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Report No. 710/79
Watertown Arsenal

December 31, 1936

The Relation of Microstructure to the Ballistic Properties of Homogeneous Armor Plate

Purpose

The purpose of this investigation was to determine the relation of microstructure to the ballistic properties of homogeneous armor plate.

Conclusions

1. A preliminary investigation indicates that homogeneous armor plate which contains segregations of elongated non-metallic inclusions, sometimes known as laminations, either as the result of poor steel making practice or insufficient cropping of the ingot, is susceptible to excessive spalling.

2. Microscopic examination indicates that crack systems resulting from bullet impact usually progress through or parallel to segregations of non-metallics.

3. In the samples of high ballistic plate examined, crack systems are not related to uniformly distributed non-metallics such as complex oxides and titanium nitride or cyano-nitride inclusions. The latter being present in titanium-treated steels.

4. Fine incipient cracks were occasionally detected at the end of elongated non-metallic inclusions present in areas below the bullet hole in partially penetrated medium ballistic plate.

5. In the plates examined, laminations are responsible for spalling and the blowing off of buttons. On the other hand laminations in these plates do not lower the ballistic limit to a marked degree.

6. It was determined that a standard chromium-molybdenum-vanadium plate having a high ballistic limit and free of spalling and laminations had a uniform microstructure typical of troostite or troostito-sorbite. Troostite and sorbite are transition constituents present in hardened and tempered steels, a definition of which is as follows:

According to some authorities troostite is a submicroscopic dispersion of iron carbide particles in alpha ferrite, while sorbite is a microscopic dispersion of iron carbide particles in alpha iron. It is believed that sorbite differs from troostite only in the size of particles which must be large enough to be observed under high magnification. The Brinell hardness of troostite is estimated as 400-500, while that of sorbite is 250-400.

7. Plates of the standard chromium-molybdenum-vanadium composition having a medium high

ballistic limit usually do not have a uniform microstructure as compared to the high ballistic plates. The former containing laminations with ferrite intermingled with troostite and sorbite. Such plates evidently were rolled from segregated portions of the ingot.

8. Titanium treated plates have good ballistic properties but the addition of titanium does not prevent spalling which was detected in the plates containing laminations.

9. Homogeneous armor plate containing 3% nickel and 2% silicon has a high ballistic limit when hardened to a Brinell hardness of 555. This plate has a relatively coarse martensitic structure and after impact contains internal cracks which are intercrystalline. Martensite is a submicroscopic dispersion of iron carbide particles or carbon particles in alpha iron and it is believed to differ from troostite only in the fact that the dispersed particles are smaller in size. The Brinell hardness of martensite varies from 500-650.

10. Cracks resulting from bullet impact in cast armor plate run parallel to the contour of the bullet hole. These cracks are not related to porous areas but mostly follow the interdendritic areas.

11. Austenitic manganese steels containing 1% carbon and 12% manganese are not suitable for use in light armor plate construction.

Experimental Procedure

Several homogeneous plates and one cast plate ware selected for examination as follows:

(a) Plate No. 29 - high ballistic properties
Size 12x12x1, manufactured by Henry Disston & Sons.

(b) Plate WJ2 - high ballistic properties.
Size 12x12x1/2, manufactured by Jessop Steel Co.

(c) Plate No. EX26 - medium ballistic properties.
size 12x12x1/2 - manufactured by Henry Disston & Sons, Inc.

(d) Plate No. 614-5 - medium ballistic properties.
Size 12x12x1/2 - manufaotured by
Watertown Arsenal Henry Disston & Sons, Inc.
Order 8542, Ingot 12-614.

(e) Plate No. 2 - poor ballistic properties
Size 12x12x1/2 - manufactured by Taylor-Wharton Co.

(f) Cast carburetor cover #A - poor ballistic properties. Size 21 1/2 x 15 x 1/2 - manufactured by Watertown Arsenal.

Representative partial and complete penetrations in each plate were sectioned and examined under the micrscope for distribution of non-metallics, study of crack systems and the uniformity and nature of micro constituents.

Physical properties were determined only on the Disston plates and cast plates.

Due to hardness of the Jessop plate and the difficulty experienced in machining austenitic manganese steel from which plate No. 2 was made by Taylor-Wharton Co., physical properties of these plates were not determined.

Chemical analysis was made on several plates, the analysis of which was not recorded in the reports submitted by Aberdeen Proving Ground.

Spectrographic analysis was made on samples cut from all plates except plates No. 2 and No. A.

The ballistic properties of the plates as determined at Aberdeen Proving Ground are found in the following partial reports on test of thin armor plate: 21, 59, 81, 82, 96 and 99.

Experimental Results

1. Spectrographic Analysis

Spectrographic analysis of the plates examined is given in Table I.

TABLE I

Spectrographic Analysis

Element	Plate No. 29	WJ2	Ex 26	614-5
Ni	Present	Faint Trace	Trace	Trace
Cu	Trace	Present	Present	Present
Al	Trace	Trace	Trace	Faint Trace
Ti	Trace	Trace	Trace	Trace
Ca	Faint Trace	Faint Trace	Faint Trace	Faint Trace
Sn	Trace	Trace	Trace	Trace

2. Heat Treatment of Plates

The heat treatment given the plates by the manufacturers is stated in Table II.

TABLE II

Heat Treatment of Plates

Plate No.	Heated to	Quenching Medium	Draw
29	1575°F	Not stated	1075°F
WJ2	Not stated	" "	Not stated
Ex 26	1700°F	oil	1150°F
614-5	1650°F	oil	1150°F
2	Not stated	Not stated	Not stated

Cast A — Heated 8 hours at 2102°F, air cooled
" 5 " " 1742°F, " "
" 5 " " 1562°F, furn. cooled
" 2 " " 1600°F, oil quenched
Drawn 2 hours at 925°F, air cooled.

3. Chemical Analysis:

The chemical analysis of the several plates examined is given in Table III.

TABLE III

Chemical Analysis

Plate No.	C	Mn	P	S	Si	Ni	Cr	Mo	Va	Cu
29	.50	.70	.023	.020	.25	--	1.12	.65	.25	.312
WJ2	.425	.66	.024	.018	2.01	3.58	.24	--	--	--
Ex 26	.38	.69	--	.17	--	---	1.14	.65	.30	.296
614-5	.51	.42	.016	.013	.14	.09	1.21	.56	.29	.252
2	1.17	11.40	.057	.018	.405	-	--	--	--	--
Cast A	.19	.54	.010	.018	.165	-	1.13	.82	.21	--

TABLE IV

PHYSICAL PROPERTIES

Plate No.	Y.S.P. 0.00% set lbs./sq.in.	Tensile Strength #/sq.in.	Elong. in 1.4" %	Reduction of Area %	Charpy Tension Impact Ft. Lbs.	Remarks
29 Long.	187,500	207,500	10.4	31.7	293.08	High Ballistic Plate
29 Trans.	187,500	207,300	12.5	39.2	322.95	" " "
Ex 26 Long.	175,000	193,500	11.4	33.5	293.08	Medium high Ballistic Plate.
Ex 26 Trans.	180,000	195,800	14.0	44.5	300.45	" " "
614-5 Long.	194,000	221,000	13.6	43.7	322.95	" " "
614-5 Trans.	196,500	223,800	9.7	27.2	264.07	" " "
"A" (Cast Plate)	144,500	159,800	3.6	3.6	79.49	Poor Ballistic Plate

4. Physical Properties

The physical properties of the plates tested are given in Table IV.

5. Ballistic Properties

The ballistic properties of the plates are shown in Table V.

6. Microscopic Examination

Microscopic examination of crack systems, distribution of non-metallic inclusions, and uniformity of structure was made by S. La Bonte Kruegel. M. R. Norton has made a study of crack systems under a magnification of 1000 diameters.

Discussion

The results of this investigation indicate that the ballistic limit is not lowered by the presence of a uniform distribution of small inclusions or angular cubic titanium nitride, or cyano-nitride found in titanium treated steels. In the plates examined, crack systems developed near the bullet hole as a result of bullet impact are not definitely related to this type of non-metallic inclusion.

Figures 1a, 2a, and 2b illustrate the distribution of non-metallics in plates of high ballistic limit; that is, numbers 29 and WJ2.

Figures 1b, 2d and 2e illustrate the characteristic complex oxides and typical nitrides or cyano nitrides found in these plates.

