Report No. 710/396

RESTRICTED

EXPERIMENTAL 1-1/2" LOW ALLOY HOMOGENEOUS ROLLED ARMOR

By

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November 15, 1942
WATERTOWN ARSENAL
WATERTOWN, MASS.

Report No. 710/396
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Experimental 1-1/2" Low Alloy Homogeneous Rolled Armor

Object

The object of this investigation was to study the ballistic properties of low alloy 1-1/2" rolled armor and to complete the analysis by carrying out a metallurgical examination of these materials including chemical analyses, macro and microscopic examinations, physical tests, and hardness surveys.

References

Watertown Arsenal letter W.A. 470.5/1888, dated June 7, 1940, Paragraph 1c-2.

The basic correspondence and material pertaining to this report are contained in Appendix A.

Conclusions

1. The results of this investigation indicate that low alloy armor plate containing no strategic elements may be produced with promising ballistic properties.

2. The plate of the series which had the best ballistic properties contained .41% carbon, 1.99% manganese, and .56% molybdenum. The ballistic limit of this plate exceeded the specification by 114 f/s.

3. A second low alloy composition which showed satisfactory ballistic properties in exceeding the specification by 80 f/s, contained .49% carbon, .53% manganese, .44% molybdenum, and .35% copper.

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APPROVED:

G. L. Cox,
Major, Ord. Dept.,
Acting Director of Laboratory.

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Introduction

Because of the desirability of conserving strategic elements in armor manufacture, a program was initiated at Watertown Arsenal covering the development of low alloy heavy rolled homogeneous armor. A preliminary report covering the results of ballistic tests on rolled armor has already been submitted to the Subcommittees for Rolled and Cast Armor. (Rolled Armor Subcommittee Report No. 1, dated December 23, 1940.) This present report covers the extension of the investigation of these materials including complete metallurgical examination.

Casting and Preparation of Experimental Ingots

Four 500-pound fluted ingots of the compositions listed in Table III were cast at Watertown Arsenal from carefully made induction furnace heats. The size of the ingots was approximately as follows: 18" long, 10½" in diameter at the top and tapering to 8½" in diameter at the bottom.

All ingots were carefully cleaned on the surface, and macro discs were cut from the top and bottom of the ingot. Drillings for chemical analyses were taken from the under side of the macro discs removed from the top of the ingot. The macrostructure of the discs removed from the top and bottom of the ingots indicated satisfactory soundness.

Rolling of Ingots

The ingots were rolled at the plant of Henry Disston & Sons, Inc. according to the procedure noted below. Ingots were first hammer-cogged to slabs from a forging temperature of 2200-2225°F and then rolled to 24x24x1½" thick plate followed by a short annealing process.

TABLE I

Rolling Temperatures

Heat No.	Type	Furnace Temperature	Finish Rolling Temperature	Brinell Hardness after Annealing
3012	Cr-Mo-V-W	2235°F	1950°F	187
3013	Ni-Si	2275°F	1940°F	241
3018	Mn-Mo	2235°F	1965°F	197
3024	Mo-Cu	2235°F	1910°F	170

After rolling, all plates were cooled in a pile. After cooling, the plates were open-furnace annealed for two hours at 1425°F.

Heat Treatment of Plates

Previous to heat treatment the microstructure of all plates was examined, particularly for segregations of grain boundary carbide. No grain boundary carbide was observed in plates 3013, 3018, and 3024, whereas plate 3012 did show grain boundary carbide, and therefore, was subjected to a homogenizing treatment consisting of 8 hours at 2200°F followed by air cooling. This treatment effectively eliminated the boundary carbide. (See Figures 3a and 3b.)

The plates were heat treated at Watertown Arsenal as follows:

TABLE II

Plate No.	Type	Heated to	Quenched in	Draw	B.H.N.
3012	Cr-Mo-V-W	2200°F - 8 hrs. 1650°F - 2 hrs.	Air Oil	1350°F - 2 hrs. Air cool.	269
3013	Ni-Si	1650°F - 2 hrs.	Oil	1350°F - 2 hrs. Air cool.	269
3018	Mn-Mo	1500°F - 2 hrs.	Oil	1200°F - 2 hrs. Air cool.	265
3024	Mo-Cu	1650°F - 3 hrs.	Oil	No draw.	269

Ballistic Tests

Ballistic tests were made at Aberdeen and reported in A.P.G. reports Nos. 18960-A18 and 314.

Metallurgical Examination

Metallurgical examination included macro and microscopic examination, chemical analyses, physical tests, and hardness determinations.

Results

1. Chemical Analyses

The chemical analyses are shown below in Table III.

