5/16"							
14	O.K.	O.K.	O.K.	418			+228
442	Bad	O.K.	O.K.	351		At 150 Ft. Range (before 1932)	-48
423	Bad	O.K.	Bad	444	Spall		-27
1/4"							
6	O.K.	O.K.	O.K.	418			+127
MS-2	O.K.	*Questionable	O.K.	402	Spall		
626-16	Bad	*Questionable	O.K.	364	Spall		
5/16"							
1	O.K.	O.K.	O.K.	418		M. G. Fire also M. G. Fire	+22
2	O.K.	O.K.	O.K.	418			
1/8"							
44	*Questionable	*Questionable	O.K.	402	Blown out		
41	*Questionable	*Questionable	O.K.		Blown out	.30 Ball MI	

(1) Microstructures have been classified as "Bad" only when some martensite is present, although ferritic structures are undesirable because of their effect in lowering the ballistic limit.

(2) Acicular troostite resulting from austempering gives high ballistic limit and does not spall on caliber .30 A.P. impact. However, a shock test might produce spalling.

* Plate lighter than 1/2", "Questionable" conditions should be considered "Bad".

TABLE I (Cont.)

Plate #	Unetched	Murakami	(1) Nital	Brinell	Spalling Characteristic	Ballistic Limit Foot Seconds Spec. K-1	Ballistic Limit Foot Seconds Spec. 31 (1932-33)
1/2" Cont.							
614-5	Bad	Questionable	O.K.	430/444	Spall	+1	+235
614-6	Bad	Questionable	O.K.	444	Spall	-5	+238
N3-3	Bad	Questionable	O.K.	444		±0	
N13-6	O.K.	Bad band center	Questionable (2)	477		+150 (H.P.)	
N10-3	O.K.	Questionable	Bad	477	Spall	-100	
N4-3	O.K.	O.K.	O.K.	444		+150(H.P.)	
K2	O.K.	O.K.	O.K.	418		+250	
G1	O.K.	O.K.	Bad	512/532	Spall		+7
G2	O.K.	O.K.	Bad	512/552	Spall		+204
626D-4	Bad streak center	O.K.	Questionable	430		pass(?)	
626D-2	" "	Questionable	Bad	477	Spall		
626-17	O.K.	Bad	Ferritic	387	Spall		
3/8"							
P4-3	O.K.	O.K.	O.K.	418		+70(H.P.)	
P5-3	Bad	Questionable	O.K.	418	Spall	+73(H.P.)	
11	O.K.	O.K.	O.K.	418			
12	O.K.	O.K.	O.K.	418			+73
13	Bad	O.K.	O.K.	370		Angle Fire	
16	O.K.	O.K.	O.K.	418	Spall	Cal. .50 MI	Ball
A-511	O.K.	*Questionable	O.K.	418			+204
B-112	O.K.	*Questionable	O.K.	444	Spall		+124
[illegible]	O.K.	Bad	O.K.	418	Petals		+204
[illegible]	*Questionable	O.K.	Bad	512	Spall		+127

TABLE 2

Out of 47 Plates		No. of Plates	Dirt	Carbide	Micro	Brinell
24 Did Not Spall	20 Passing	18	O.K.	O.K.	*Ferritic	387
					O.K.	14 {418
						3 {430 to 477
		1	Bad	O.K.	O.K.	444
		1	O.K.	**Bad	O.K.	418
	4 Below Passing	2	O.K.	O.K.	Ferritic	358-[illegible]
		1	Bad	O.K.	Ferritic	351
		1	O.K.	Bad	Ferritic	340-[illegible]
23 Spalled		7	O.K.	Bad	Ferritic	2 {352 to 387
					O.K.	1 {400
						4 {418 to 444
		3	Bad	O.K.	O.K.	1 370
						4 {418 to 47[illegible]
		4	Bad	Bad	O.K.	364-4[illegible]
		4	O.K.	O.K.	Bad	2 {477
						2 {512 to 532
		2	Bad	O.K.	Bad	{444 to 512
		1	Bad	Bad	Bad	460

*Passed only on old (1932) specification 31, no tests on more rigid specifications of recent years available.

**This condition (i.e., carbide segregation in bands) does not seem to be detrimental on caliber .30 impacts when the hardness lies in the softer range.

Experimental Results

Macro and Microstructure

Macro and micro studies were made on the longitudinal sections, the results of which are shown in Figures 1 to 19, inclusive.

Table I is a tabulation of the microstructure and ballistic properties of each individual plate.

Table 2 is an analysis of the results of the investigation.

Discussion

A considerable amount of rounded, uniformly distributed nonmetallic inclusions exerts no influence upon the spalling characteristics of homogeneous armor-plate. For example, Plate #29 in Figure 1 has dirt content typical of ten other plates (Nos. 22, 26, 28, 11, 12, 14, 16, 6, 1 and 2 listed in Table 1). However, decidedly elongated nonmetallic inclusions invariably cause spalling. Tables 1 and 2, Plates No. D, 614-5, 614-6, P5-3, and 13, are a proof of this statement. Illustrations of Plate No. D tested by 37 mm. shot are found in Figure 2. The structures of Plate No. 614-5 which are the same as those of 614-6 are given in Figure 3. These, together with P5-3 (Fig. 6), were tested by caliber .30 armor piercing ammunition.

Figure 1

1" Plate #29

Brinell Hardness 418 - Cr-Mo-V Steel - No Spall - Highest Partial 2500 ft/sec. with caliber .50 A.P., Specification 51.

(a) Uniform distribution of small rounded non-metallic inclusions.
Unetched MA-127

(b) Considerable amounts of carbide show no tendency towards segregations either in bands or at grain boundaries.
Murakami etch MA-969

(c) Troostito-sorbitic microstructure shows slight amounts of ferrite segregation.
1% Nital etch MA-978

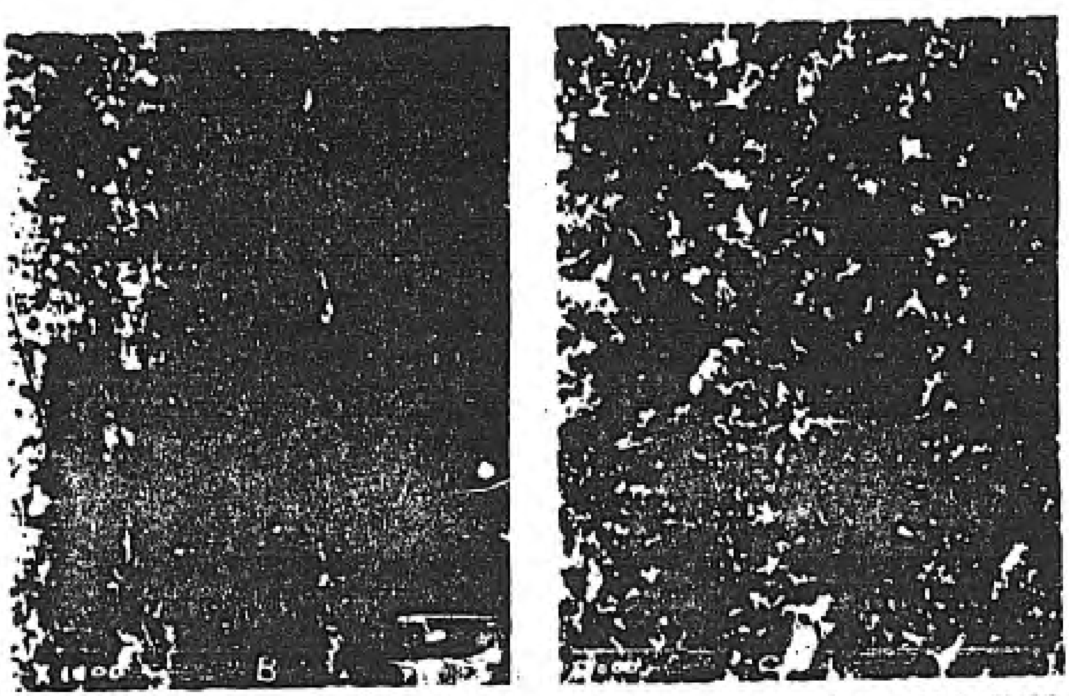
Note: These photomicrographs are typical of structures also found in Plates 1, 2, 6, 11, 12, 14, 16, 22, 26, 28.

FIGURE 1

PLATE 1

#29

(A)
X100



W.A. 639-1342

Figure 2

1" Experimental Plate #D

Brinell Hardness 477 - Mn-Mo-W Steel - Spalled - Ballistic Limit 2909 ft/sec., caliber .50 A.P., Specification AXS54-K-1.

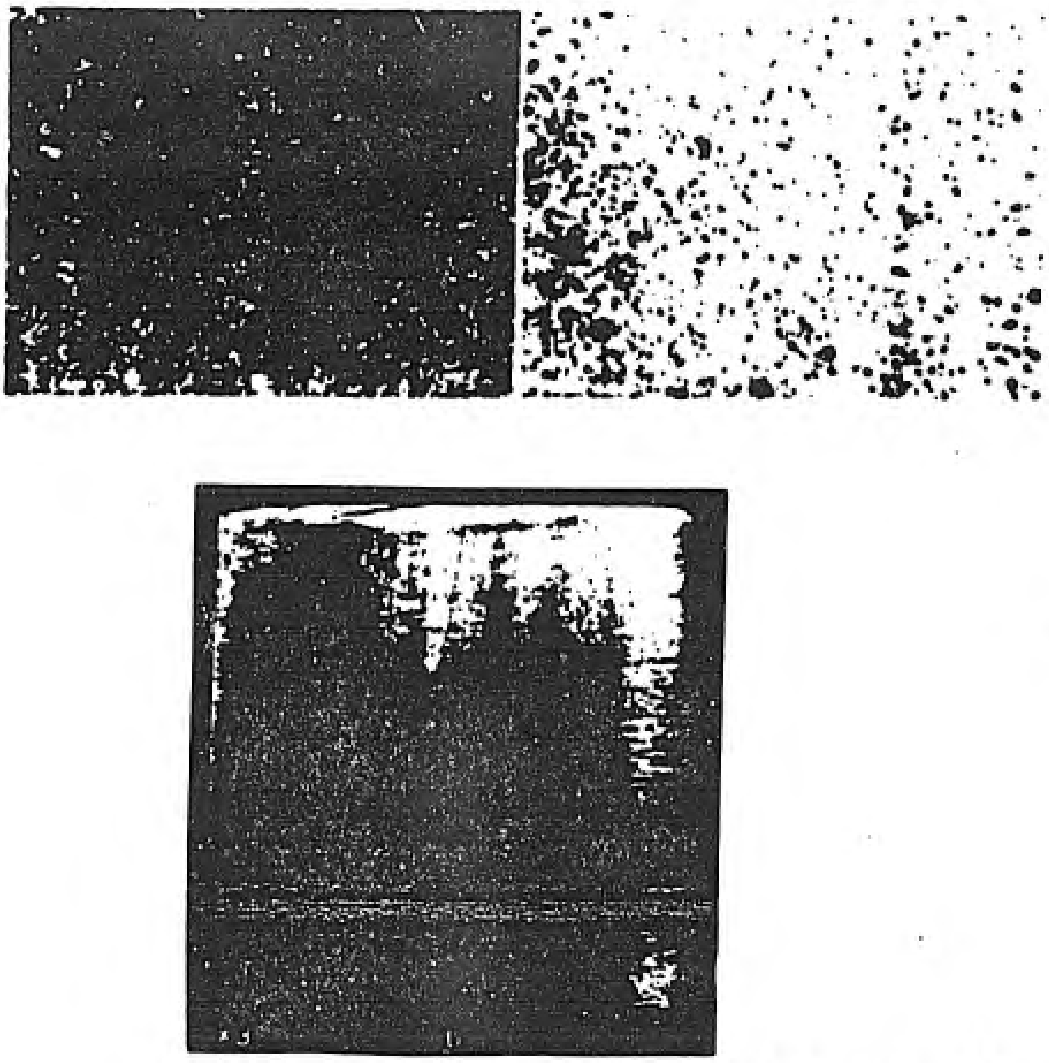
(a) Nonmetallic inclusions are drawn out into serious laminations.
Unetched MA-1184

(b) Very fine and uniform sorbito-troostite.
1% Nital MA-1206

(c) Uniform distribution of carbides.
Murakami etch MA-1200

(d) Oberhoffer's reagent shows macro segregation.
MA-1191

FIGURE 2



W.A. 639-1265

Figure 3

1/2" Plate #614-5*

Brinell Hardness 430/444 - Cr-Mo-V Steel - Spalled - Ballistic Limit 2451 ft/sec., caliber .30 A.P., Specification AXS54-2.

(a) Very bad laminations of elongated non-metallics.
Unetched MA-145

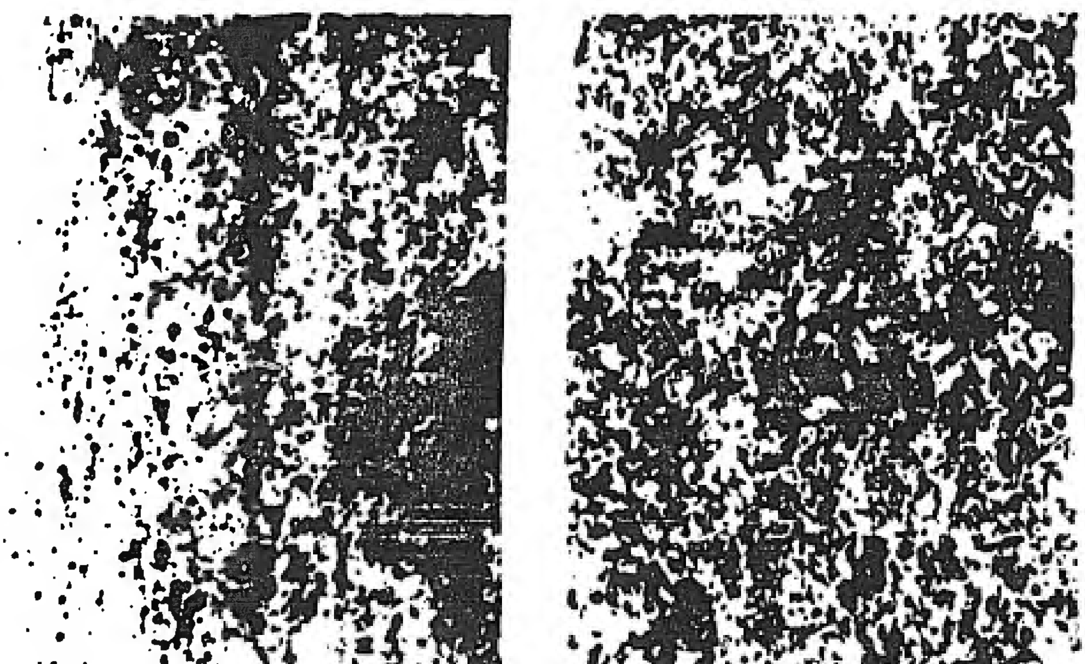
(b) Rather large carbides are fairly uniformly distributed throughout the steel.
Murakami etch MA-973

(c) Troostite-sorbite shows slight amount of ferrite.
1% Nital etch MA-980

*Microstructures and dirt content the same as those of Plate #614-6.