Macrostructures showing the occurrence of cracks resulting from bullet impact in the unetched sections of these high ballistic plates are shown in Figures 1c, 1d, 2f, 2g, and 2h. Although plate WJ2 had a high ballistic resistance, an examination of the unetched cross sections revealed the presence of some internal ruptures near the bullet hole, see Figure 2f. This condition was typical of this plate containing 3.58% nickel and 2.01% silicon. The standard chromium-molybdenum-vanadium plate of high ballistic resistance was relatively free from internal cracks or ruptures as shown in Figures 1c and 1d.

T A B L E V

BALLISTIC PROPERTIES

Plate No.	Thickness	Brinell	Ballistic Limit Spec. 31 F.S.	Ballistic Limit Spec. 31 Ft.lbs.	Ballistic Limit AXS-54 F.S.	Ballistic Limit AXS-54 Ft. lbs.	Manufacturer
29	1"	418			*2568	10,985	Henry Disston & Sons, Inc. Cal. .50 AP M1 - 100 yds.
WJ2	1/2"	555	** 2945	--	--	--	Jessop Manufacturing Co. Cal. .30 AP M1922 - 100 yds.
Ex 26	1/2"	402-418	2700	2671	2380	2075	Henry Disston & Sons, Inc. Cal. .30 AP M1922 - 100 yds.
614-5	1/2"	430-444	2685	2642	2451	2201	Watertown Arsenal Henry Disston & Sons, Inc. Cal. .30 AP M1922 - 100 yds.
2	1/2"	255	2252	1858	--	--	Taylor-Wharton Co. Cal. .30 AP M1922- 50 yds.
Cast "A"	1/2"	418	--	--	1897	1312	Watertown Arsenal Cal. .30 AP M1922 - 100 yds.

* Withstood Cal. .50 AP M-1 Ammunition at distance of 100 yards.
** " " .30 AP M-1922 " " " " " "

Plates of medium ballistic limit, numbers Ex 26 and 614-5 of standard chromium-molybdenum-vanadium composition are susceptible to spalling although the ballistic limit is not lowered to a marked degree. It is believed that spalling in these plates is due to the presence of laminations or elongated non-metallic inclusions as illustrated in Figures 3a, 3c, 3d, 3e, 4a, 4b, 4c, 4d, 4e, and 4f. Photographs of cross sections of bullet holes showing the various stages of formation of spalls are illustrated in Figures 5c, 5c1, 5d, 5e, and 5f. Figure 5b illustrates an armor piercing bullet actually penetrating a plate in the act of breaking off a spall on the back face. Figure 5a shows the result of a button blown off the back face. In many cases it was determined that spalls or buttons separated from the plate along the laminations or elongated non-metallics, see Figure 6.

Titanium treated steels have good ballistic properties but titanium additions do not overcome the tendencies to spalling caused by laminations.

In Figure 7 it is interesting to note that a crack produced by a bullet impact was deflected by a non-metallic inclusions, in fact the crack crossed the non-metallic at an angle of about 30 degrees.

Moreover, in several cases, it appeared as though a tiny crack either originated or terminated at a small rounded non-metallic as illustrated in Figures 8 and 9. In the case shown in Figure 9, this particular crack progressed at random for a short distance through several non-metallics found in a segregated area of a medium high ballistic plate. Occasionally cracks resulted from slip along cleavage planes as shown in Figure 10. Some of the non-metallics in the vicinity of impact were shattered as illustrated in Figure 11. Furthermore, tiny cracks were evident at the extreme ends of the non-metallics.

Crack systems, as the result of bullet impact in cast armor plate, are shown in Figures 12a, 12b, and 12c. The cracks were not closely associated to porosity in the cast plate but closely followed segregated areas; that is, areas between the axes of the dendrites.

Crack systems in the high manganese plate (11.4% manganese and 1.17% carbon) progressed through clear metal. This steel was relatively clean as shown in Figures 12d, 12e, 12f and 12g.

In this investigation it was determined that plate of the standard chromium-molybdenum-vanadium composition having a high ballistic resistance to spalling had a uniform sorbito-troostitic structure as shown in Figure 13a. This particular plate was an inch thick and was not penetrated with a Caliber .50 A P with a striking velocity of 2568 foot-seconds.

Plates of the same composition only one-half inch in thickness which spalled under impact of Caliber .30 A P bullets exhibited a less uniform sorbito-troostitic structure intermingled with ferrite as illustrated in Figure 13c, 13d, and 13e.

The Brinell hardness of this plate was 418.

Due to the fine grain of the high and medium ballistic plates it was impossible to determine if the crack systems were inter or intra-crystalline.

In all plates some decarburization was detected, a typical example of which is shown in Figure 13g.

A plate one-half inch in thickness and which contained 3.58% nickel and 2.01% silicon having a high ballistic resistance (highest velocity not completely penetrating with Caliber .30 AP at a striking velocity of 2945 foot-seconds) was free from spalling but contained pronounced irregular cracks or ruptures shown in Figure 2f. The microstructure of this plate was martensitic as shown in Figure 2c and had a Brinell hardness of 555. Crack systems in this plate were intercrystalline; that is, they followed the grain boundaries, see Figure 2c.

Austenitic manganese steel, the microstructure of which is shown in Figures 13h and 13f are not suitable for good quality armor plate.

A survey of the physical properties of the plates investigated indicate that in the transverse direction of plate 614-5, the most severely laminated plate of the standard chromium-molybdenum-vanadium composition, the charpy tension impact value was 59 foot-pounds lower than the value in the longitudinal direction.

The ductility of this plate in the transverse direction was relatively lower than in the longitudinal direction as noted in Table IV. Physical properties were not determined on plate WJ2, the nickel silicon plate due to the fact that it was too hard to machine.

No particular relation could be correlated between the physical and ballistic properties of plate 29 the high ballistic plate and plate Ex26 with medium high ballistic properties.

The physical properties of the cast plate were poor in respect to ductility and impact values. The ballistic limit of this plate was slightly lower than that specified.

True stress strain curves are shown in Figures 14, 15 and 16.

Results

The results of this investigation indicate that:

1. Plate containing laminations either as the result of poor steel making practice or insufficient cropping of the ingot is susceptible to spalling.

2. Plate of the standard chromium-molybdenum-vanadium composition having a high ballistic resistance has a sorbito-troostitic structure with few internal cracks.

3. Plate containing 3.58% nickel and 2.01% silicon having a very high ballistic limit has a martensitic structure although it contains many internal cracks which are intercrystalline.

Respectfully submitted

E. L. Reed

E. L. Reed
Research Metallurgist

1. Inclusions and Crack Systems

(All pictures unetched unless otherwise noted)

Arrows point direction of bullet's path through plate.

Plate with High Ballistic Properties #29 and #WJ2

Plate #29

Microscopic Examination: Fairly dirty steel, uniform distribution of very fine non-metallics.

Size:	12 x 12 x 1 inches
Manufacturer:	Henry Disston & Sons, Inc.,
Type	Homogeneous
Ammunition:	Cal. .50 AP, 750 grain, M-1
Distance from plate to muzzle:	100 yards
Brinell Hardness	418

Chemical Composition:

C	0.50
Mn	0.70
Si	0.25
S	0.020
P	0.023
Va	0.25
Cr	1.12
Mo	0.65
Cu	0.312

Figure 1 Plate #29

a) Shows typical distribution of non-metallics and crack progressing from bullet hole. (Compare with other good plate, Figure 2 (a). There is no indication that the crack has anything but a random connection with the inclusions. See area enclosed in circle, Figure (c)

X100 Round 2 MA 127

b) Typical inclusions, the spear head probably a manganese sulphide, the cubic crystal titanium nitride, or titanium cyano-nitride. Compare with other good plate, Figure 2 (d) and (e).