TABLE III

Plate No.	Type	C	Mn	P	S	Si	Ni	Cr	Mo	V	W	Cu
3012	Cr-Mo-V-W	.52	.64	.007	.018	.17	--	1.22	.55	.24	1.02	.--
3013	Ni-Si	Total .39 Graphitic .33	.72	.011	.018	2.22	3.21	--	.63	.26	--	-
3018	Mn-Mo	.41	1.99	.012	.019	.24	--	--	.56	--	--	-
3024	Mo-Cu	.49	.53	.013	.017	.18	--	--	.44	--	--	.35

2. Macroscopic Examination

a. Deep Etch

The metal of all plates appears to have satisfactory cleanliness throughout. Plate 3013 shows a fine dendritic structure near the top and bottom surfaces. (See Figure 1.)

b. Oberhoffer Etch

The Oberhoffer etch reveals satisfactory uniformity throughout, (see Figure 2) but traces of residual dendrites in plates 3013 and 3018.

3. Microscopic Examination

a. Heats in Rolled and Annealed Condition

Heat 3012, carbon .52%, chromium 1.22%, molybdenum .55%, vanadium .24%, and tungsten 1.02%, showed the presence of grain boundary carbide and also spheroidized carbide. (See Figure 3a.) Homogenization at 2200 °F for 8 hours dissolved the grain boundary carbides as shown in Figure 3b.

Heat 3013, 3.21% nickel, 2.22% silicon, and .33% graphitic carbon, evidently graphitized during the annealing of the plates subsequent to the rolling operation. (See Figure 3c.) Some evidence of grain boundary carbide was also noted in this heat. (See Figure 3d.)

Heat 3018, .41% carbon, 1.99% manganese, and .56% molybdenum, exhibits a fine pearlitic structure with no grain boundary segregates. (See Figure 3e.)

Heat 3024, .49% carbon, .44% molybdenum, and .35% copper, exhibits ferrite segregations associated with coarse pearlite. (See Figure 3f.)

Figures 4a, b, c, d, and e illustrate the relative amounts of nonmetallic inclusions in the four heats investigated. Heats 3018 and 3024 are relatively clean, whereas Heat 3012 contains numerous spheroidal nonmetallic inclusions. Occasional elongated nonmetallics of considerable size were found in the central layers of the cross section. (See Figure 4b.)

b. Heat

Figures 5a, b, c, d, 6a, b, c, and 7 illustrate the microstructures of the plates after heat treatment.

Heat 3012 has a fine sorbitic structure with evidence of spheroidized carbide and traces of ferrite. (See Figures 5a and 6a.) Figures 5b and 3c indicate that a portion of the graphitic carbon in Heat 3013 dissolved in the austenite during the heating operation before quenching. Fine spheroidized carbides were present in the cleavage planes as shown in Figure 6c.

A banded structure is evident in Heat 3018, Figures 5c and 7. This steel, however, is extremely free from nonmetallic inclusions. (See Figure 4d.)

A sorbite-troostite structure with some segregation of ferrite areas and also a certain amount of cleavage ferrite is to be noted in plate 3024. (See Figures 5d and 6b.)

4. Decarburization

Plate No.	Type	Front Face	Rear Face
3012	Cr-Mo-V-W	.032"	.036"
3013	Ni-Si	.045"	.030"
3018	Mn-Mo	.045"	.040"
3024	Mo-Cu	.028"	.030"

5. Physical Tests

The physical properties are recorded in Table IV.

TABLE IV

a. Tensile tests, .357" diameter bar, 1.4" gauge length.

Plate No.	Type	Y.S. Lbs./Sq.In. .01% Offset	T.S. Lbs./Sq.In.	Elong. %	Red. of Area -%	Remarks
3012-1	Cr-Mo-V-W	87,000	127,000	20.0	59.2	Fracture cupped, pitted.
3012-2*	"	105,500	126,600	18.6	52.9	Irregular 90° break.
3013-1	Ni-Si	82,000	138,600	16.4	33.5	Irregular 90° break.
3013-2*	"	84,000	137,600	16.4	30.3	Cupped, pitted.
3018-1	Mn-Mo	102,500	130,200	18.6	55.2	Cupped, pitted.
3018-2*	"	103,500	130,200	17.1	49.4	Cupped, pitted.
3024-1	Mo-Cu	97,000	128,000	15.7	43.6	Cupped, pitted.
3024-2*	"	92,000	127,000	15.0	40.2	Cupped, pitted.

b. Tensile Impact Tests

Plate No.	Type	Ft.Lbs.	Remarks
3012-1	Cr-Mo-V-W	35.0	Cupped, pitted, woody structure
3012-2*	"	35.5	Cupped, pitted, woody structure.
3013-1	Ni-Si	25.0	Partially cupped, woody structure.
3013-2*	"	26.4	Partially cupped, woody structure.
3018-1	Mn-Mo	37.1	Partially cupped, laminated.
3018-2*	"	42.2	Partially cupped, laminated.
3024-1	Mo-Cu	20.8	90° break, crystalline structure.
3024-2*	"	15.5	90° break, crystalline structure.