FIGURE 3

PLATE #614-5



W.A. 639-1344

Plate No. 13, 3/8" thick, was tested with caliber .50 ball ammunition. However, plates with a Brinell hardness below 363 tested only with caliber .30 A.P. did not spall even though considerable laminations were present, Table 1, Plates No. Ex-28 and 442.

An illustration of the way in which cracks open up along elongated nonmetallics and grain boundaries is shown in Figure 4a, Plate No. 626-16. This plate has slight traces of grain boundary carbide (Fig. 4b) which undoubtedly played a part in producing the considerable amount of spalling despite its low Brinell hardness (364).

Plate No. B, a brittle plate, is an example of the combined effects of a moderate amount of elongated non-metallics, and some fine grain boundary carbides when subjected to 37 mm. impact (see Fig. 5). Neither condition alone should have caused as much spalling as resulted from both.

Figure 6a shows bad segregations of elongated nonmetallic inclusions in Plate P5-3. Figure 6b shows local segregations of carbides in the same plate which have a tendency to outline remnants of grain boundaries. This carbide condition was undoubtedly a contributory factor in spalling.

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Figure 4

1/4" Plate #626-16

Brinell Hardness 364 - Ni-Si Steel - Spalled - Ballistic Limit 1710 ft/sec., caliber .30 A.P., 150 ft. range.

(a) Cracks opening up . 'ng laminations of nonmetallic inclusi ..s and grain boundaries.

Unetched MA-1090

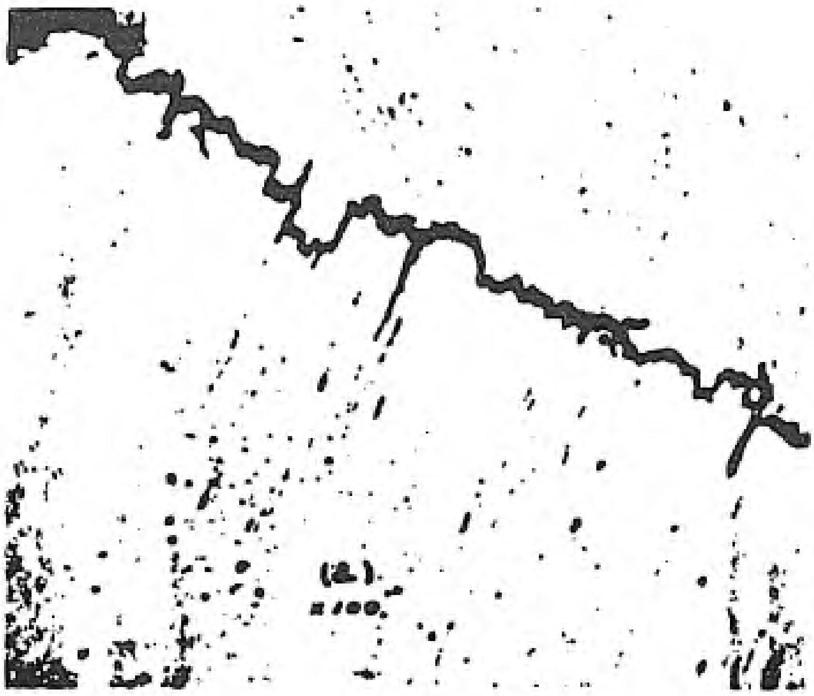
(b) Very fine carbides show tendency to segregate in portions of grain boundaries.

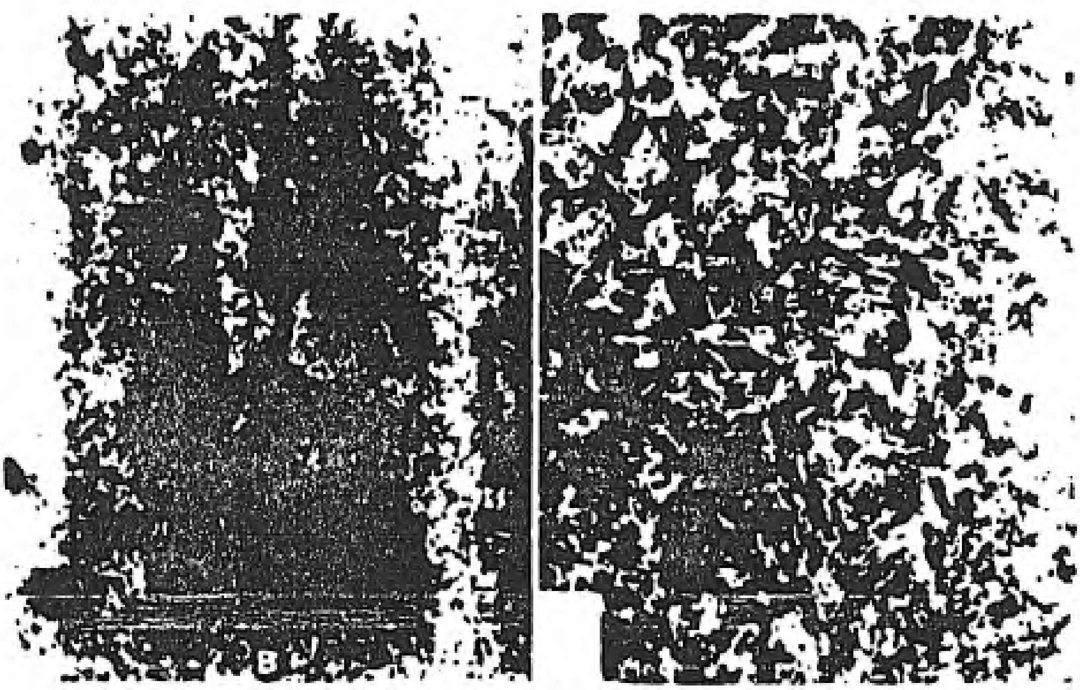
Murakami etch MA-1099

(c) Microstructure is a coarse intermixture of considerable ferrite with troostito-sorbite.

1% Nital etch MA-1219

FIGURE 4
PLATE 626-10





W.A. 639-1345

Figure 5

1" Experimental Plate #B

Brinell Hardness 430/444 - Cr-Mo-V-W Steel
Spalled - Ballistic Limit 2910 ft/sec.,
caliber .50 A.P., Specification AXS54-K-1

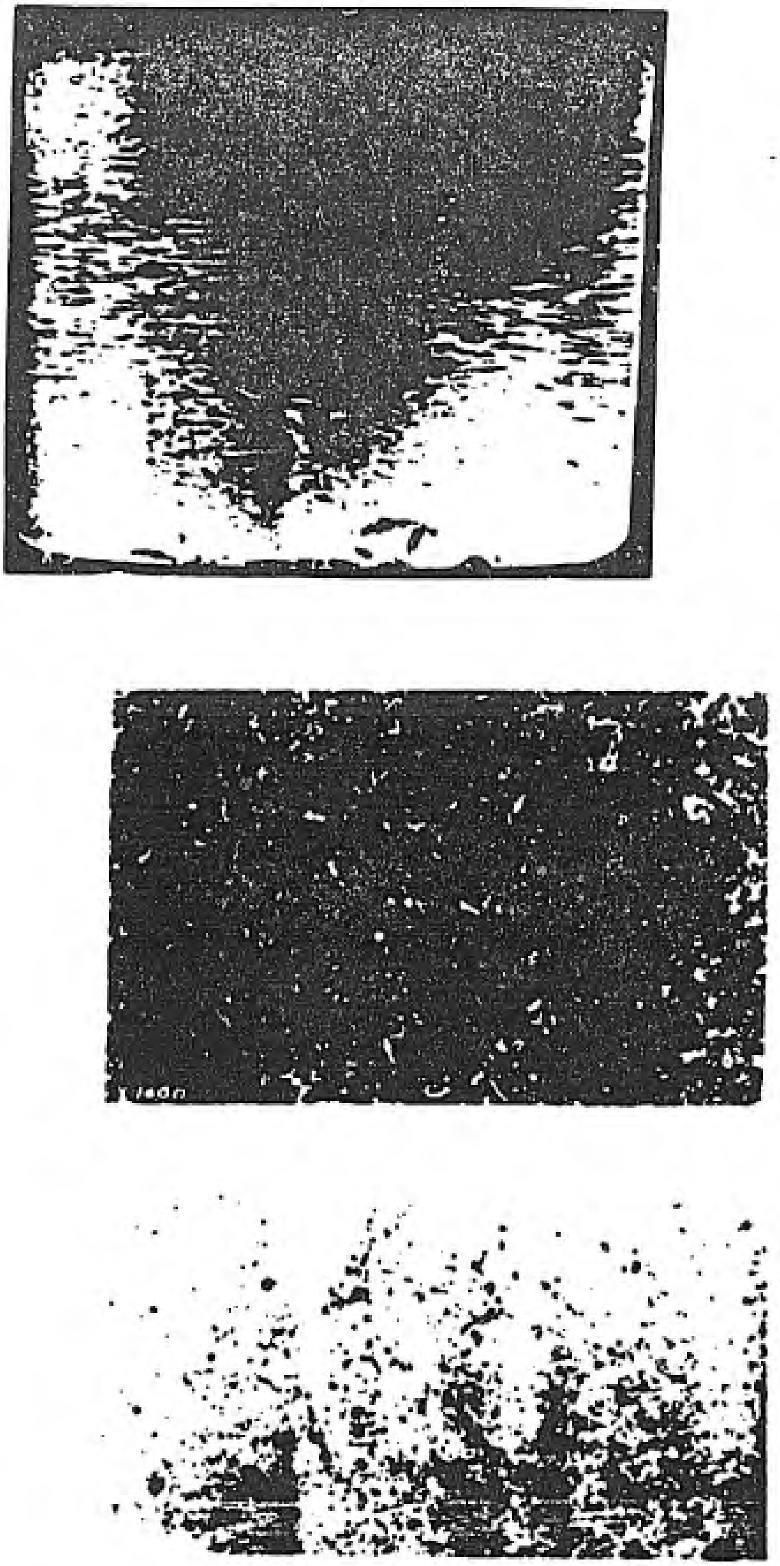
(a) Oberhoffer's etch shows macro segregation.
MA-1192

(b) Short laminations of nonmetallic inclusions.
Unetched
MA-1183

(c) Fairly uniform troostito-sorbite.
1% Nital etch
MA-1208

(d) Carbides segregated in grain boundaries.
Murakami etch
MA-1201

FIGURE 5



W.A. 639-1262

Figure 6

3/8" Plate #P5-3

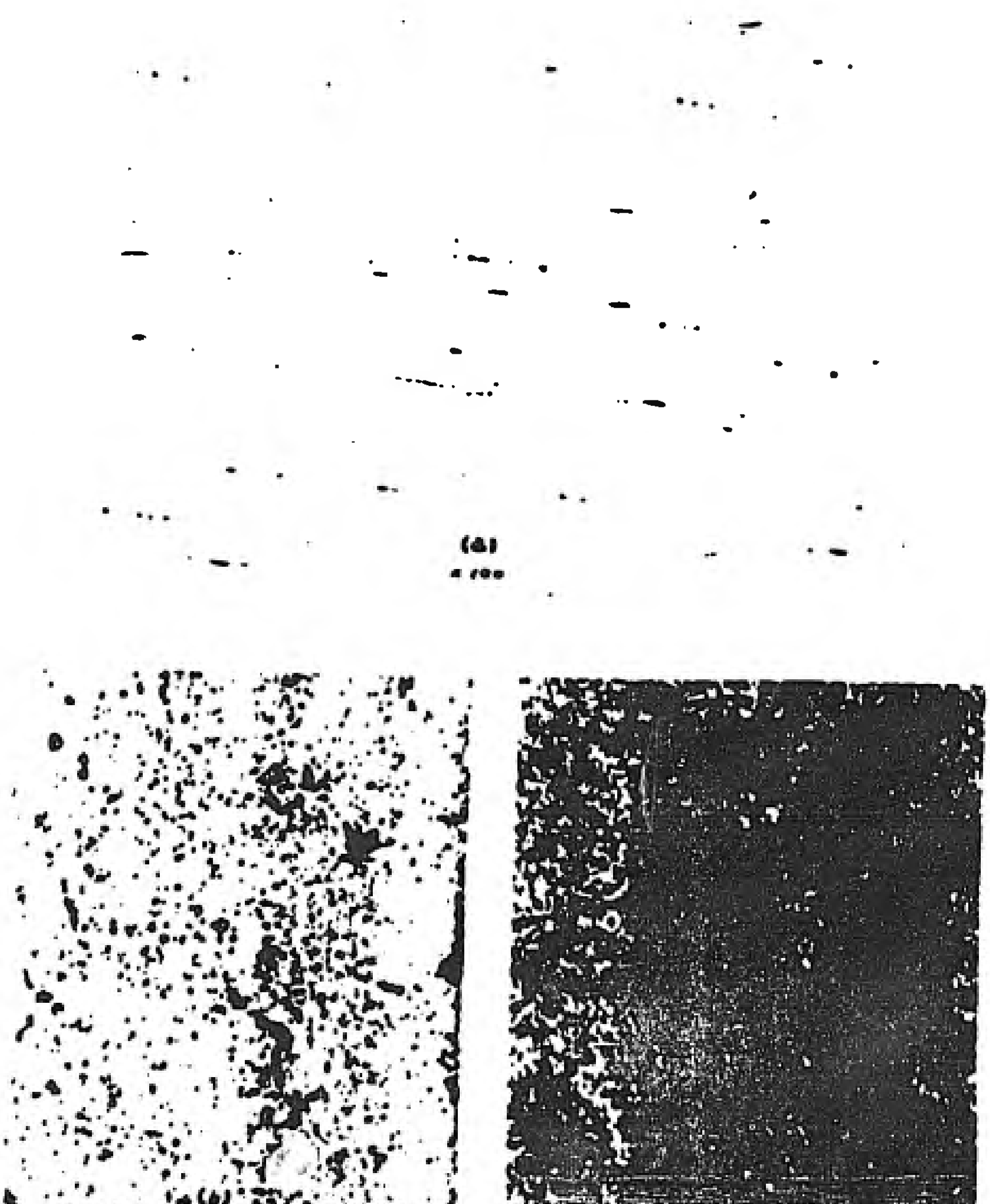
Brinell Hardness 418 - Cr-Mo-V Steel
Spalled - Highest Partial 2168 ft/sec.,
caliber .30 A.P., Specification 31

(a) Long and very numerous laminations of nonmetallic inclusions.
Unetched MA-1292

(b) Localized segregations of fairly large carbides show slight tendency to outline remnants of grain boundaries.
Murakami etch MA-1047

(c) Very fine and uniform troostito sorbite.
1% Nital etch MA-1150

FIGURE 6
PLATE P5-3



W.A. 639-1347

Amounts of laminations, which in themselves would not be serious, often in combination with carbide segregations, cause spalling. An illustration of this is found in Figure 7, Plate No. 44, which is typical of Plate No. 41.

The laminations illustrated are not serious enough in themselves to produce spalling, but when combined with the slight amount of carbide segregation present they contribute to spalling.