X1000 Round 2 MA 126

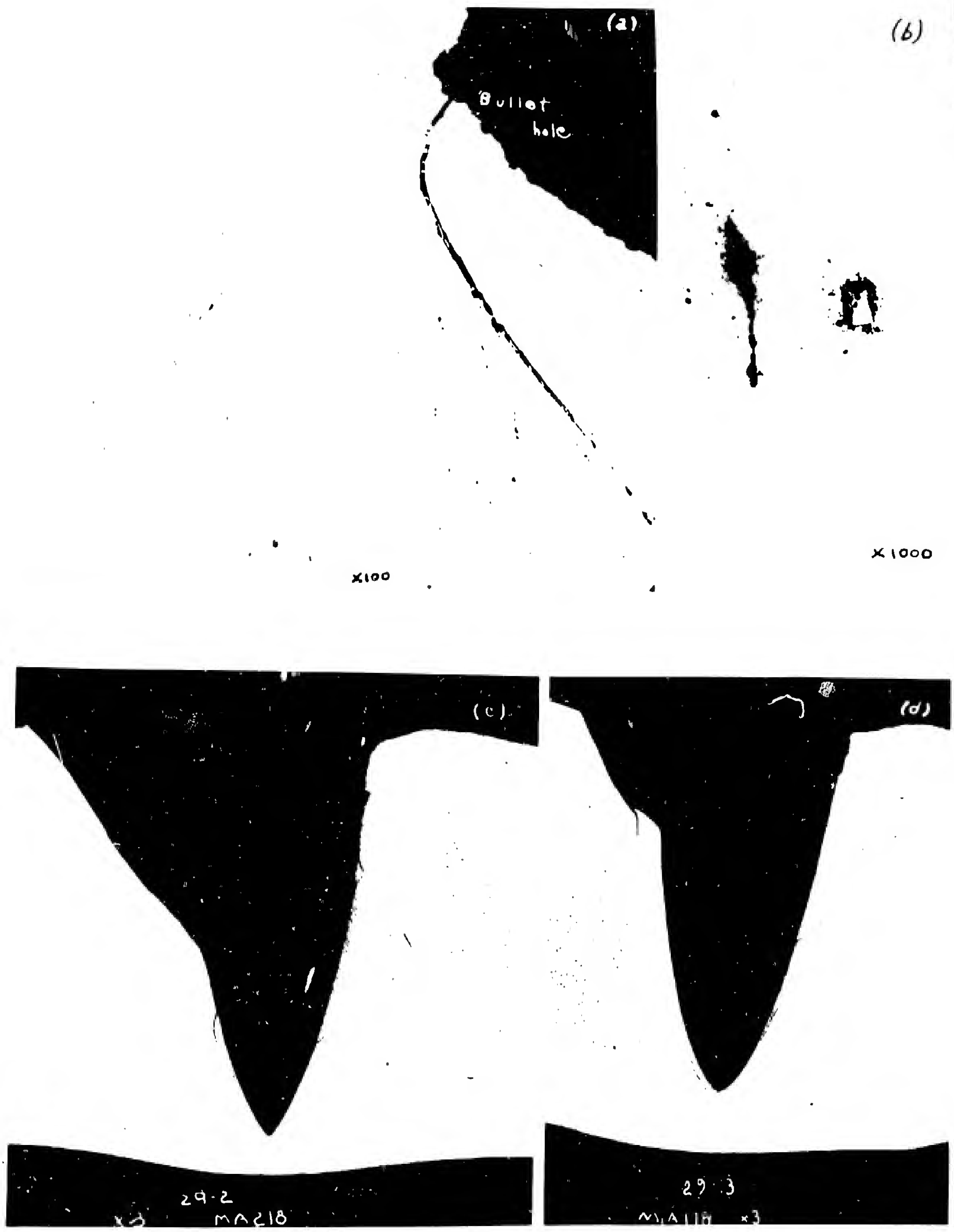
c) Highest velocity not completely penetrating.
Partial penetration
Striking velocity 2568 ft./sec.
Height of bulge in back 0.06 inches
Depth of indent 0.98 inches

X3 Round 2 - MA 218

d) Partial penetration
Striking velocity 2540 ft/sec.
Height of bulge in back 0.06 inches
Depth of indent 0.96 inches

X3 Round 3 - MA 178

Note: c) and d) show bad etching pits, due to deep etching on specimen before repolishing for these photographs. They were not removed because of the expense involved.



W.A.639-535

1. Plate with High Ballistic Properties

Plate #WJ2

Micro-examination: Fairly dirty steel, uniform distribution of fine rounded non-metallics. No laminations.

Size: 12 x 12 x 1/2 inches

Manufacturer: Jessop Steel Co.

Ammunition: Cal. .30 AP 165 gr. bullet M1922

Distance from Plate to Muzzle: 100 yards

Brinell Hardness: 555

Chemical Composition:

C	0.425
Mn	0.66
Si	2.01
S	0.018
P	0.024
Ni	3.58
Cr	0.24

Figure 2 Plate #WJ3

a) Typical fine unfformly distributed non-metallics. Compare with Figure 1 (a)

X100 Round 9 - MA 125

b) End of crack progressing from bullet hole see Figure (g) #142, which follows grain boundaries, a behavior characteristic of cracks in this plate.

X100 Round 5 - MA 142

c) To demonstrate that these cracks do follow along grain boundaries, this specimen was etched with 1% Nital to show up the grains, and the crack is clearly seen to follow the contours of the grains.

X1000 Round 3 - MA 402

d) Typical nitride inclusion. Compare with Figure 1 (b) See #154 Figure (g).

X1000 Round 5 - MA 154

e) Non-metallic inclusion of the sulphide type. Compare with Figure 1 (b). See Figure (g) #147

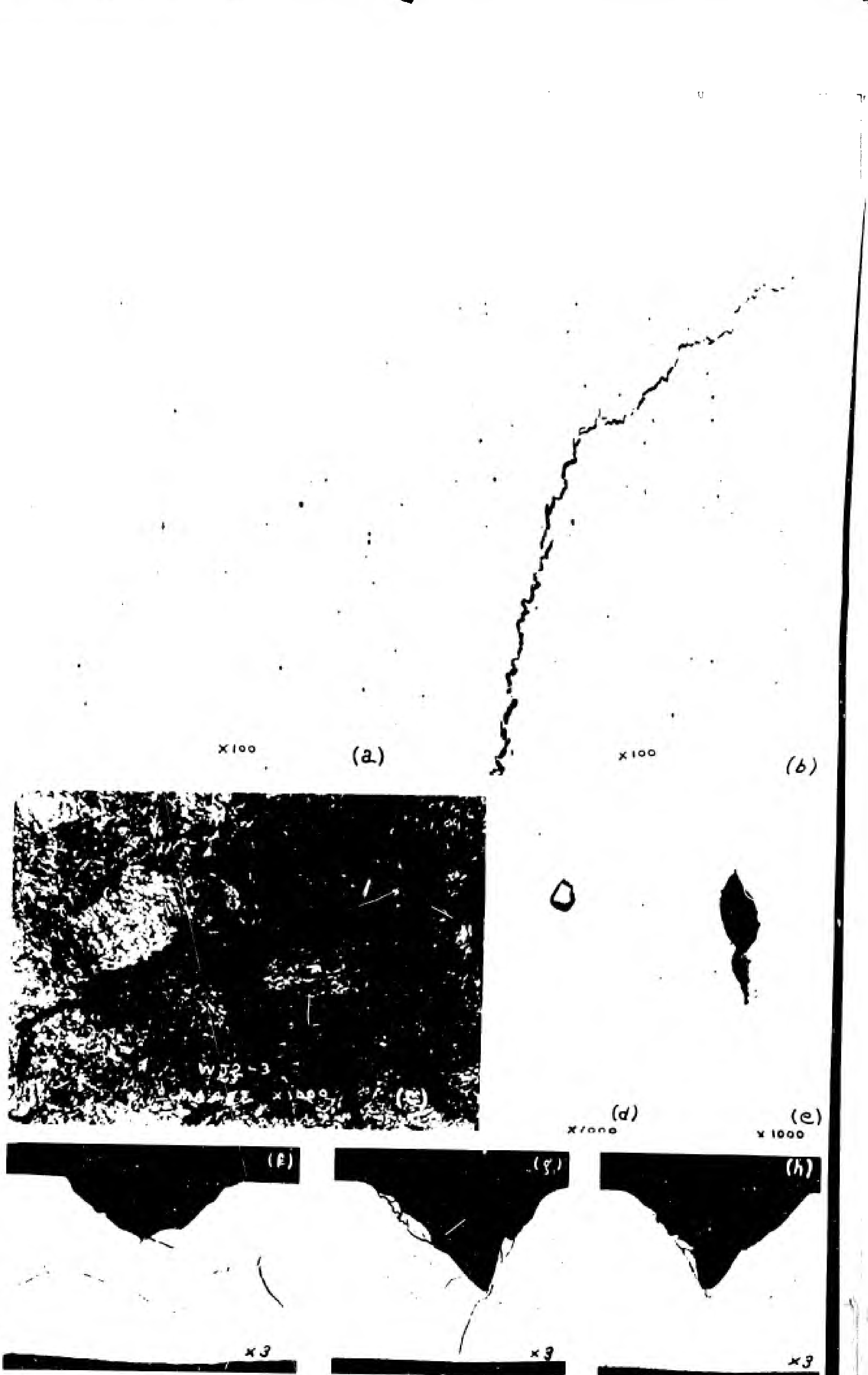
X1000 Round 5 - MA 147

f) Highest velocity not completely penetrating
Partial penetration
Striking velocity 2945 ft./sec.
Height of bulge in back 0.01 inches

X3 Round 9 - MA 106

g) Partial penetration
Striking Velocity 2639 ft./sec.
Height of bulge in back 0.00 inches
X3 Round 5 - MA 140

h) Partial penetration
Striking velocity 2599 ft./sec.
X3 Round 3 - MA 139



H.A. 639-57C

2. Plate with Medium Ballistic Properties:

EX 26 and #614-5

Microscopic Examination:

Fairly dirty steel with rather large, segregated inclusion, stringers of non-metallics.