*No. 2 test bars cut at right angles to No. 1 test bars.

6. Ballistic Tests

Ballistic tests as reported in A.P.G. Reports 18960-A18 and 314 are summarized below.

TABLE V

Ballistic Tests

Plate Sizes - 24"x24"x1½"

Distance from muzzle to plate - 100 yds.

Ammunition: 37 mm. A.P. M51, 37 mm. T.P. M51, and Caliber .50 A.P. M1.

Plate No.	Thickness	Angle of Plate	Projectile	Lowest Complete F/S	Highest Partial F/S	Ballistic Limit F/S	Specified Limit F/S	Shock Test	Remarks
3012	1½"	Normal	37 mm. M51 A.P.	1547	1499	1523	1500		
Cr-Mo-V-W		20°	"	1651	1600	1626	1600		
		Normal	37 mm. M51 T.P.	---	2485	---		O.K.*	No spalls.
3013	1½"	Normal	37 mm. M51 A.P.	1330	1291	1311	1500	Failed*	
Ni-Si		Normal	37 mm. M51 T.P.	---	2432	---			37 mm.T.P. broke piece of plate 10x14". Radial cracks.
3018	1½"	Normal	37 mm. M51 A.P.	1634	1594	1614	1500	O.K.*	No spalls.
Mn-Mo		20°	"	1720	1683	1702	1600		
		Normal	37 mm. M51 T.P.	---	---	---			
3024	1½"	Normal	37 mm. M51 A.P.	1600	1560	1580	1500	No Shock Test	No spalls.
Mo-Cu		Normal	Cal..50 A.P. M1	2964	2927	2946			

*Plates were shock tested with two rounds of 37 mm. M51 T.P. instead of 75 mm. A.P. because of the small size which prevented firing with 75 mm. after determination of ballistic limits.

7. Hardness Determinations

Plate No.	Type	Impressions on Plate	Impressions on Metallographic Samples
3012	Cr-Mo-V-W	269	262
3013	Ni-Si	269	269-277
3018	Mn-Mo	265	269-277
3024	Mo-Cu	269	269

Discussion

A survey of the ballistic test results of the various compositions investigated indicates that there is no improvement in ballistic properties of the Cr-Mo-V analysis by the addition of 1% tungsten. In fact, the ballistic limit of this plate was 91 f/s below that of the most satisfactory plate which contained .41% carbon, 1.99% manganese, and .56% molybdenum.

The plate containing 3.22% nickel and 2.22% silicon was found to be brittle under projectile impact because of the temper carbon which presumably formed during the annealing subsequent to hot rolling. It was impossible to effect a solution of all of the temper carbon (.33%) during a practical heating cycle prior to quenching.