Carbides which outline the grain boundaries with any degree of continuity cause spalling and formation of petals in plate that otherwise would have an excellent structure (i.e. one which has uniform troostito-sorbitic and no laminations). An example of this is shown in Figure 8, Plate No. 35 (also typical of Plate No. 36). These are from the same heat of steel as the high ballistic Plate No. 29, shown in Figure 1. Note that the only difference between the good and poor ballistic plate is in the carbide arrangement. An example of very definite chains of grain boundary carbides in brittle plate is shown in Figure 8, Plate No. A412, and this also is free of laminations and has a uniform structure.

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Figure 7

1/8" Plate #44*

Brinell Hardness 402 - Cr-Mo-V Steel
Cracked and blown out - Ballistic Limit 1003 ft/sec., caliber .30 A.P., Specification 31

(a) Short laminations of the "stringer" type common to plate of this gage.
Unetched MA-1045

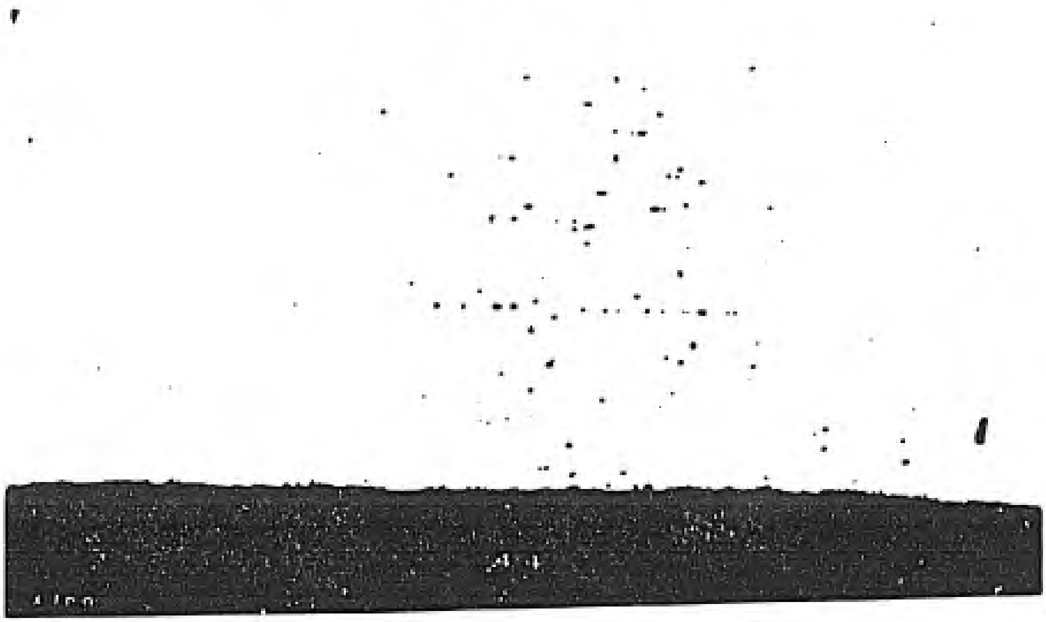
(b) Slight degree of segregation into bands of the larger carbides.
Murakami etch MA-1031

(c) Very small and uniformly distributed patches of ferrite are evident in this troostito-sorbite.
1% Nital etch MA-1091

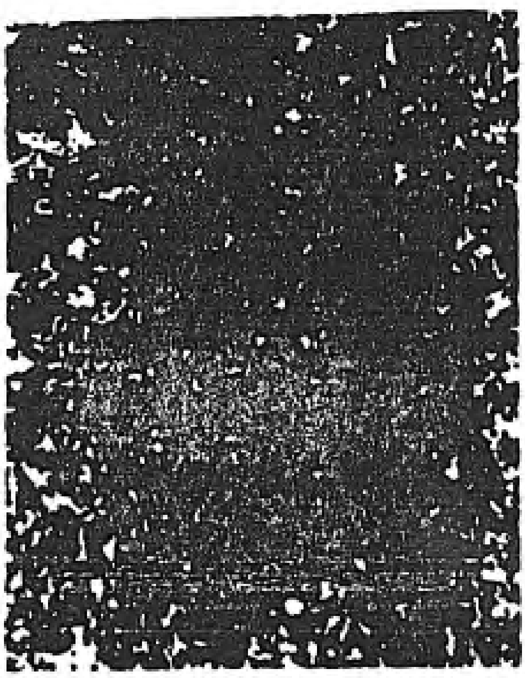
*Structures very similar to 1/8" Plate #41.

FIGURE 7

PLATE #44



(b)
x1000



W.A. 639-1348

Figure 8

3/4" Plate #35* **

Brinell Hardness 430 - Cr-Mo-V Steel
Petals - Machine gun fire, 26 hits, cal .50 A.P.

(a) Patches where carbides outline the grains are found.

(b) Other parts are entirely free of carbide segregations and resemble distribution in high ballistic Plate #29 (see Fig. 1b).
Murakami etch MA-970 & MA-971

(c) Typical microstructure of this sort of steel (see Fig. 1c).
1% Nital etch MA-984

*Structures same as Plate #36.
**Dirt content same as Plate #29 (Fig. 1a)

3/8" Plate #A412*

Brinell Hardness 418 - Cr-Mo-V Steel - Petals and punching started. Ballistic limit 2227 ft/sec., caliber .30 A.P., Specification 31

(d) Segregations of carbides in very definite chains outline grain boundaries alternate with

(e) areas quite free of chains or any tendency on the part of carbides to collect at grain boundaries. Murakami etch MA-1027 & MA-1028

(f) Fine and uniform sorbito-troostite gives good microstructure. 1% Nital etch MA-1215

*Average dirt, medium rounded.

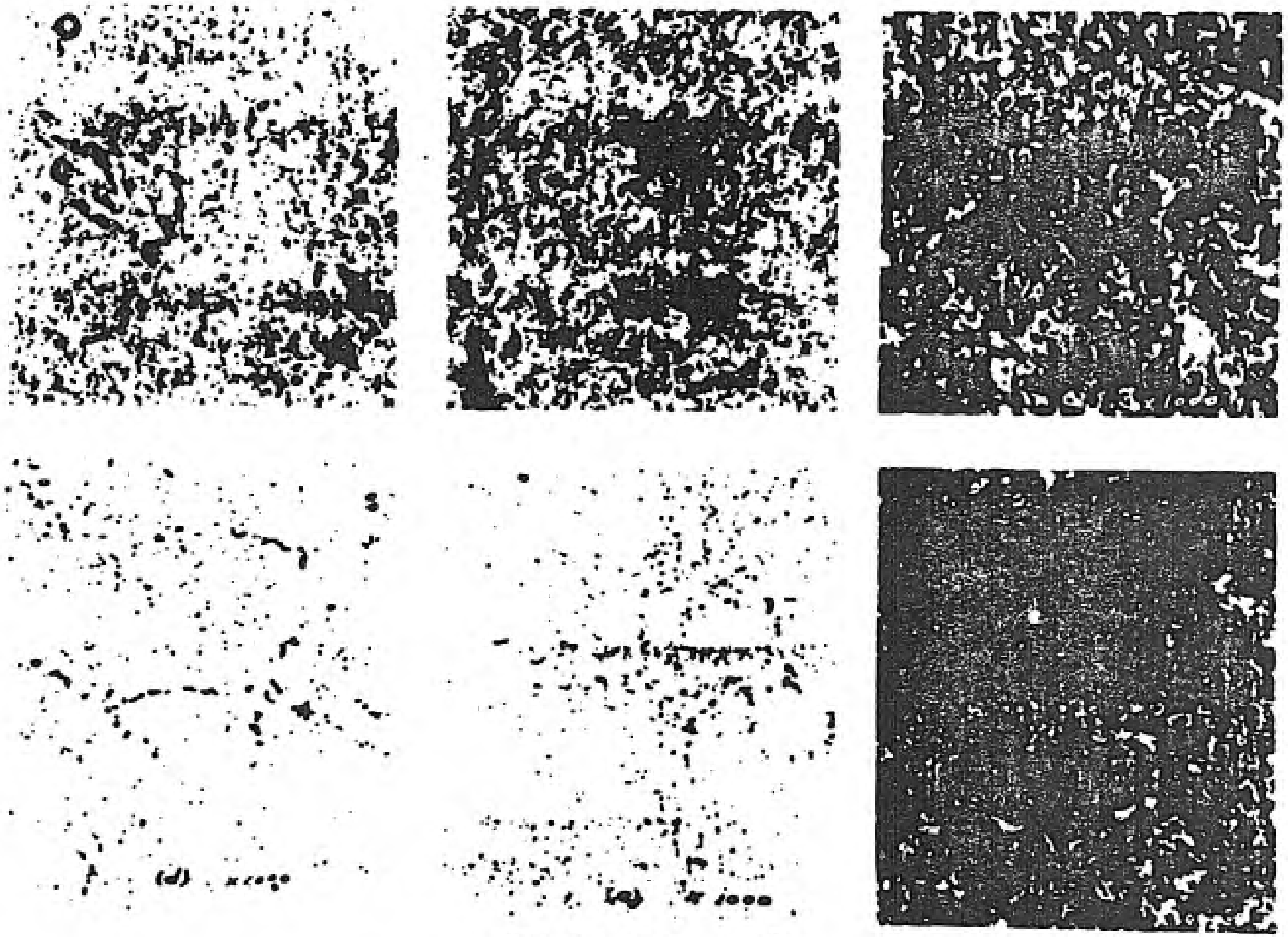


PLATE #35

PLATE #A418

FIGURE 8

W.A. 63º-1349

On the basis of the present tests, it is believed that segregated carbides in combination with tiny elongated nonmetallics cause spalling in plate 1/4 inch thick and lighter. Figure 9 is a good illustration of this point, Plate No. M3-2 (Figs. 9a, b, c) being a 1/4 inch plate with a microstructure and arrangement of dirt similar to that of a 3/8" Plate No. P4-3 (Figs. 9d, e, f). Plate No. M3-2 spalled while Plate No. P4-3 did not. In heavier gages, these conditions must be more pronounced in order to produce spalling with caliber .30 A.P. impact.

It has been noted that carbide banding of the type shown in Figures 10a, and 10c, will cause spalling in the case of relatively high Brinell hardness (Plate No. B-112, Brinell hardness 444), while the same carbide condition in Plate No. A-311 (Brinell hardness 418) does not cause spalling when subjected to caliber .30 A.P. ammunition.

In the case of chromium-molybdenum-vanadium steels, an example of the ideal carbide arrangement and microstructure is illustrated, in Figures 11a and 11b - Watertown Arsenal Experimental Plate No. N4-3, which has rounded dirt uniformly distributed. This uniform troostito-sorbitic structure is the same as that of

Figure 9

1/4" Plate #M32*

Brinell Hardness 412 - Cr-Mo-V Steel - Spalled - Highest Partial 1736 ft/sec., caliber .30 A.P. at 150 ft. range.

(a) & (b) Random segregations of carbides in this plate are seen by comparing these two micrographs taken close together on the same specimen.
Murakami etch   MA-1098 a & b

(c) Microstructure consists of a not very fine troostito-sorbite.
1% Nital   MA-1218

3/8" Plate #P43*

Brinell Hardness 418 - Cr-Mo-V Steel - No spalls - Ballistic Limit 2170 ft/sec., caliber .30 A.P., Specification 31.

(d) & (e) While (d) shows an area with considerable carbide and slight evidence of a chain of large carbides, (e) displays a nice even distribution of smaller carbides.
Murakami etch   MA-1083 & 1084

(f) Troostito sorbite very similar to that of #M3-2 (see (c) above).
1% Nital etch   MA-1252

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*Dirt content of both plates consisted of short laminations of nonmetallics.

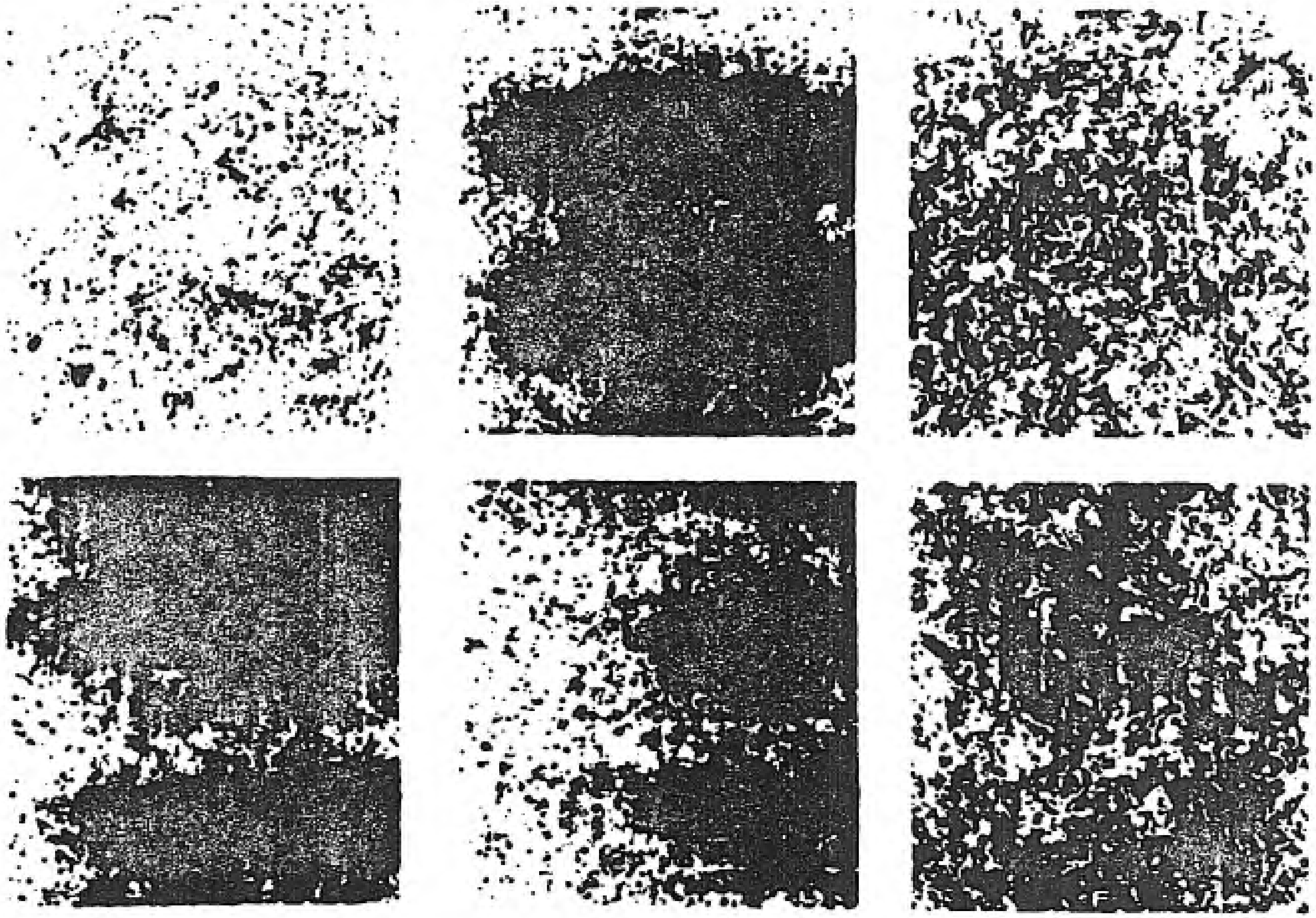

FIGURE 9

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Figure 10

3/8" Plate #B112*

l Hardness 444** - Cr-Mo-V Steel -
blown out - Ballistic limit 2304**ft/sec.,
r .30 A.P., Specification 31

ry definite bands of larger carbides in
background of very fine evenly distri-
ted carbides.
Murakami etch MA-1029a & b

d sorbito-troostitic structure.
1% Nital MA-1214

3/8" Plate #A511*

Hardness 418** - Cr-Mo-V Steel -
ls - Ballistic limit 2224**ft/sec.,
.30 A.P., Specification 31

e carbide condition as (a) above.
Murakami etch MA-1008

ostito-sorbitic microstructure -
s troostitic than (b) above.
1% Nital etch MA-1016

---

lates have same average distribution
nded dirt.

that where other things are equal
dirt and carbide) the plate with the
Brinell has a higher ballistic limit.