Size -	18 x 18 x 1/2
Manufacturer:	Henry Disston & Sons, Inc.
Type -	Homogeneous
Ammunition:	Cal. .30 AP 165 grain bullet M 1922

Distance from Plate to Muzzle: 100 yards

Brinell Hardness: 402-418

Chemical Composition:

C	0.38
Mn	0.69
Si	0.17
Va	0.30
Cr	1.14
Mo	0.65
Cu	0.296

Figure 3   Plate #Ex 26

a) Showing inclusions elongated by rolling. At the upper left is the end of a wide crack parallel to the laminated inclusions, and which trails off into a thin chain of non-metallics. See (i) below.

X100 Round 8 - MA 124

b) These titanium nitride, or titanium cyano-nitride crystals occur with the same frequency as in the good plate.

X1000 Round 5- MA 122

c) This crack very nearly resulted in a button, see (g) below. Exactly parallel to it is a stringer of non-metallics indicating the probability of this "button crack" having opened up along just such a stringer. A higher power picture of the encircled portion of the stringer follows.

X100 Round 5 - MA 115

d) Structure of stringer indicated in preceding picture.

X1000 Round 5 - MA 121

e) Typical portion of a slag segregation showing angular and cubic non-metallics strung in long practically straight lines.

X1000 Round 1 - MA 123

f) Complete penetration, one petal

Striking velocity	2704 ft./sec.
Diameter of hole	0.41 inches

X3 Round 4 MA 136

g) Complete penetration, core in plate removed by machining.

Striking velocity	2696 ft./sec.
Core through back	0.55 inches
Core through front	0.02 inches

X3 Round 5 - MA 137

h) Complete penetration, core in plate removed by machining.

Striking velocity	2672 ft./sec.
Core through back	0.30 inches
Core through front	broken off

X3 Round 1 - MA 135

i) Partial penetration, highest velocity not completely penetrating.

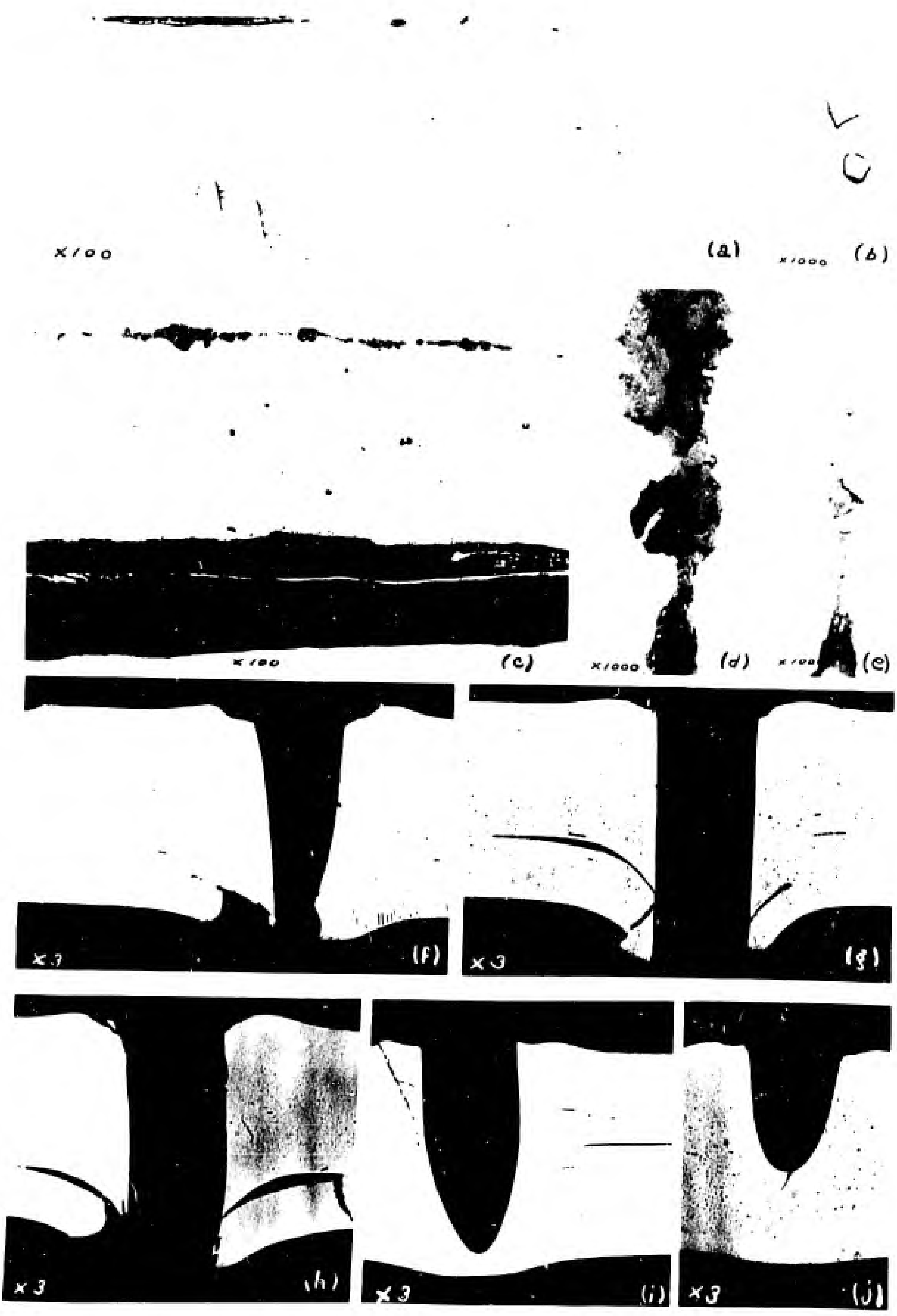
Striking velocity	2371 ft./sec.
Height of bulge in back	0.05 inches

X3 Round 8 MA 107

j) Partial penetration

Striking velocity	2286 ft./sec.
Height of bulge in back	0.03 inches

X3 Round 7 - MA 138



T.A.C70-537

2. Plate with Medium Ballistic Properties:

#614-5

Size: 18 x 18 x 1/2 inches

Manufacturer: Watertown-Disston
W. A. Order 8542, Ingot 12-614

Ammunition: Cal. .30 AP 165 grain M1922

Distance from Plate to Muzzle: 100 yards

Brinell Hardness: 430-444

Chemical Composition:

C	0.51
Mn	0.48
Si	0.14
S	0.013
P	0.016
Ni	0.09
Va	0.29
Cr	1.81
Mo	0.56
Cu	0.258

Micro-Examination:

Fairly dirty steel and extremely laminated.

Figure 4 Plate #614-5

a) Illustrating a typical behavior of cracks in the steel, this crack progress from the bullet hole parallel to the laminae of non-metallics, following one of them at its end, in this case. See figure 5 (d)

X100 Round 10 - MA 143

b) This crack again shows itself tailing off into the same direction as the segregated non-metallics in this area. See figure 5 (b) #119.

X100 Round 3 - MA 119

c) A series of cracks, progressing along non-metallic segregations parallel to other segregations. For higher power picture of the segregations, see (e) below. Also see Figure 5 (b) #117.