FIGURE 10

PLATE #B112

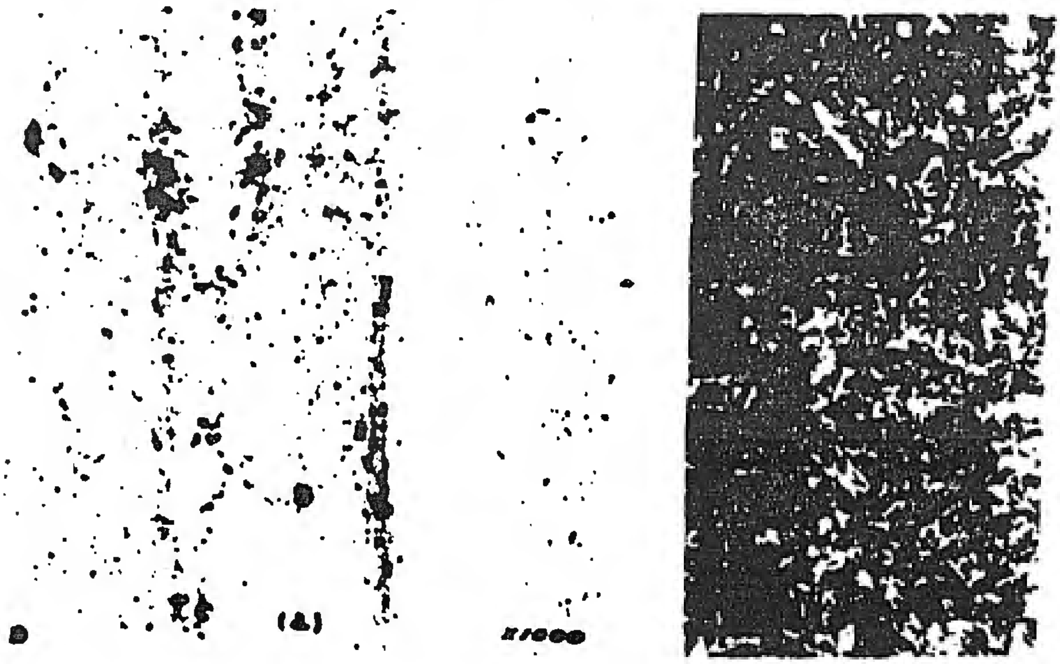
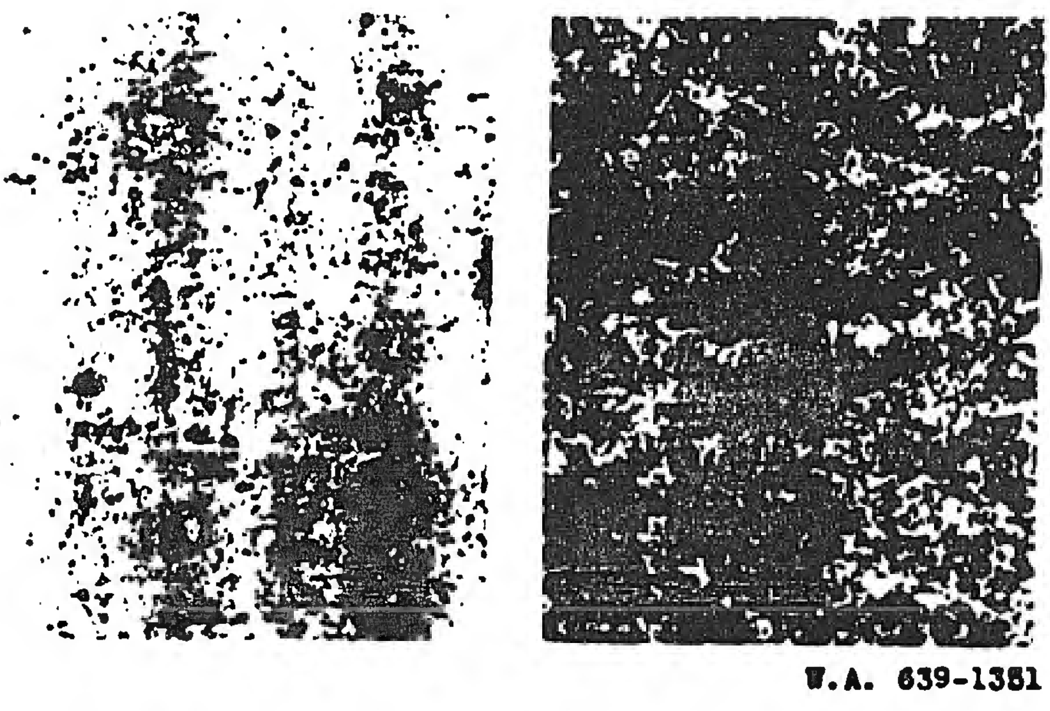


PLATE #A811



W.A. 639-1381

Figure 11d. The plate shown here is No. N3-3, which had bad laminations as well as the slightly segregated carbide arrangement shown in Figure 11c. The ballistic limit of Plate No. N3-3 was 150 foot seconds lower than the ideal Plate No. N4-3. Despite the fact that it contained the above-mentioned detrimental conditions (i.e., laminations and segregated carbides, No. N3-3 did not spall under the caliber .30 A.P. impact. This we believe is due to the compensating effect of the extremely uniform troostito-sorbitic structure. Another high ballistic plate showing this extremely uniform carbide distribution and microstructure, accompanied by a uniform distribution of nonmetallic inclusions, is Watertown Arsenal Experimental Plate No. X-2, Figure 12.

Plates whose microstructures show considerable ferrite segregations have ballistic limits too low to pass Specification No. AXS-54K-1, although they sometimes pass Specification No. 31, see Table 1. Plates Nos. W10, W9, Ex 28, and A,(see Fig. 13) show two examples of such segregation:- ferrite banding in Plate No. W10, Figure 13a, and ferrite patches in Plate No. A, Figure 13c. These plates again demonstrate that slight amounts of grain boundary carbides, Figures 13b and d, do not cause spalling in soft plate

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Figure 11

1/2" Experimental Plate #N4-3*

Brinell Hardness 444 - Cr-Mo-V Steel -
No spalls - Highest Partial 2600 ft/sec.,
caliber .30 A.P., Specification AXS54-2.

(a) Best possible carbide condition is this very uniform distribution of tiny carbides.
Murakami etch MA-1004

(b) Very fine and uniform sorbito-troostite.
1% Nital etch MA-1209

1/2" Experimental Plate #N5-3**

Brinell Hardness 444 - Cr-Mo-V Steel -
No spalls - Ballistic Limit 2450 ft/sec.,
caliber .30 A.P., Specification AXS54-2

(c) Slightly segregated carbides of size considerably larger than those in (a) above.
Murakami etch MA-1003

(d) Very fine uniform sorbito-troostite.
1% Nital etch MA-1015

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*Shows average distribution of rounded dirt.

**Has quite a few long laminations of nonmetallics.

FIGURE 11

PLATE #Y4-3

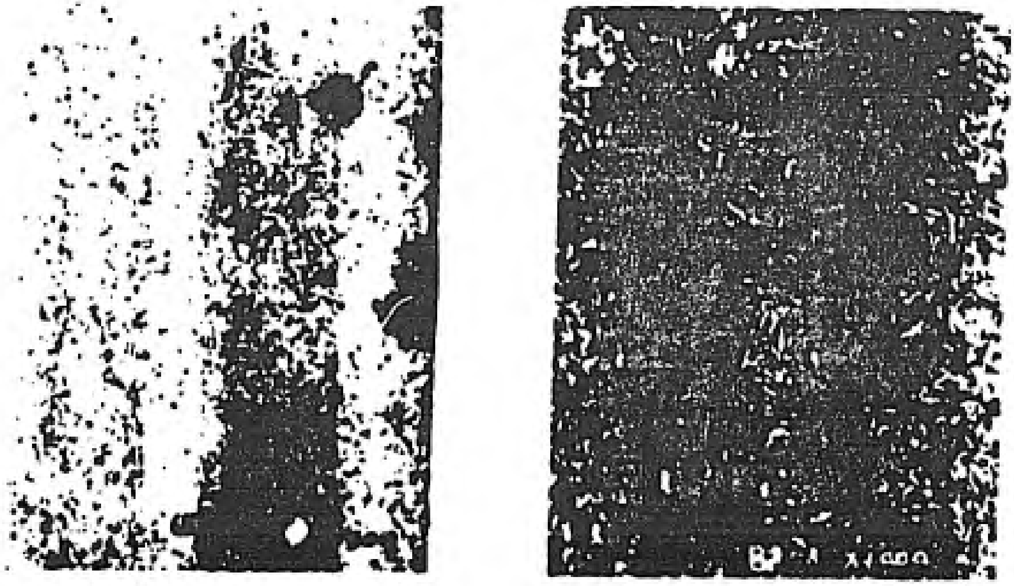
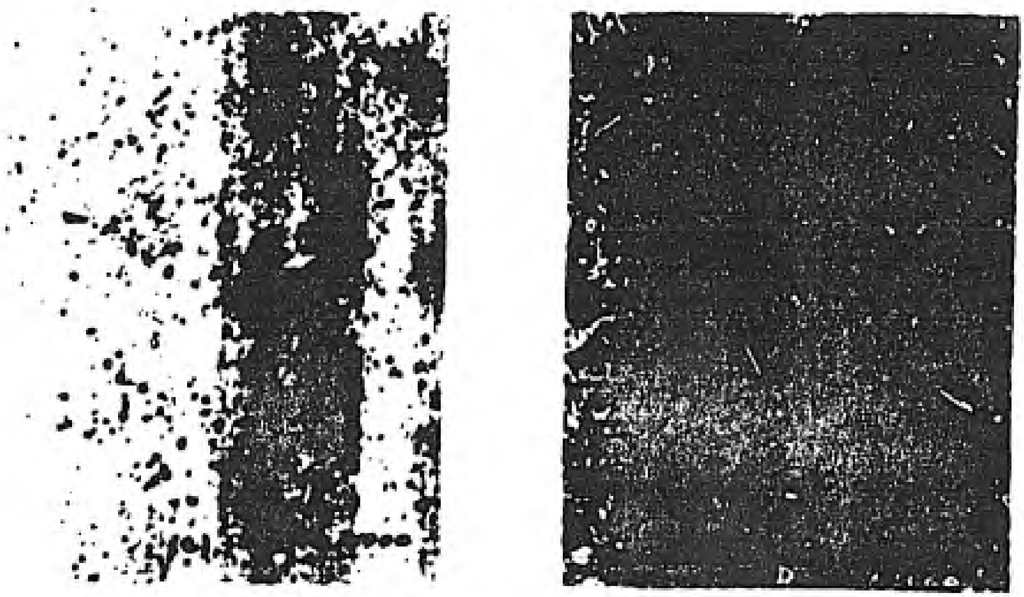


PLATE #N3-3



W.A. 639-1353

Figure 12

1/2" Experimental Plate #K2

Brinell Hardness 418 - Cr-Mo-V Steel
No spalls - Ballistic limit 2700 ft/sec., caliber .30 A.P., Specification AXS54-2.

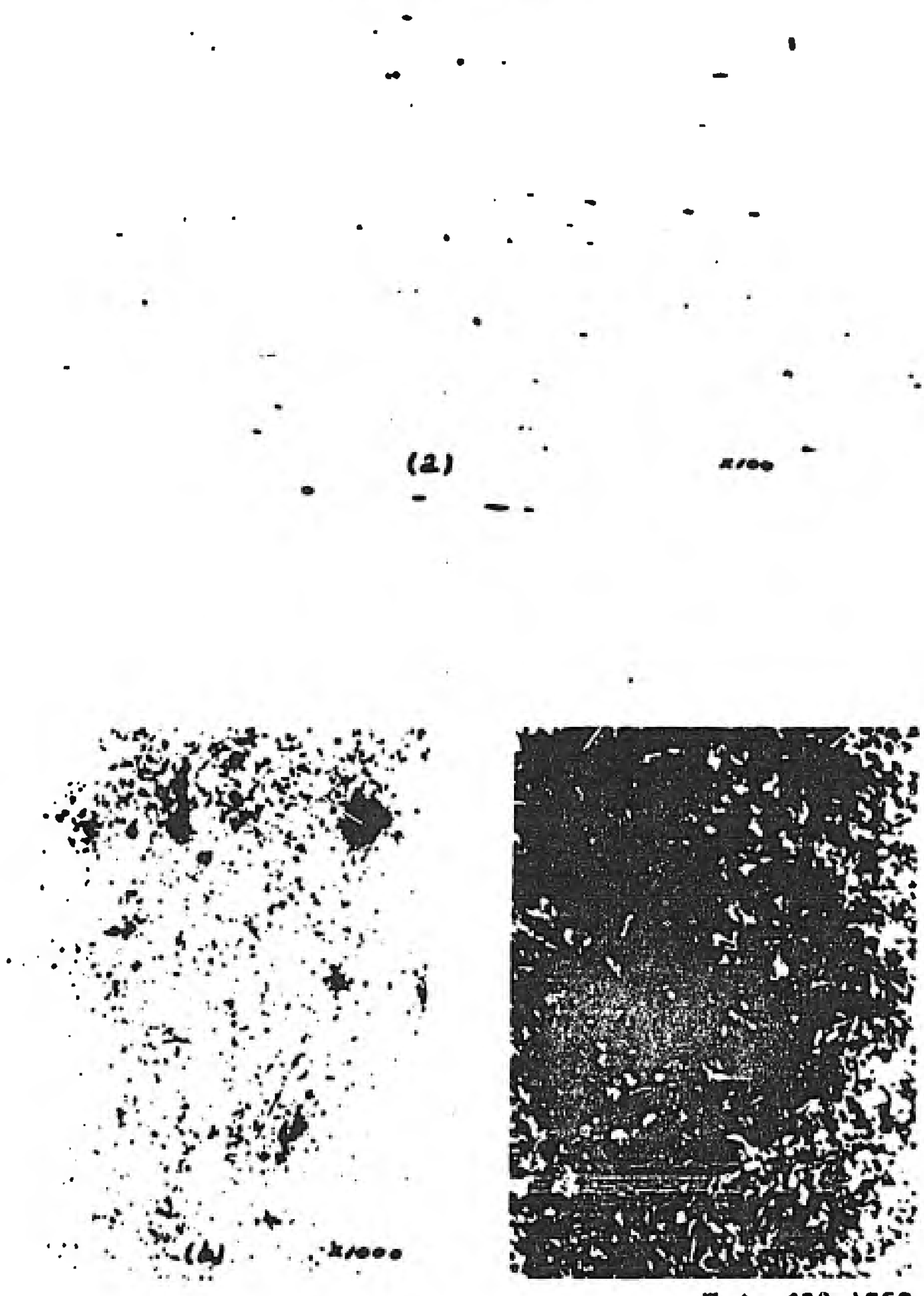
(a) Very short elongations of nonmetallic inclusions. Laminations no longer than this are not considered detrimental.
Unetched MA-1293

(b) Uniform distribution of extremely fine carbides.
Murakami etch MA-998

(c) Good, uniform troostito-sorbite.
1% Nital etch MA-1297

FIGURE 12

PLATE K2



W.A. 639-1353

Figure 13

1" Plate #W-10*

Brinell Hardness 352/363 - Cr-Mo-V Low Carbon Steel - No Spalls - Ballistic Limit 2445 ft/sec., caliber .50 A.P., Specification AXS54-1

(a) Ferritic segregations in bands, traces of troostite surrounding ferrite, sorbite in alternate bands.
1% Nital etch MA-1236

(b) Very faint tiny carbides form chains around grain boundaries.
MA-1232

1/2" Plate #A*

Brinell Hardness 387 - Cr-Mo-V Low Carbon Steel - No Spall - Ballistic Limit 2561 ft/sec., caliber .30 A.P., Specification 31,- also machine gun fire, 20 bursts.