X100 Round 3 - MA 117

d) Typical distribution of non-metallics. Compare with good plate in Figure 1 (a) and Figure 2 (a). See Figure 5 (a)

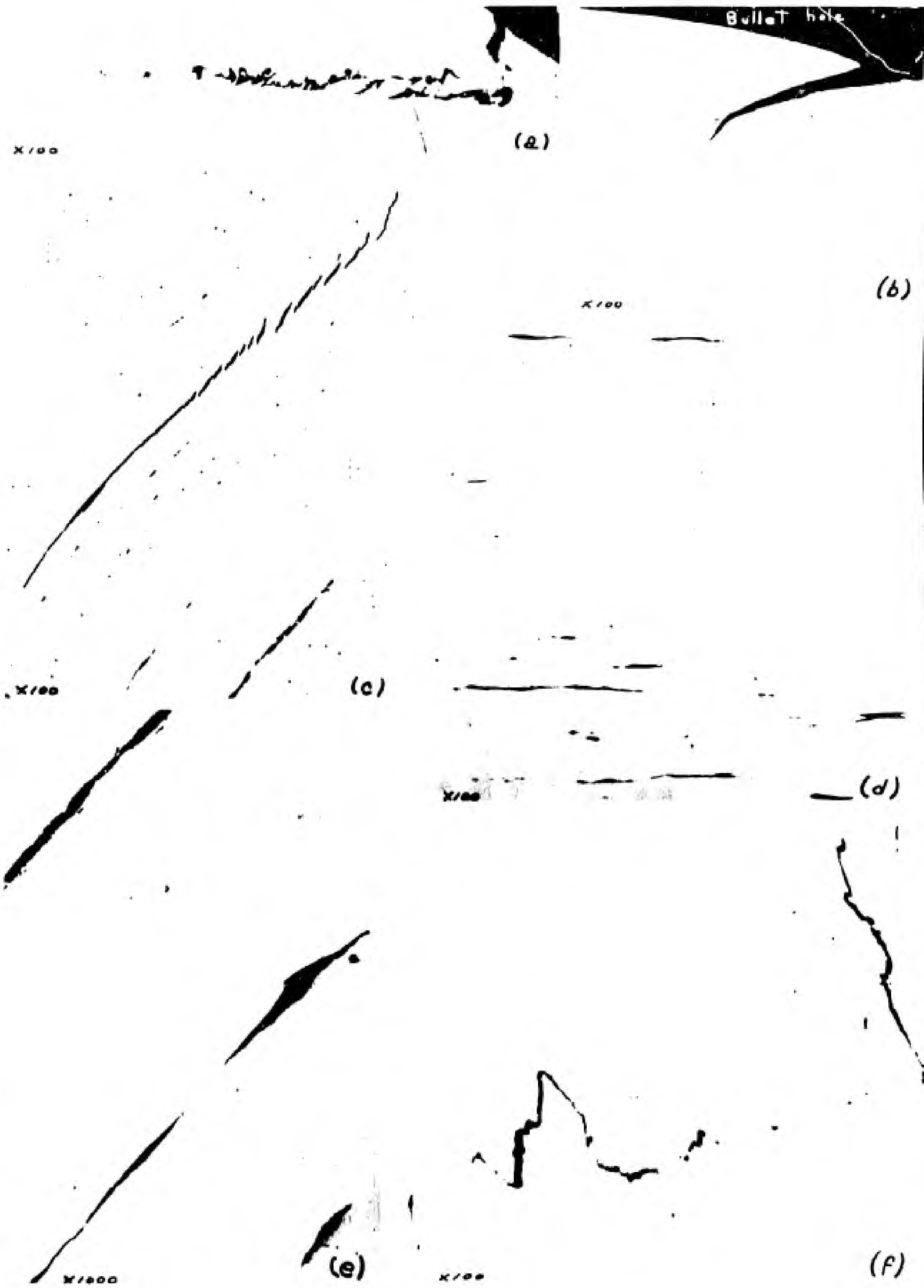
X100 - Round 2 - MA 145

e) Non metallic inclusion parallel to crack (upper left corner). High power of area enclosed in Figure (c) above.

X1000 - Round 3 - MA 118

f) This is the end of the crack indicated in Figure 5 (f). It is seen to progress along a series of fine non-metallic inclusions, giving rise to the belief that the major portion of the crack may have done the same.

X100- Round 8 - MA 120



H.4.C30-538

Figure 5 Plate #614-5

a) Complete penetration. Button blown off back
Core in plate removed by machining.
Striking velocity 2696 ft./sec.
Core through back 0.29 inches

X3 - Round 2 - MA 134

b) Complete penetration.
Core in plate
Striking velocity 2673 ft./sec.
Core through back 0.28 inches

X3 - Round 3 - MA 110

c) Complete penetration
Striking velocity 2495 ft./sec.
Diameter of hole in back 0.01 inches
Section approximately through bullet axis.

X3 - Round 5 - MA 410

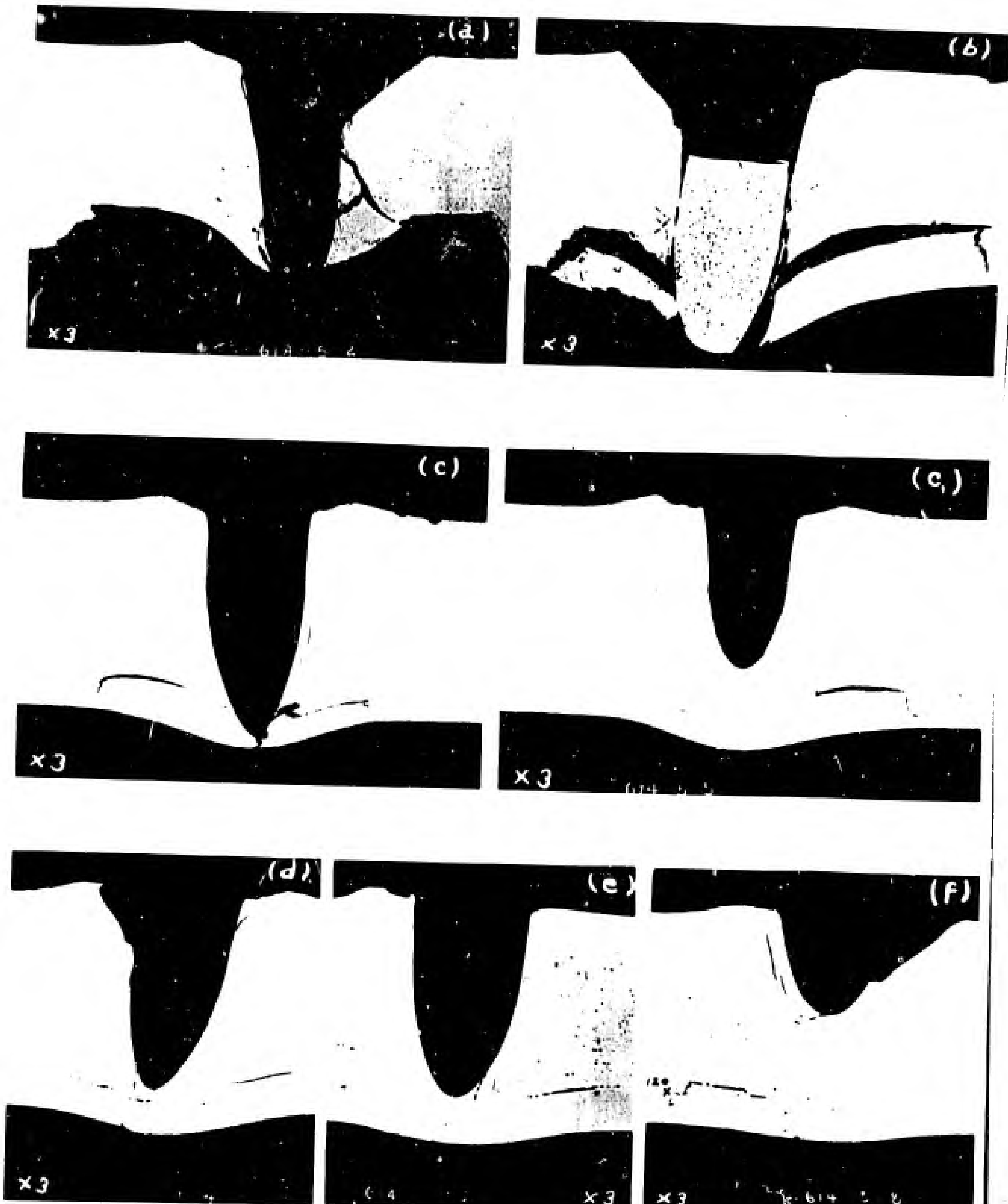
c_1) Sectioned off axis of bullet hole
X3 - Round 5 - MA 113

d) Partial penetration
Highest velocity not completely penetrating.
Striking velocity 2446 ft./sec.
Height of bulge in back 0.06 inches
X3 - Round 10 - MA 111

e) Partial penetration
Striking Velocity 2409 ft./sec.
Height of bulge in back 0.05 inches
X3 - Round 9 - MA 112

f) Partial penetration
Striking velocity 2391 ft./sec.
Height of bulge in back 0.03 inches

X3 - Round 8 - MA 114



W.A. 639-539

Figure 6 Plate #614-8

Partial penetration
Striking Velocity 2391 ft./sec.
Height of bulge back .03"
Showing early stages of development of spall on back side of plate.