(a) Ferrite segregated into definite patches in troostito-sorbite.
1% Nital etch MA-944

(b) Carbides form faint network around the ferrite.
Murakami etch MA-924

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*Dirt content in both plates average, no laminations of nonmetallics.

FIGURE 13

PLATE W 10

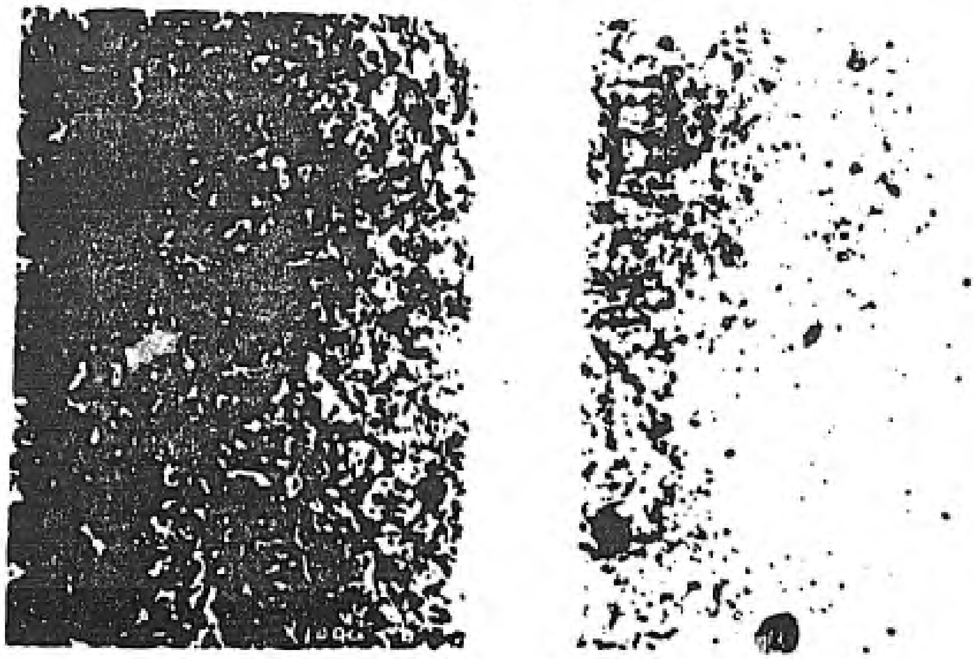
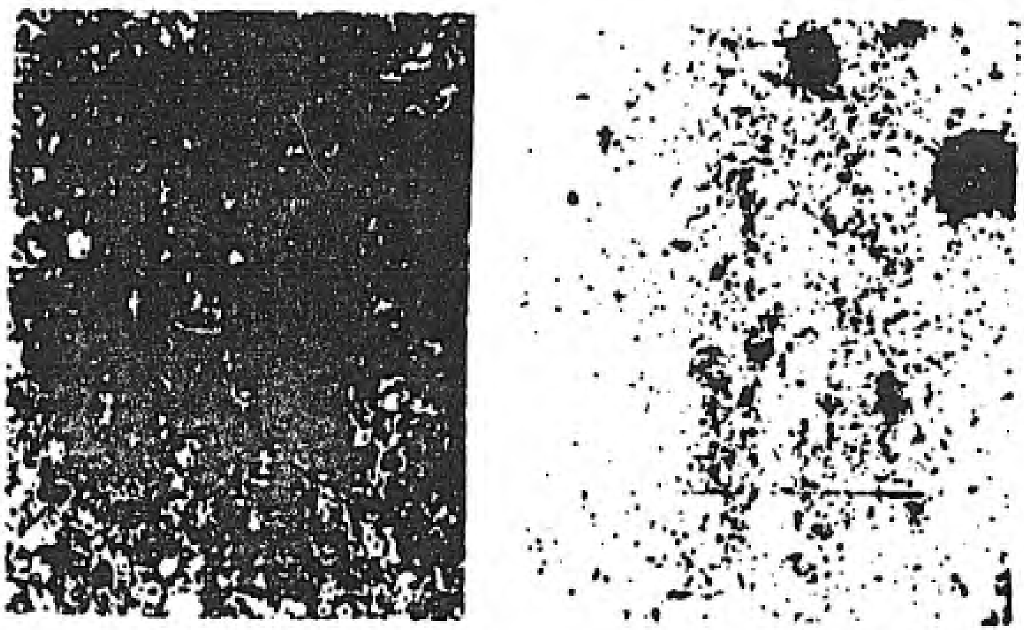


PLATE A



W.A. 639-1354

(352-387 Brinell hardness). Plate No. Ex-29 is a sorbitic structure showing no ferrite segregations, but because of its low Brinell hardness (364/375), its ballistic limit is too low to pass Specification No. AXS-54K-1. However, a soft Plate No. W-9 (352/363 Brinell hardness), see Figures 14a and b, with a sorbitic structure revealing grain boundaries of relatively large size and with traces of ferrite in cleavage planes (Fig. 14c) but with definite chains of carbides outlining the grains (Fig. 14d), spalled under caliber .50 A.P. impact and cracked under caliber .50 A.P. machine gun fire.

Plates in the Brinell hardness range of 477 and above invariably spall as noted in Plates Nos. 414, G-1, G-2, N-10-3, and 13.

An example of the troostito-martensite found in plates with a Brinell hardness of roughly 512 is illustrated in Figure 15. Since the dirt content and carbide arrangement in these plates are acceptable, the only cause of their spalling must be this martensitic condition.

Furthermore, spalling is produced in plates with troostito-martensitic structures and grain boundary

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Figure 14

1/2" Plate #EX-29*

Brinell Hardness 364/375 - Cr-Mo-V Low Carbon Steel - No Spall - Ballistic Limit 2221 ft/sec., caliber .50 A.P., Specification AXS54.

(a) Sorbitic structure shows ferrite well distributed throughout.
1% Nital etch MA-906

(b) Small carbides show a very vague indication of outlining ferrite.
Murakami etch MA-922

*Very short stringers of nonmetallics.

3/4" Plate #W-9**

Brinell Hardness 352/363 - Cr-Mo-V Low Carbon Steel - Cracked and blown out - Ballistic Limit 1873 ft/sec., caliber .50 A.P., Spec. AXS54-1, - also machine gun fire, 25 rounds.

(c) Sorbitic structure in which relatively large grain boundaries can be detected, with traces of ferrite in cleavage planes.
1% Nital etch MA-943

(d) Definite chains of carbides outlining grains.
Murakami etch MA-925

**Average distribution of rounded nonmetallics.

FIGURE 14

PL. IL #LX29

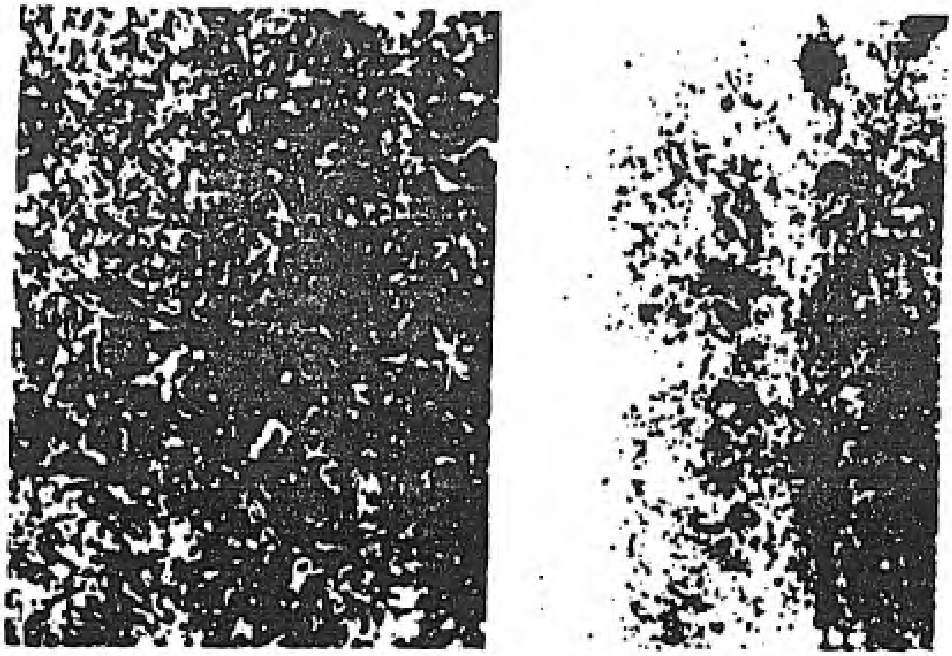
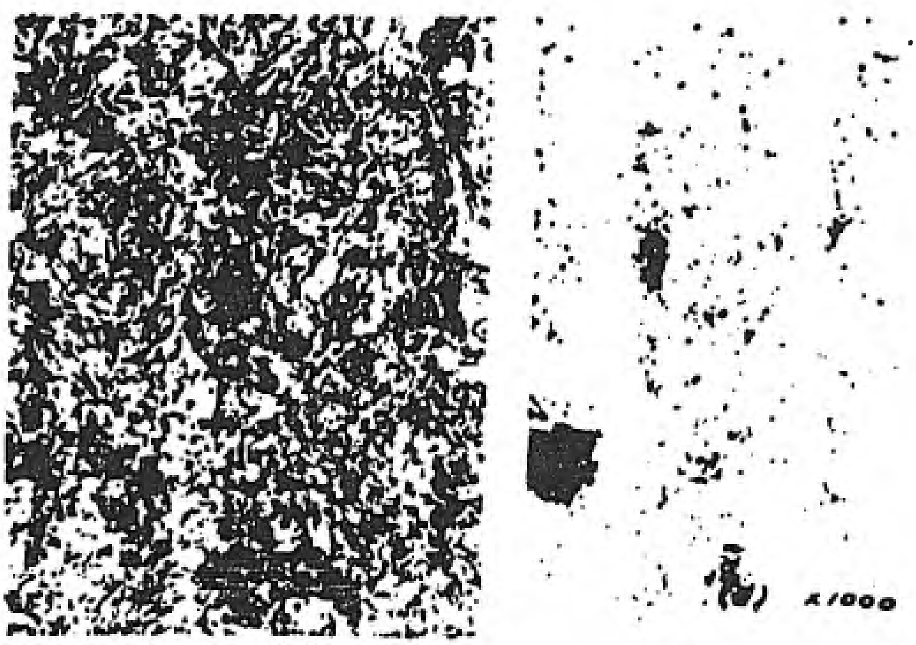


PLATE #W-9



x1000

W.A. 63?-1355

Figure 15

1/2" German Plate #2*

Brinell Hardness 477/532 - Ni-Si-Cr-W Steel - Spalled - Ballistic Limit 2654 ft/sec., caliber .30 A.P., Specification 31.

(a) Fairly dirty steel but inclusions are rounded, not drawn out into stringers.
Unetched MA-951

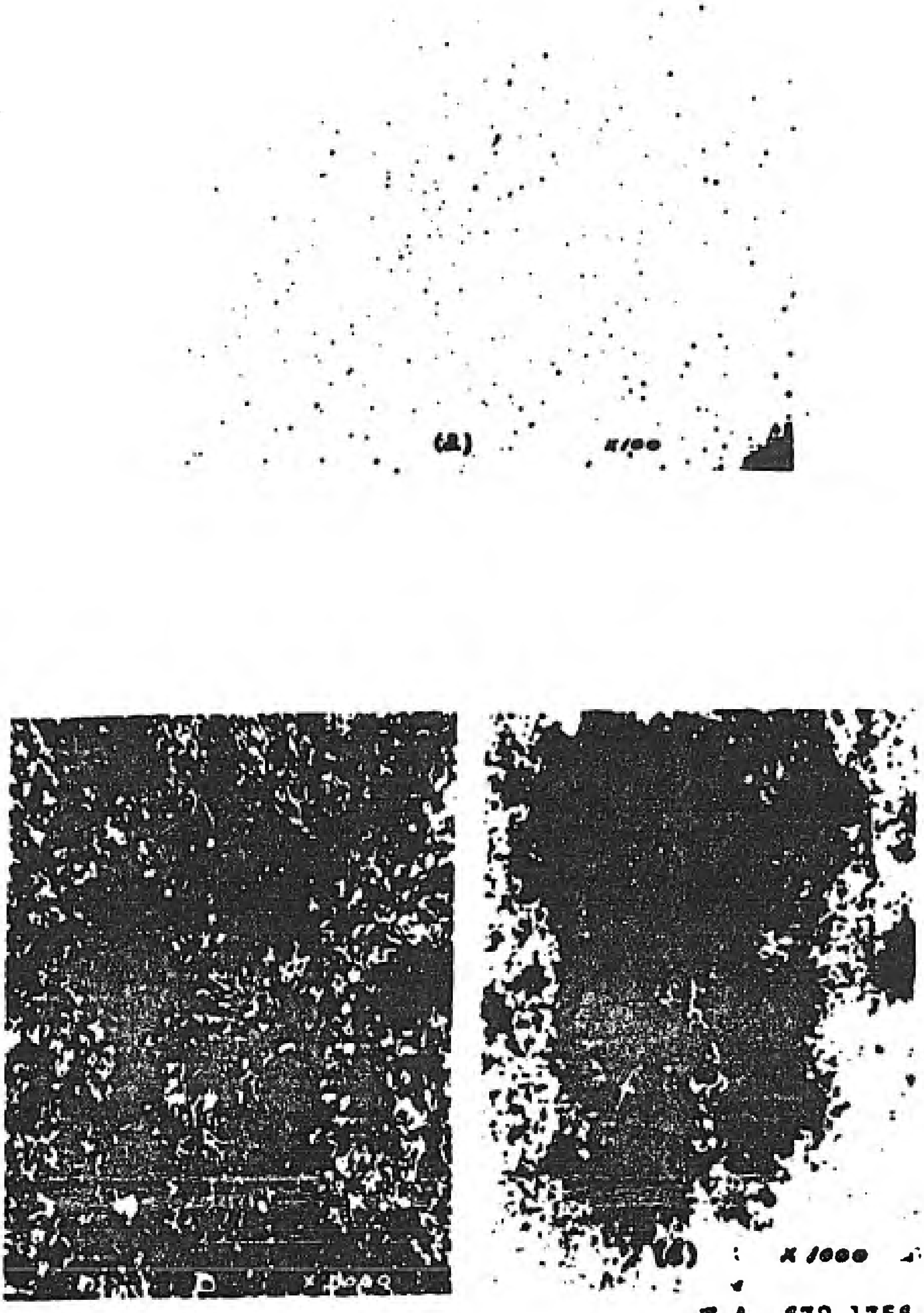
(b) Troostito martensitic structure.
1% Nital etch MA-982

(c) Uniform distribution of fine carbides.
Murakami etch MA-972

*Structures identical to those of German Plate #1.