X10 Unetched - Round 8
HA1-2

Figure 7

Same as sample above.
Illustrating crack deflected by a non-metallic
This is the only case in which this type of crack system was observed.

X1000 Unetched - Round 8
HA1 - 35

Figure 8 Plate #614-8

Partial penetration
Striking velocity 2391 ft./sec.
Height of bulge back .03"

Illustrating crack originating or terminating in a small non-metallic

X1000 unetched - Round 8
HA1 - 67

FIG 6

FIG. 7

FIG. 8

W.A. 639-540

Figure 9

Illustrating crack progressing through several non-metallics and also either originating or terminating in a small non-metallic inclusion. Such cracks were occasionally observed progressing through an occasional non-metallic in very dirty steel.

X1000 unetched - Round 8
HA1 - 69

Figure 10 Plate 614-8

Partial penetration	
Striking Velocity	2391 ft./sec.
Height of bulge	.03"

Illustrating evidence of slip along cleavage.

X1000 unetched - Round 8

Figure 11

Illustrating the shattering effect of a non-metallic under bullet impact. Note the tiny crack progressing from the end of the non-metallic inclusion. It is difficult to determine if the crack was the result of bullet impact or from the rolling operation.

X1000 unetched - Round 8
HA1 - 87

FIG.9

FIG 10

FIG.11

W.A.639-541

3. Plate with poor Ballistic Properties

Plate #2

Microscopic Examination: Relatively clean steel with uniform distribution of inclusions.

Size: 12 x 12 x 1/2 inches

Manufacturer: Taylor-Wharton Company

Type: Homogeneous

Ammunition: Cal. .30 AP 165 grain M1922

Distance from Plate to Muzzle - 50 yards

Brinell Hardness - 255

Chemical Composition:

C	1.17
Mn	11.40
Si	0.405
S	0.018
P	0.057

This is a Hadfield Manganese steel which has been chrome plated on the front face.

4. Carburetor Cover Casting #A

Plate with Low Ballistic Properties

Micro-examination: Dirty steel with porosity and segregations of non-metallics.

Size: 21 1/2" x 15" x 1/2" on flat surface and 3/4" on bulged surface.

Manufacturer: Watertown Arsenal

Type: Homogeneous

Ammunition: Cal. .30 AP 165 grain M1922

Distance from plate to muzzle - 100 yards

Brinell Hardness: 418

Chemical Composition:

C	0.19
Mn	0.54
Si	0.165
S	0.018
P	0.010
Mo	0.82
Cr	1.13
Va	0.21

Figure 12

Carburetor Cover Casting #A

a) These two parallel cracks apparently have no connection, or no tendency to deviate toward or from the non-metallics. There is however some indication that they follow grain boundaries. See Figure (c) #130

X100 - Round 16 - MA 130

b) Cracks show no relation to porosity. See Figure (c) #129 below.

X100 - Round 16 - MA 129

c) Cracks similar to these which follow the contour of the bullet hole were found in practically all castings, although often not so completely surrounding it as in this case.

Partial penetration	
Highest velocity not completely penetrating.	
Striking velocity	1871 ft./sec.
Height of bulge in back	0.02 inches
Depth of indent	0.46 inches

X3 - Round 16 - MA 220

Plate #2

d) Crack progressing from bullet hole appears to follow grain boundaries. See Figure (g)

X100 - Round C - MA 128

e)

Complete penetration	
Striking velocity	2357 ft./sec.
Diameter of hole in back	0.25 inches
Height of bulge in back	0.14 inches

X3 - Round D - MA 109

f)

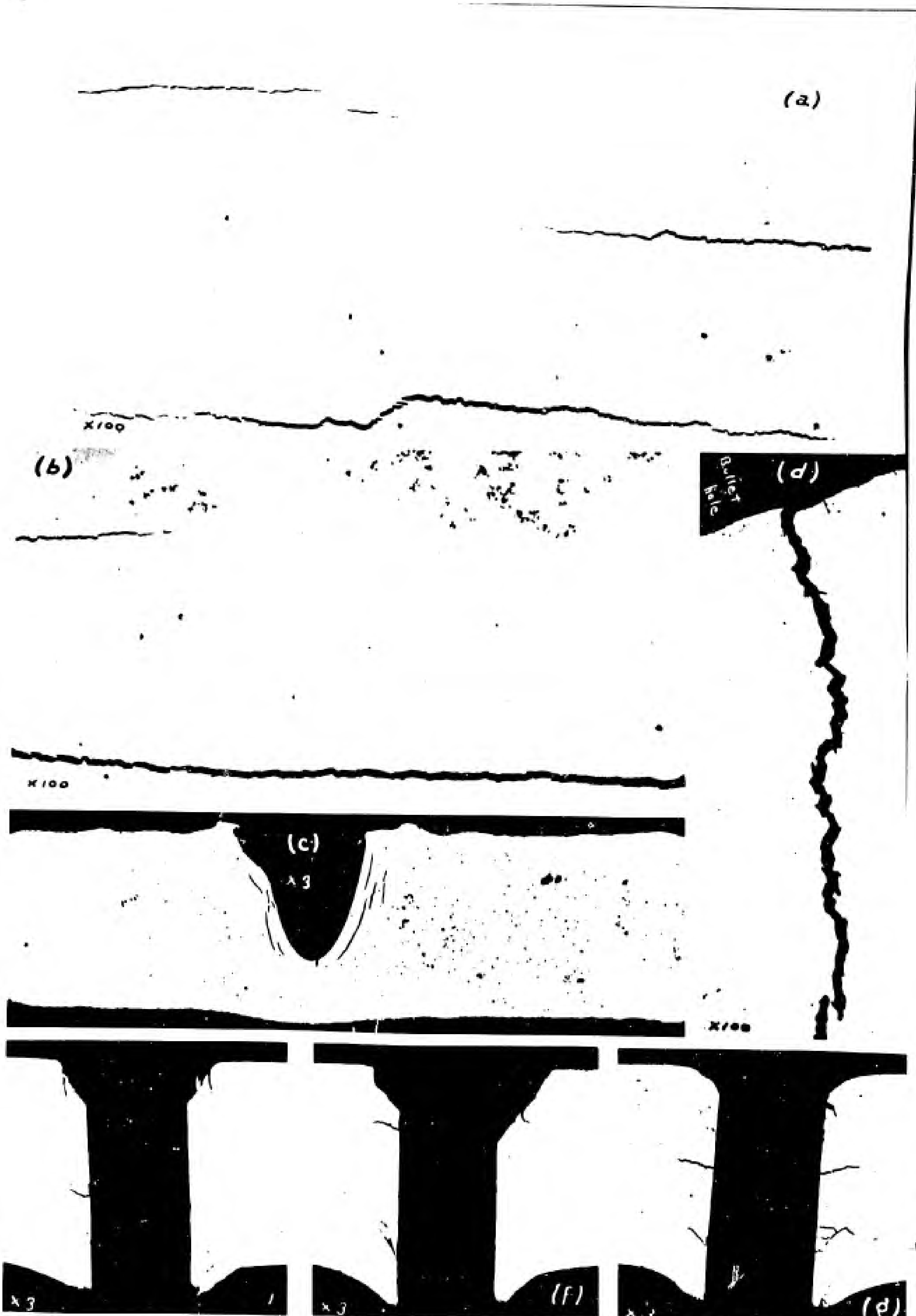
Complete penetration	
Striking velocity	2283 ft./sec.
Diameter of hole in back	0.25 inches
Height of bulge in back	0.17 inches

X3 - Round E - MA 108

g)

Complete penetration	
Core in plate removed by machining.	
Striking velocity	2215 ft./sec.
Core through back	0.53 inches
Core through front	0.07 inches

X3 - Round C - MA 141



W.A.639-542

Figure 13

Microstructure of all Plate

a) #29 Typical of normal (i.e., not in the vicinity of bullet hole, and therefore presumably undistorted by the impact) structure of this steel. Very uniform sorbite.

X1000 - Round 2 - MA 234

b) #WJ2 Partially tempered martensite, typical of all specimens of this plate.

X1000 - Round 3 - MA 403

c) and d) #EX 26 . 6) Round 7 - longitudinal section. Sorbite with a tendency for the ferrite to go to grain boundaries.

X1000 MA 158

d) Round 8 - longitudinal section. Also sorbite, but this shows an elongation of the ferrite.

X1000 MA 160

This plate was not uniform, since both these structures occur.

e) #614-5 Sorbitic structure typical of this plate. It is not so uniform as that in the goodplate #29 See (a) above.

X1000 Round 2 - MA 153

f) #2 Austenitic grains, with pronounced slip lines. See (h) following.

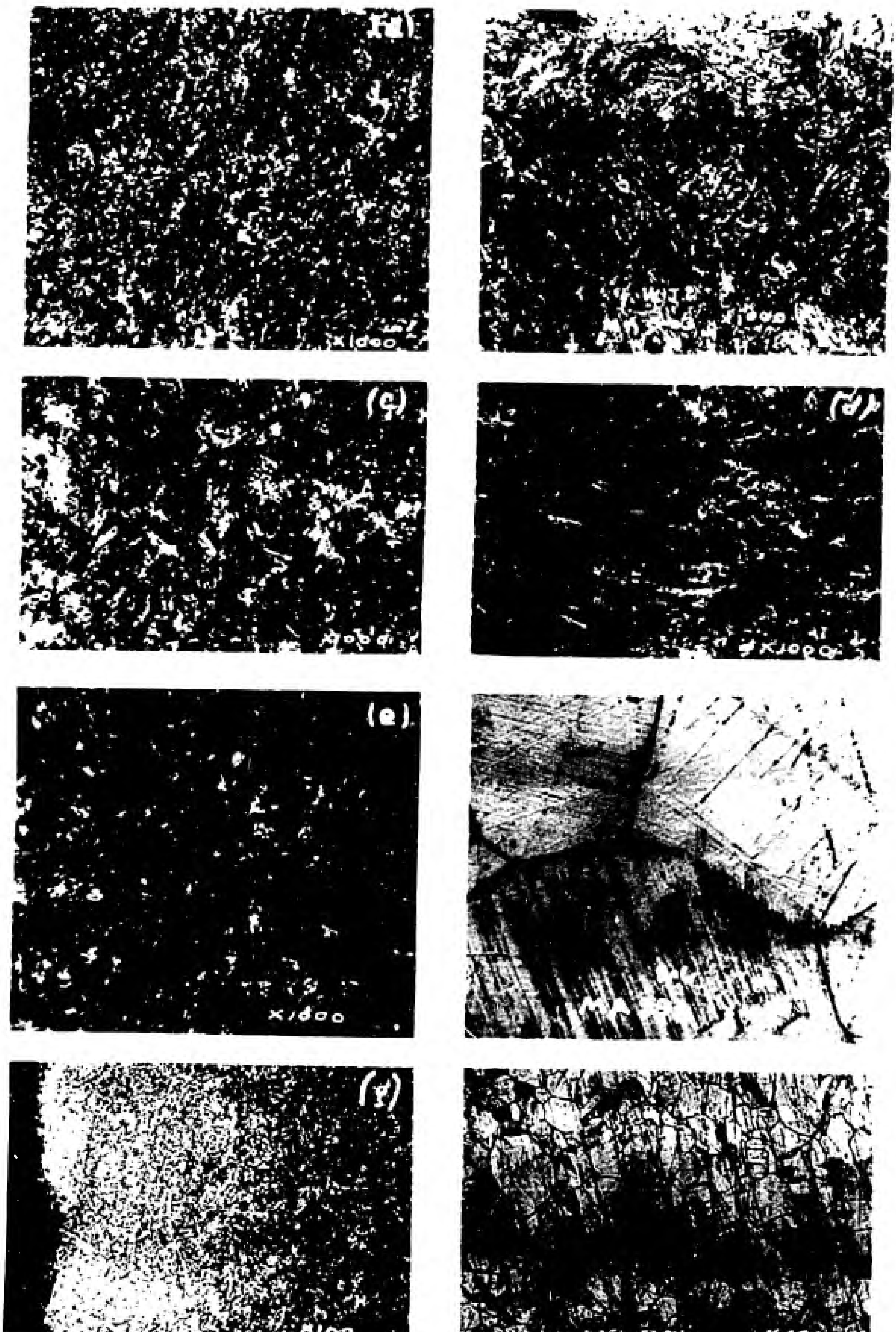
X1000 - Round C - MA 393

g) Ex 26 - Showing evidence of a slight decarburization in all heat treated armor plate. This is representative of all plate, regardless of individual composition.

X100 - Round 7 - MA 155

h) #2 Austenite, showing grains with slip lines and twinning. See Figure (f) above.

X100 - Round C - MA 390



N.A.079-543

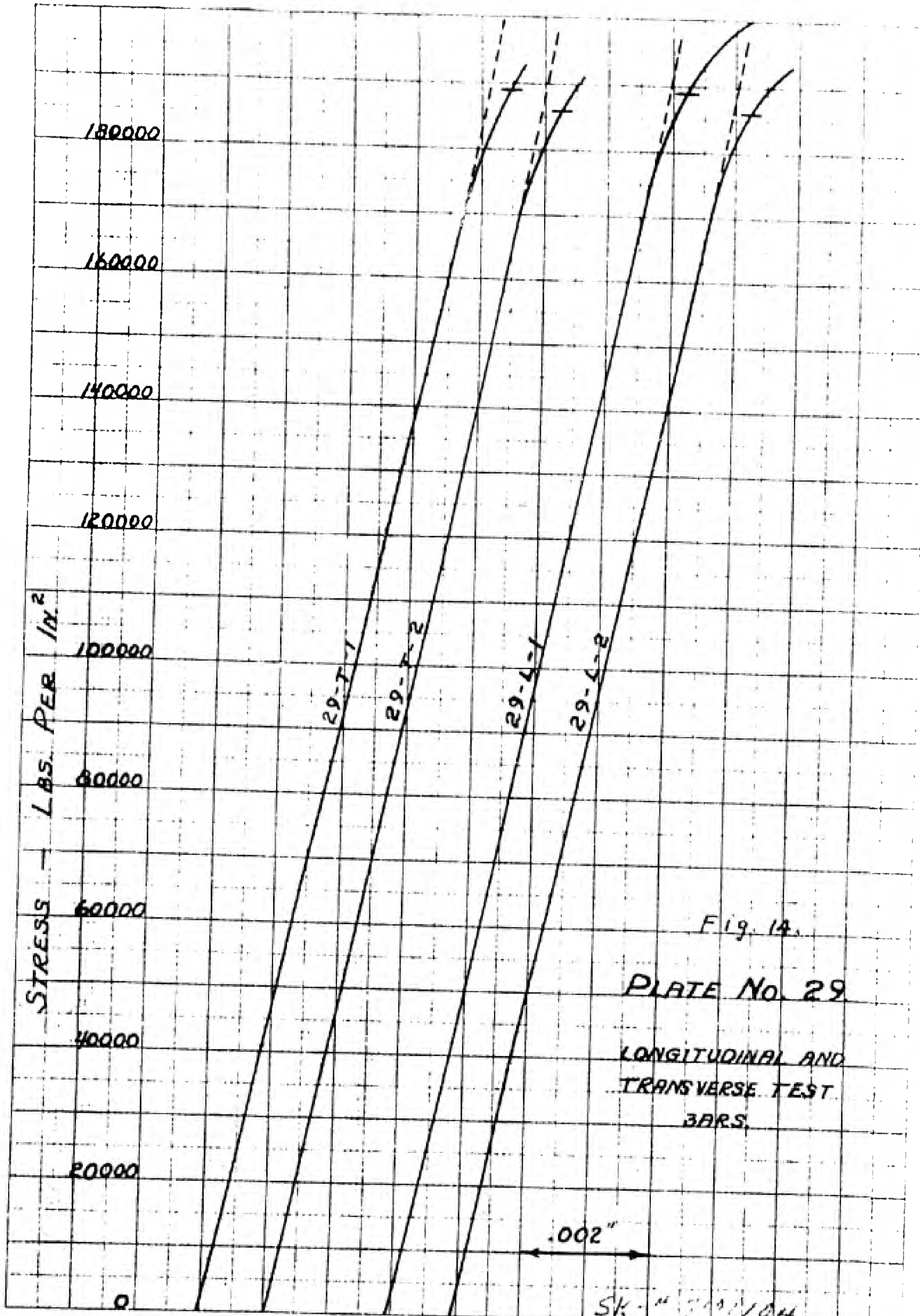


Fig. 14.