FIGURE 15

GERMAN PLATE #2



W.A. 639-1356

carbide. This is illustrated in Figure 16, Plate No. N-10-3 with a Brinell hardness of 477. A carbide condition which revealed evidence of some grain outline was found in this plate (Fig. 16b) which was quenched from 1600°F into a salt bath at 500°F and held at that temperature for 12 hours. This particular troostito-martensitic structure (Fig. 16a) is really an aged martensite produced by the austempering treatment described above.

Austempering another plate, No. N-13-6, of the same composition as Plate No. N-10-3, by quenching it from 1600°F into a salt bath at 600°F and holding at this temperature for 1-1/4 hours, produces a troostito-martensitic structure which is known as acicular troostite, Figure 16c. Steels having this acicular troostitic structure have been shown by E. C. Bain to possess a fine combination of strength and toughness. Plate No. N-13-6, when tested with caliber .30 A.P. ammunition, is a high ballistic plate, notwithstanding the fact that it has a streak (less than .001" wide) of segregated carbides in the central portion of the plate (Fig. 16d), although the body of this plate exhibits a fine even distribution of carbides.

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Figure 16

1/2" Experimental Plate #M10-3*

Brinell Hardness 477 - Cr-Mo-V Steel - Buttoned and cracked - Ballistic Limit 2350 ft/sec., caliber .30 A.P., Specification AXS54-2

(a) Coarse troostito-martensite
1% Nital etch MA-1298

(b) Large carbides segregated in the interstices of remnants of the original dendritic segregation.
Murakami etch MA-997

*Few short laminations of nonmetallic inclusions.

1/2" Experimental Plate #M13-6**

Brinell Hardness 477 - Cr-Mo-V Steel - No Spall - Highest partial 2600 ft/sec., caliber .30 A.P., Specification AXS54-2.

(a) Acicular troostite (fine troostito-martensite) produced by austempering.
1% Nital etch MA-1299

(b) Streak less than .001 inches wide of fairly large carbides runs through the center of this plate. The remainder of the plate shows the same structure as can be seen on either side of this streak - i.e., uniform distribution of small carbides.
Murakami etch MA-1017

**Few short stringers in center.

FIGURE 16

PLATE #N10-3

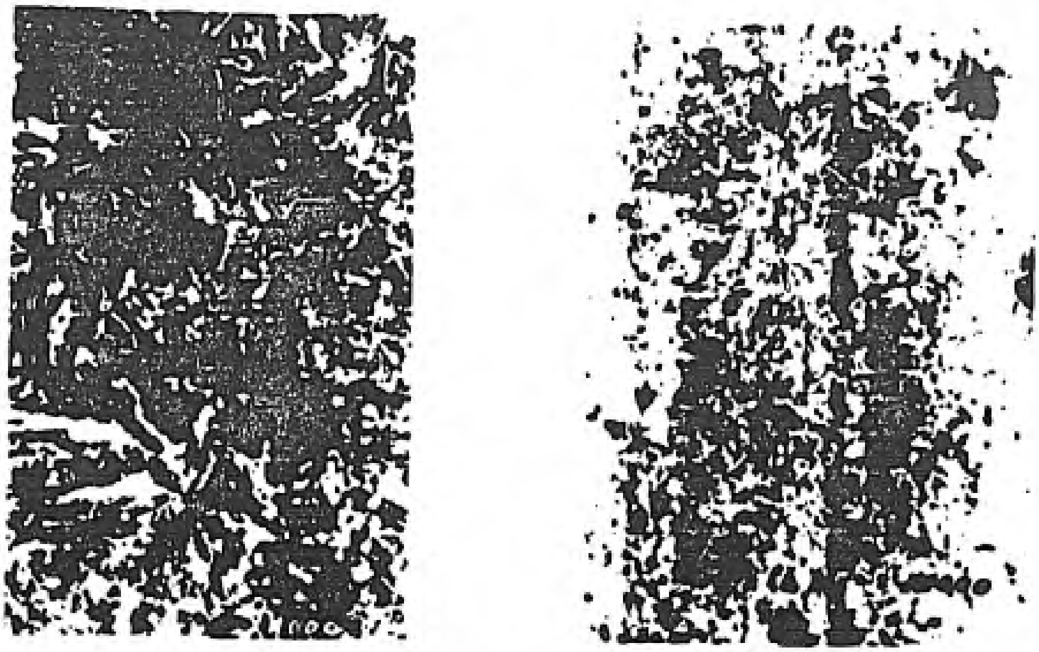
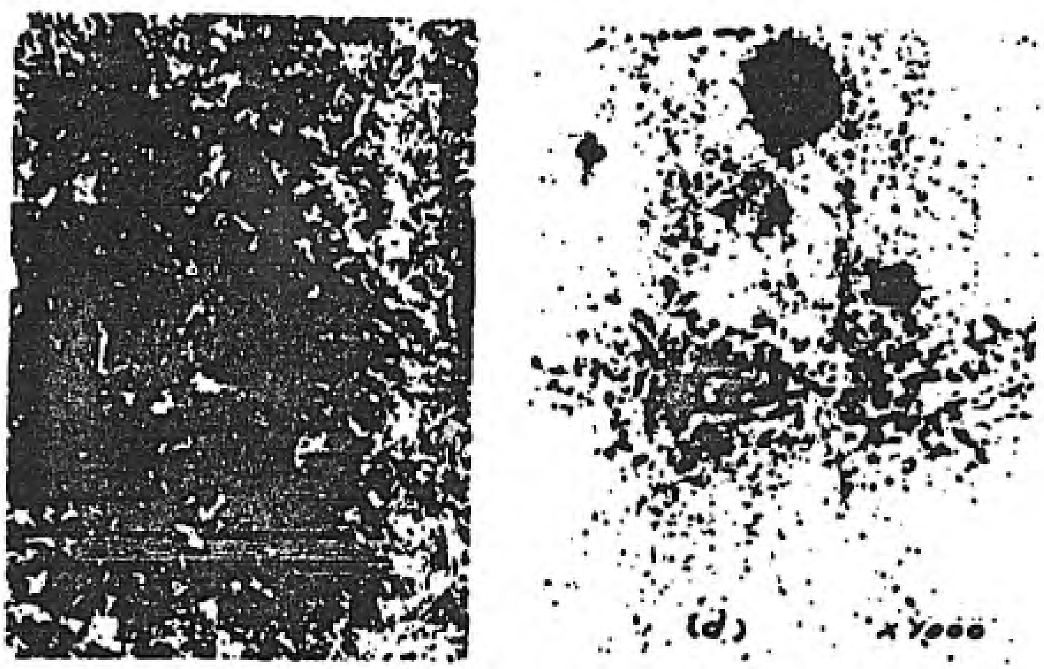


PLATE #N13-6



W.A. 672-1357

In every case in which martensitic structures accompanied laminations, spalling occurred, see Table 1, Plates Nos. 414 and 423.

In the case of plates containing about 3% nickel and 2% silicon, a less rigid definition of uniformity in microstructure applies, see Figures 17a and b, 1/2" Plate No. 626D-4. Even a bad streak of laminations in the center of this plate did not cause spalling under caliber .30 A.P. impact.

Microstructures of poor quality nickel silicon plate are shown in Figure 18. The distribution of ferrite in these poor plates is not so uniform as in the good ballistic Plate No. 626-17, Figure 18f. The carbides in the grain boundary, in this case, caused more spalling in this plate than in Plate No. 626D-2.

In the study of macrostructures of armor plate, the longitudinal sections were identified by the difference in banding evident after an Oberhoffer etch. A typical example of this difference is shown in Figures 19a and b.

The three types of macro segregations common to all armor plate are illustrated in Figures 19c and d, and Figures 20a, b, c, and d. It is evident that each type of structure is found in varying degrees both in good and poor plate.

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Figure 17

1/2" Plate #626-D-4

Brinell Hardness 430 - Ni-Si Steel - No Spall - Ballistic Limit 2637 ft/sec., caliber .30 A.P., 150 ft. range - Complete at 2600 ft/sec., caliber .30 A.P., Specification AXS54

(a) Pronounced micro-segregation in the form of banding.
1% Nital etch MA-1211

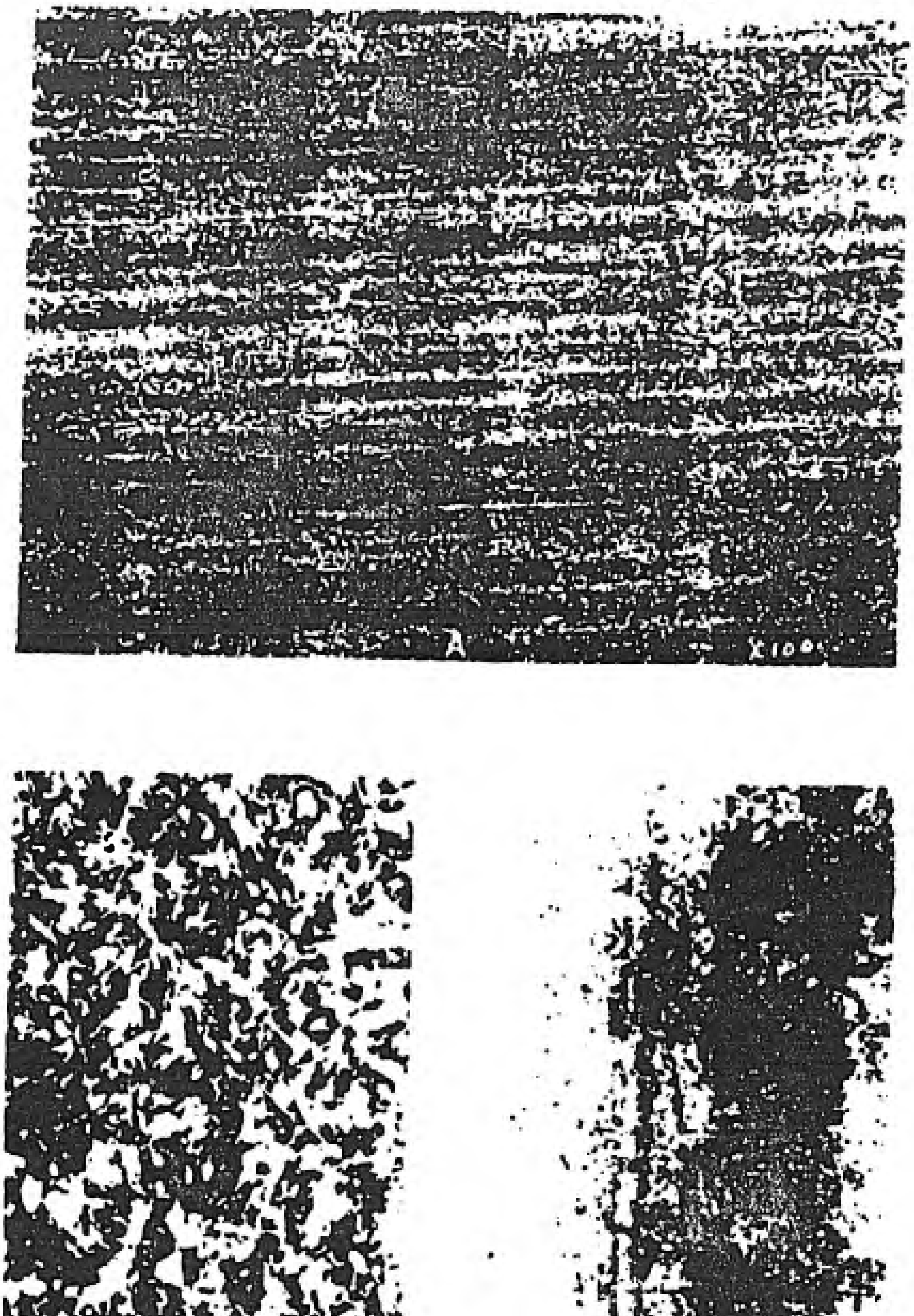
(b) Coarse troostitic structure with some sorbite. Remnants of martensitic pattern are evident along with considerable ferrite.
1% Nital etch MA-1210

(c) Carbides show faint evidence of segregating around patches of ferrite.
Murakami etch MA-1095

Dirt consists of tiny laminations and a bad streak of elongated nonmetallics in center.