PLATE No. 29

LONGITUDINAL AND TRANSVERSE TEST BARS.

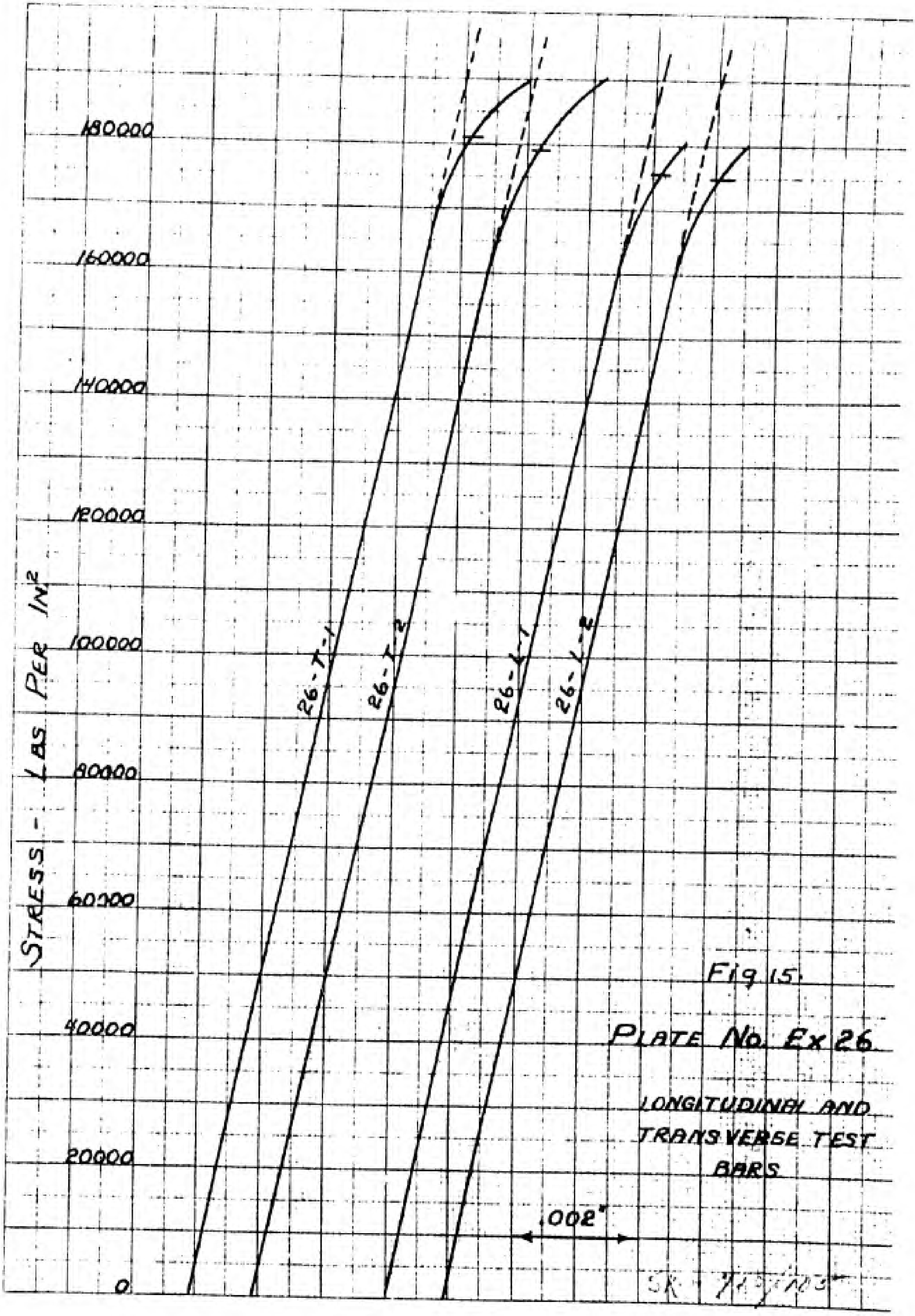
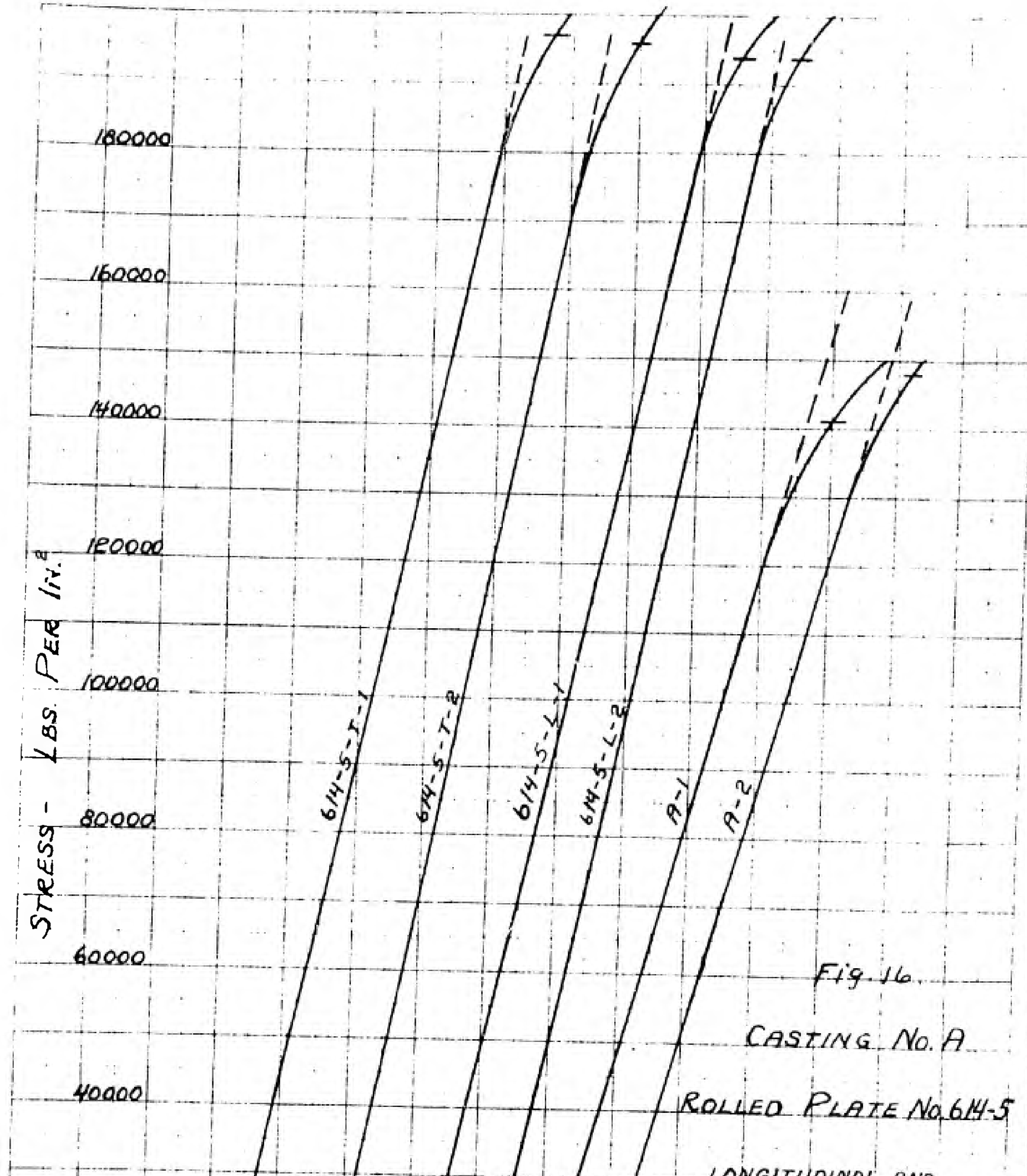


Fig 15.

PLATE No. Ex 26

LONGITUDINAL AND TRANSVERSE TEST BARS


STRESS - LBS PER IN.²
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
.002"
614-5-T-1
614-5-T-2
614-5-L-1
614-5-L-2
A-1
A-2
Fig. 16.
CASTING No. A
ROLLED PLATE No. 614-5
LONGITUDINAL AND
TRANSVERSE TEST
BARS.