FIGURE 17

PLATE TYPE D 4-(½")



W.A. 670-1358

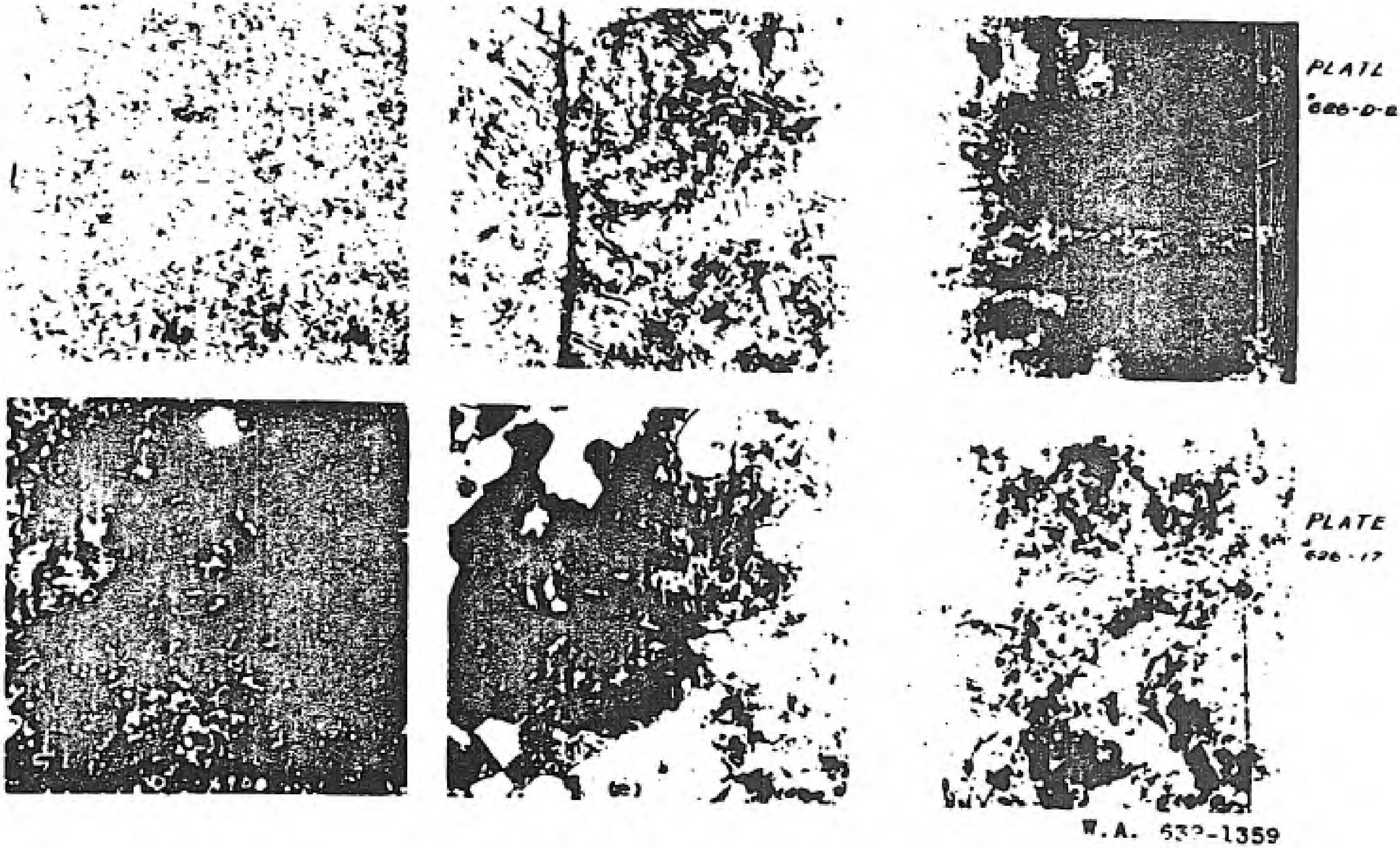


FIGURE 1.8

Figure 18

1/2" Plate #626-D-2*

Brinell Hardness 477 - Ni-Si Steel - Spalled - Ballistic Limit 2791 ft/sec., caliber .30 A.P., 150 ft. range.

(a) No particular micro-segregation.
1% Nital etch MA-1256

(b) Various-sized, randomly-scattered ferrite patches in martensite.
1% Nital etch MA-1254

(c) Carbides outline ferrite patches.
Murakami etch MA-1081

1/2" Plate #626-17**

Brinell Hardness 387 - Spalled - Ni-Si Steel -

(d) Ferrite network and large globules of free ferrite.
1% Nital etch MA-1212

(e) Large martensitic grain outlined by ferrite next to a large grain of ferrite.
1% Nital etch MA-1213

(f) Chains of carbides outlining grains and ferrite patches.
Murakami etch MA-1094

---

*Bad streak of much dirt and laminations through center - probably a pipe.
**Few fairly short laminations.

Figure 19*

(a) German Plate #1, transverse section. Note choppy condition of banding and slight evidence of residual dendritic structure. MA-986

(b) Same plate as (a) above, but this time a longitudinal section. Banding now consists of quite long straight lines with considerably more contrast. No evidence of dendritic structure. MA-1022

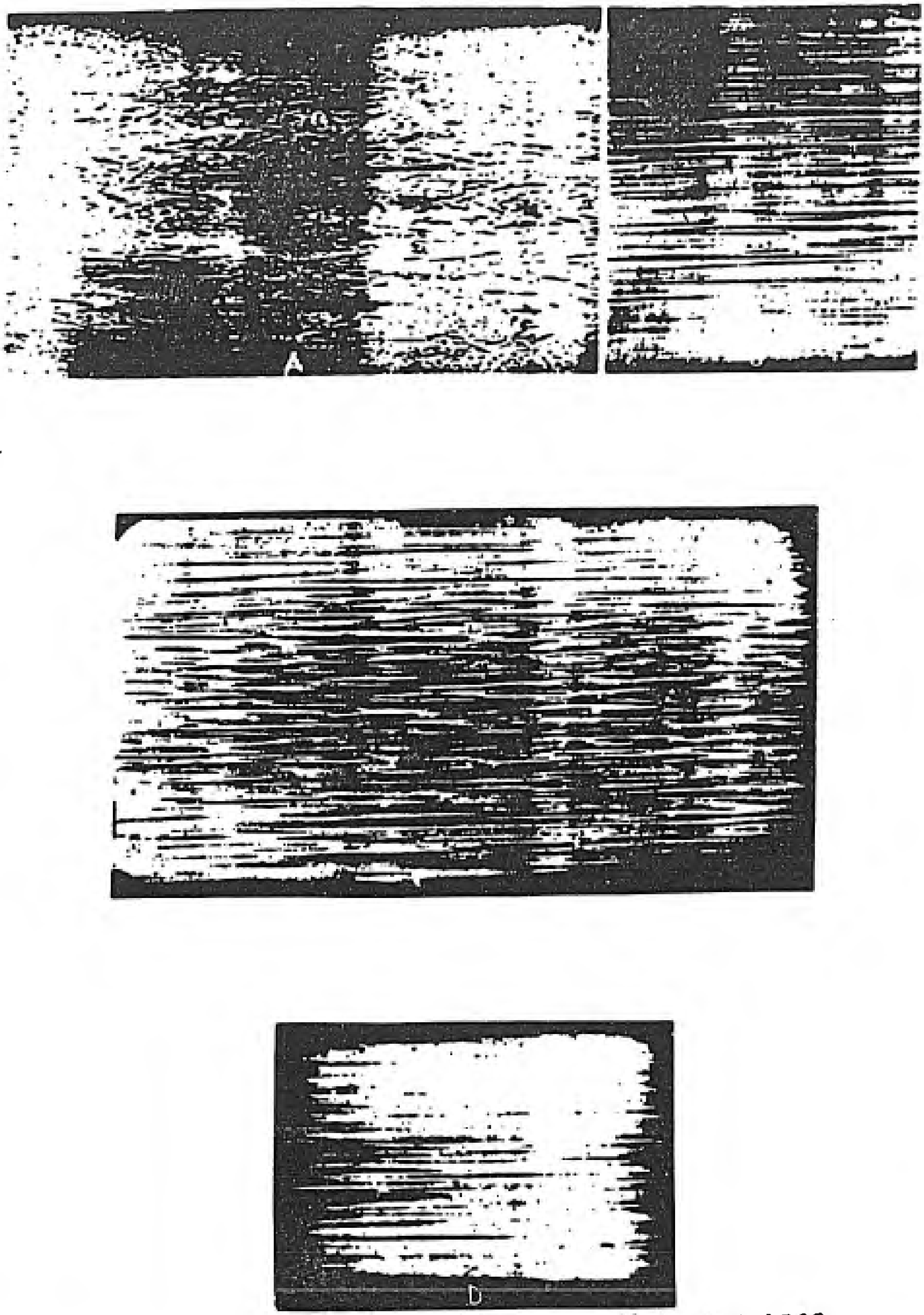
(c) 1/2" German Plate #2 - Bad plate which has a fine even macro banding. MA-985

(d) 3/8" Plate #11 - Good plate with same type of banding as (c) above, a poor plate. MA-968

*All etched in Oberhoffer's reagent. No elongated nonmetallics in longitudinal sections of above two steels.

FIGURE 19

X5 MAGNIFICATION



W.A. 639-1360

Figure 20

(a) 1/2" Plate #N10-3 - Poor plate, shows wide streaks in center and more fuzzy banding then the type shown in Figure 19 (c or d).

MA-1010

(b) 1/2" Plate #N13-6 - Good plate, shows same type of banding as (a) above.

MA-1302

(c) 1/2" Plate #626-D-2 - Poor plate, shows dendritic structure approximately one-quarter of way in on each surface, even on the longitudinal cross section.

MA-1070

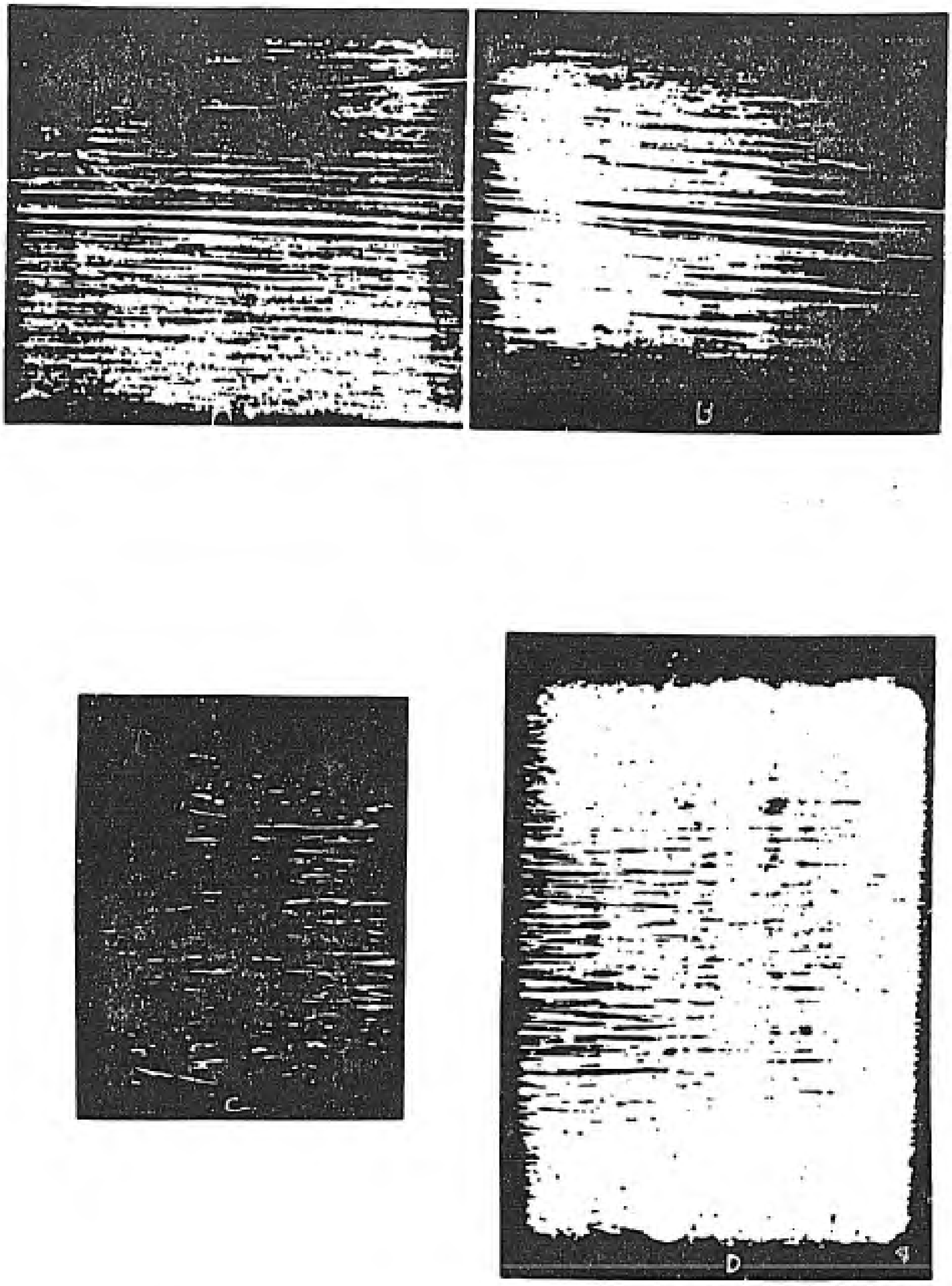
(d) 3/4" Plate #36 - Good plate, also shows dendritic structure for considerable way in from each surface on longitudinal section.

MA-993

All etched in Oberhoffer's reagent.

FIGURE 20

X5 MAGNIFICATION



W.A. 639-1361

It is interesting to note that the poor ballistic plate, No. N-10-3, has the same composition as high ballistic plate, No. N-13-6. Although both of these plates show the same type of pronounced banding, Figures 20a and b, the ballistic properties of Plate No. N-13-6 have been improved by the austempering treatment.

Grain size determinations were studied in high and low ballistic plate by the McQuaid-Ehn test, that is, pack carburizing for a sufficient time followed by slow cooling. This treatment results in a hypereuteotoid case with free cementite outlining the resulting grain boundaries.

Armor plate of the chromium-molybdenum-vanadium composition carburizes slowly. Therefore, a 60-hour carburizing was necessary.

A sample of K-2 representing a high ballistic plate and a sample of N-10-3 typifying a poor ballistic plate were so treated.

It was found that the resulting grain size of Plate No. K-2 was relatively larger than that of Plate No. N-10-3, see Figure 21a, b. It is a known fact that steels having a large grain size respond more readily to deep hardening than steels having a smaller grain size.

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Figure 21

(a) Poor ballistic Plate #N-10-3, after carburizing 60 hours at 1700°F, slowly cooled in box. Mixture of fine and relatively coarse grains in case; slightly abnormal structure; suggestive of shallow hardening steel.

MA-1035 a, b, c

(b) Good ballistic Plate #N-8, after carburizing 60 hours at 1700°F, slowly cooled in box. Fairly uniform. Large grain size in case, suggesting a more deep hardening steel than Plate No. N-10-3. Abnormality not so pronounced.

MA-1034

(c) Poor ballistic Plate #N-10-3, heated 1 hour at 1600°F, quenched in salt bath at 500°F, held 12 hours, quenched in water. Reheated 3 hours at 1250°F, furnace cooled. Note carbide precipitation at grain boundaries.

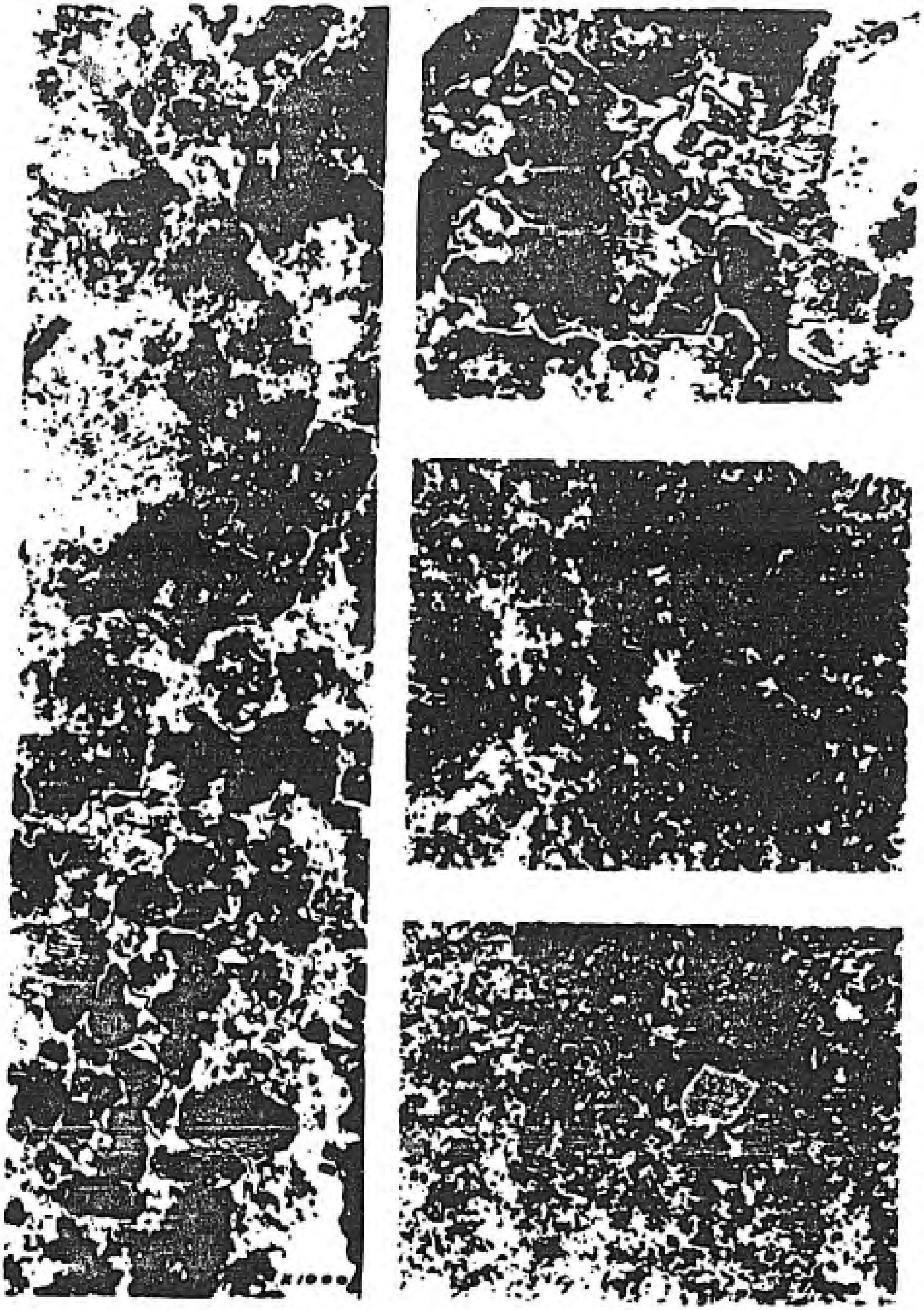
MA-1089

(d) High ballistic Plate #N-9, heated to 1600°F, 2 hours, slow cooled in furnace to 1450°F, oil quenched, drawn 2 hours at 925°F, air cooled. Reheated 3 hours at 1250°F, furnace cooled. Note no precipitation of carbide.

MA-1088

All etched in 1% Nital.

FIGURE 21



W.A. 639-1362

Another study on these compositions showed that after annealing (see Figures 21c and d) the high ballistic plate gave evidence of a more uniform carbide precipitation than the poor ballistic plate.

It is possible that further studies along these lines may reveal some relation between grain size and ballistic properties, although nothing conclusive can be stated about the above tests.

Summary

1. Out of 47 plates examined, elongated nonmetallic inclusions were detected in 14. Of these, all but 2 spalled. One of these nonspalling plates was extremely ductile due to large amounts of ferrite and was too soft to pass the specified ballistic limit. The other had such a uniform microstructure that it overcame the handicap of elongated nonmetallic inclusions.

2. Of 14 plates showing bad carbide conditions, only 2 did not spall. Since neither of these 2 plates was subjected to a shock test, it is reasonable to presume that all plates having bad carbide condition are susceptible to spalling.

3. Of 5 plates having ferritic conditions (i.e., Brinell hardness 387 or lower), 4 could not resist velocities as of Specification No. AXS54-K-1. The fifth

plate was tested under old Specification No. 31 (1932) and would in all probability fall below modern specifications.

4. Of the 47 plates examined, only 7 showed the presence of martensite in the microstructure and all of these spalled. An eighth plate, which has an acicular troostitic structure (aged martensite) produced by austempering, had good ballistic properties but it is questionable whether it would pass shock tests.

5. Out of 17 plates showing excellent dirt, carbide and micro condition, all passed ballistic tests. 14 of these had a Brinell hardness of 418, the hardness of the other three ranging from 430 to 477.

Respectfully submitted,

E. L. Reed.

E. L. Reed,
Research Metallurgist.

S. L. Kruegel

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

APPENDIX

TABLE III

Giving the following properties of the plates examined.

(a) Chemical Analysis

(b) Ballistic Data

(c) Heat Treatment

(d) Brinell Hardness

(e) Manufacturer

C	Mn	Si	S	P	Ni	Cr	V	Mo	W
.45/.55	1.25/1.50	.20/.35						2.50/2.75	.60/.80
.45/.55	.50/.80	.20/.35				1.10/1.30	.20/.30	.40/.80	.60/1.50
.50	.70	.25	.020	.023		1.12	.25	.65	
.29	.44	.26	.012	.011	.05	1.36	.22	.71	
.50	.70	.25	.020	.023		1.12	.25	.65	
.29	.44	.26	.012	.011	.05	1.36	.22	.71	
.50	.70	.25	.020	.023		1.12	.25	.65	
.23	.50	.23	.010	.010		1.37	.26	.77	
.26	.52	.20	.012	.010		1.21	.27	.80	
.285	.47	.205	.018	.008		1.26	.24	.63	
.50	.70	.25	.020	.023		1.12	.25	.65	
.50	.70	.25	.020	.023		1.12	.25	.65	
.50	.70	.26	.020	.023		1.12	.28	.66	
.51	.42	.14	.013	.016	.09	1.21	.29	.56	
.51	.42	.14	.013	.016	.09	1.21	.29	.56	
.525	.63	.23	.017	.008		1.21	.24	.66	

TABLE 3A

o	W	CAL SHOT	SPEC. AXS54	SPEC. 31	SPEC. 150' RANGE	SPALLY CHARACTER	BRINELL HARDNESS	HEAT TO °F
/2.75	.60/80	.50	2909				477	1450 1550 1650
/80	.60/1.50	.50	2910				430/444	165
5		.50		2560 HP			418	157
71		.50	2445	2769			352/363	
65		.50		2573 HP			418	
71		ALSO M.G. .50	1873	2245		SPALL	352/363	
		.50 M.G. FIRE				PETALS	430	
5		ALSO M.G .50		2694 HP		PETALS	418/444	
77		.30	2160	2526			340 FRONT 364 BACK	1750 1535
0		.30	2221	2527			375 FRONT 364 BACK	1750 1535
3		ALSO M.G. .30		2561			387	
5		.30		2593			418	157
5		.30 .50		2702 1932		.50 SHOWS A FEW CRACKS	418	1575
6		.50		1956			418	157
6		.30	2451	2658		SPALLS	430 444	165
6		.30	2445	2678		BUTTON	444	165
6		.30	2450				444	1600

NELL)NESS	HEATED TO °F	QUENCHED IN	AT °F	DRAW °F	FOR MIN	MANUFACTUF
·77	1450 1550 1650	OIL		850		WATERTOWN ARSENAL
/444	1650	OIL		1050		" "
18	1575	OIL		1075		DISSTON
/363		OIL		1000		"
-18						"
/363		OIL		1000		"
30						"
/444						"
FRONT BACK	1750 1535	DOUBLE OIL		1000		"
FRONT BACK	1750 1535	DOUBLE OIL		1000		"
87						"
18	1575	OIL		1075		"
18	1575	OIL		1075		"
18	1575	OIL		1075		"
30 44	1650	OIL		1150	120	WATERTOWN ARSENAL
44	1650	OIL		1150	120	" "
44	1600	OIL		925	120	DISSTON-WATERTOWN ARSENAL.

W	FOR MIN	MANUFACTURER
'O		WATERTOWN ARSENAL EXPERIMENTAL
0		" " "
5		DISSTON
0		"
		"
'O		"
		"
		"
)0		"
0		"
		"
'5		"
5		"
5		"
0	120	WATERTOWN ARSENAL - DISSTON D
)	120	" " "
5	120	DISSTON-WATERTOWN ARSENAL EXPERIMENTAL HEAT TREATMENT

C	Mn	Si	S	P	Ni	Cr	V	Mo	W	
.525	.63	.23	.017	.006		1.21	.24	.66		
.525	.63	.23	.017	.006		1.21	.24	.66		
.545	.57	.24	.017	.011		1.29	.24	.60		
.455	.58	.275	.019	.018		1.13	.25	.55		
.37	63	1.60	.016	.017	3.60	.22	NIL	.14	.43 Cu .09	
.36	.64	1.60	.016	.017	3.58	.22	NIL	.14	.44 .08	
.40B .38D	1.07	1.96 D	.031	.019	3.09					
.33	1.02	1.63			3.04					
.415	.99	2.07	.026	.022	3.01	.09				
.45/.55	.40/.60	.15/.25	.02	.02		1.10/1.30	.20/.30	.60/.80		
.45/.55	.40/.60	.15/.25	.02	.02		1.10/1.30	.20/.30	.60/.80		
.50	.70	.25	.020	023		1.12	.25	.65		
.50	.70	.25	.020	023		1.12	.25	.65		
.50	.70	.25	.020	023		1.12	.25	.65		.5
.50	.70	.25	.020	023		1.12	.25	.65		3
.45/.55	.60/.80	.15/.30	.03	03		1.00/1.35	.20/.30	.60/.80		
.45/.55	.60/.80	.15/.30	.03	03		1.00/1.35	.20/.30	.60/.80		
.45/.55	.60/.80	.15/.30	.03	03		1.00/1.35	.20/.30	.60/.80		
.50	.71	.20	.007	.015		.90		.28		
.42	1.10	2.03			3.10					

TABLE 3B

Mo	W	CAL. SHOT	SPEC. AXS54	SPEC. 31	SPEC. 150' RANGE	SPALLY CHARACTER	BRINELL HARDNESS	HEA TO
66		.30	2600 HP				477	16
56		.30	2350			BUTTONS	477	16
0		.30	2600 HP				444	16
55		.30	2700				418	16
14	.49 Cu .09	.30		2457		SPALLED	532 EDGE 512 CENTER	
14	.44 .08	.30		2654		SPALLED	532 EDGE 512 CENTER	
		.30	2600		2837		430	14
		.30			2791	SPALLED	477	14
						SPALLED	387	
0/.80		.30		2170 HP			418	
0/.80		.30		2168 HP		SPALLED	418	
.65		.30		2173			418	15
65							418	15
65		.50 M1 BALL		2550		BAD CRACKS, PORTIONS BLOWN OFF	370	15
65		.30 .30 BALL		2304 2835			418	15
0/.80		.30		2224			418	15 16
0/.80		.30		2304			418 / 444	15 16
0/.80		.30		2227			418	15 16
.28		.30			1936	SPALLED	512	
		.30			2156	SPALLED	460	14

NELL INESS	HEATED TO °F	QUENCHED IN	AT °F	DRAW °F	FOR MIN	MANUFACTUR
77	1600	SALT → 600° / WATER		600	75	DISSTON - WATERTOWN ARSE
77	1600	SALT → 500 / WATER		500	720	" " "
-4	1600	OIL		925	120	" " "
8	1600	OIL		925	120	" " "
E EDGE CENTER						GERMANY
EDGE CENTER						"
30	1485	OIL	170	IN DIE 845	30	DISSTON
77	1485	OIL	142	630	30	"
7						
18						"
8						"
8	1575		1075			"
8	1575		1075			"
70	1575	OIL		1075		"
8	1575					"
8	1550 1600	OIL	1550	1100 1200		"
-4	1550 1600	OIL	1550	1100 1200		"
8	1550 1600	OIL	1550	1100 1200		"
2		OIL	1600	850	30	CRUCIBLE
30	1480	OIL	170	IN DIE 835	25	DISSTON

DRAW °F	FOR MIN	MANUFACTURER
600	75	DISSTON - WATERTOWN ARSENAL EXPERIMENTAL
500	720	" " " "
925	120	" " " "
925	120	" " " "
		GERMANY
		"
845	30	DISSTON
830	30	"
		"
		"
		"
		"
075		"
		"
100 200		"
100 200		"
100 200		"
350	30	CRUCIBLE
DIE 335	25	DISSTON

D

C	Mn	Si	S	P	Ni	Cr	V	Mo	W
.50	.70	.25	.020	.023		1.12	.25	.65	
.50	.71	.20	.007	.015		.90		.28	
.50	.71	.20	.007	.015		.90		.28	
.50	.70	.25	.020	.023		1.12	.25	.65	
.45/55	.40/60	.15/.25	.02	.02		1.10/1.30	.20/.30	.60/.80	
.50	1.08	1.80			3.15				
.50	.70	.25	.020	.023		1.12	.25	.65	
.50	.70	.25	.020	.023		1.12	.25	.65	
.50	.70	.25	.020	.023		1.12	.25	.65	
.50	.70	.25	.020	.023		1.12	.25	.65	

TABLE 3C

Mo	W	CAL. SHOT	SPEC. AX S 54	SPEC. 31	SPEC. 150' RANGE	SPALLY CHARACTER	BRINELL HARDNESS
.65		.30		2128			418
.28		.30			1852		351
.28		.30			1823	SPALLED	444
.65		.30		1827			418
.60/.80		.30			1736 HP	SPALLED	402
		.30			1710	SPALLED	364
.65		.30 .30 BALL M1 .276 T161		1528 2230 1565			418
.65		.30 BALL MG					418
.65		.30 BALL .30		1747 1003		PIECES BLOWN OUT	402
.65		.30 BALL		1029		PIECES BLOWN OUT BETWEEN ROUNDS	

R

PALLY ARACTER	BRINELL HARDNESS	HEATED TO °F	QUENCHED IN	AT °F	DRAW °F	FOR MIN.	MANUF.
	418	1575	OIL		1075		DISSTON
	351		OIL	1600	1300	45	CRUCIBLE
PALLED	444		OIL	1600	1000	30	"
	418	1575		1075			DISSTON
PALLED	402						"
PALLED	364	1475	OIL	190	IN DIE 1075	10	"
	418	1575		1075			"
	418	1575		1075			"
CES BLOWN OUT	402	1575		1075			"
CES BLOWN BETWEEN [illegible]		1575		1075			"
			C				

...CHED N	AT °F	DRAW °F	FOR MIN.	MANUFACTURER
L		1075		DISSTON
L	1600	1300	45	CRUCIBLE
L	1600	1000	30	"
	1075			DISSTON
				"
L	190	IN DIE 1075	10	"
	1075			"
	1075			"
	1075			"
	1075			"

D