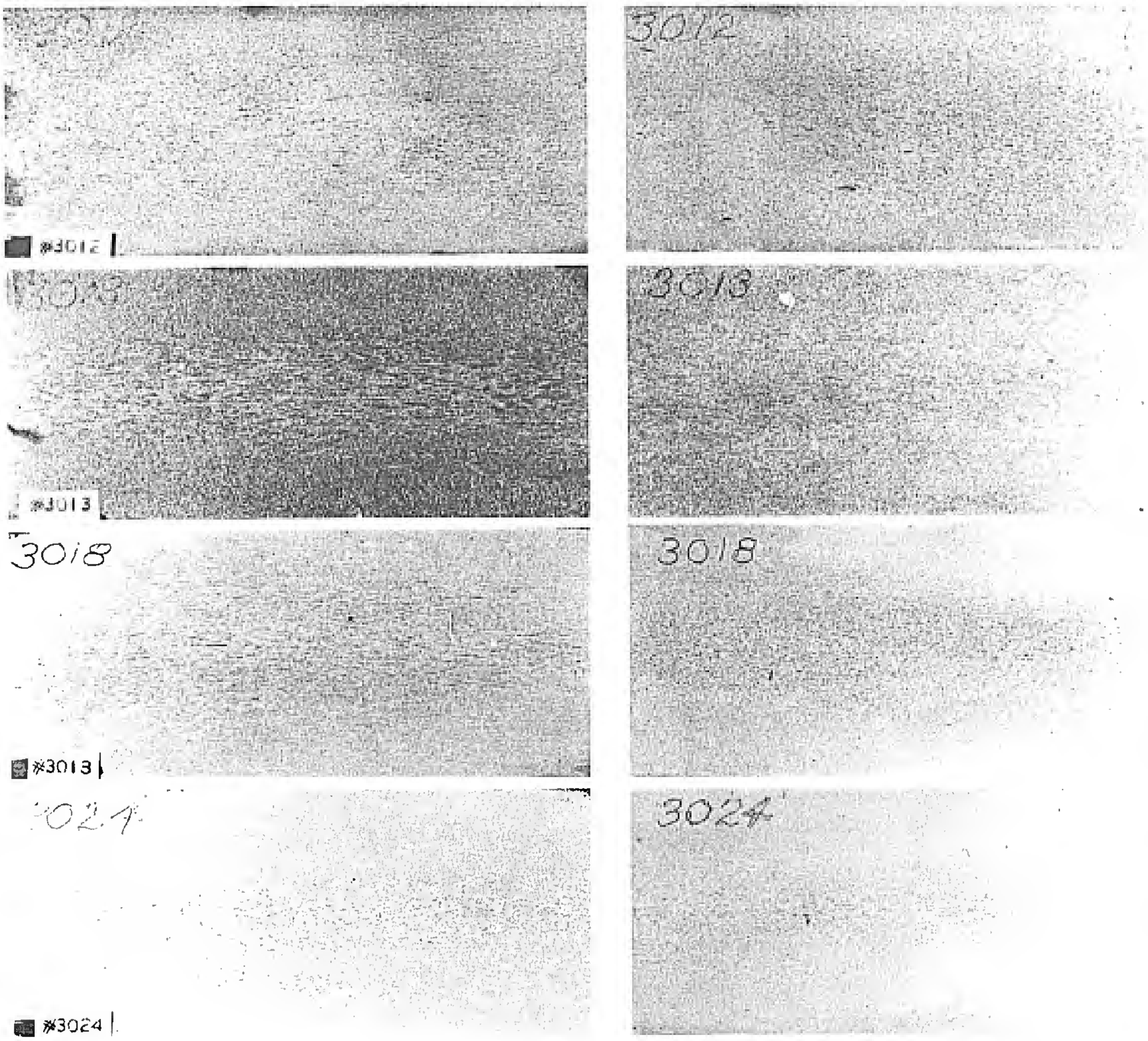
The microstructure of the best ballistic plate referred to above consisted of a banded structure, sorbite, and some cleavage ferrite, which was not associated with nonmetallic inclusions. Apparently banding to the extent found in this plate is not detrimental to good ballistic properties providing the plate is heat treated to a relatively low range of hardness.

The plate containing .49% carbon, .53% manganese, .44% molybdenum, and .35% copper also had satisfactory ballistic resistance. The microstructure consisted of cleavage ferrite and sorbite-troostite, resulting from the oil quench. It is believed water quenching would have improved the microstructure and perhaps the ballistic properties. It is important to note, however, that the presence of heterogeneity in the structure, especially the ferrite, did not promote spalling.

The results of the investigation indicate that certain low alloy steels containing no strategic elements have promising ballistic properties. This program is being continued with an effort being made to achieve satisfactory ballistic properties with low alloy content and a lower carbon content to result in a composition having more satisfactory weldability characteristics.

Figure 1

Macrostructure of plates 3012, 3013, 3018, and 3024 after hot etching.



INCHES 1 2 3

ORDNANCE DEPT U.S.A.
WATERTOWN ARSENAL

1 1/2" ROLLED HOMOGENEOUS ARMOR PLATE
AUGUST 30, 1941 W.A.710-1375

FIG 1

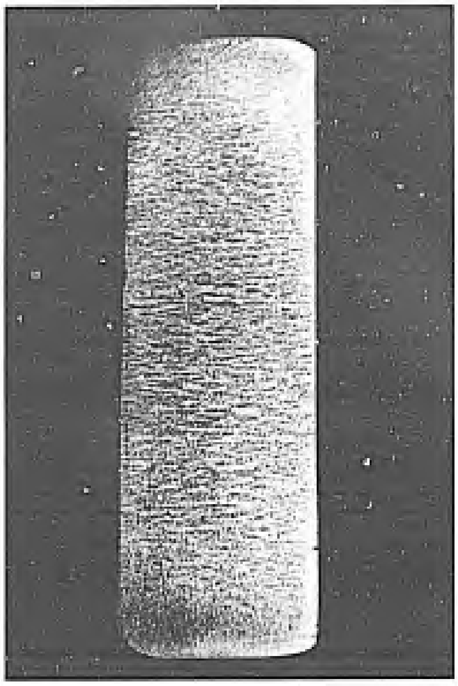
Figure 2

Macrostructure of plates 3012, 3013, 3018, and 3024 after the Oberhoffer etch.

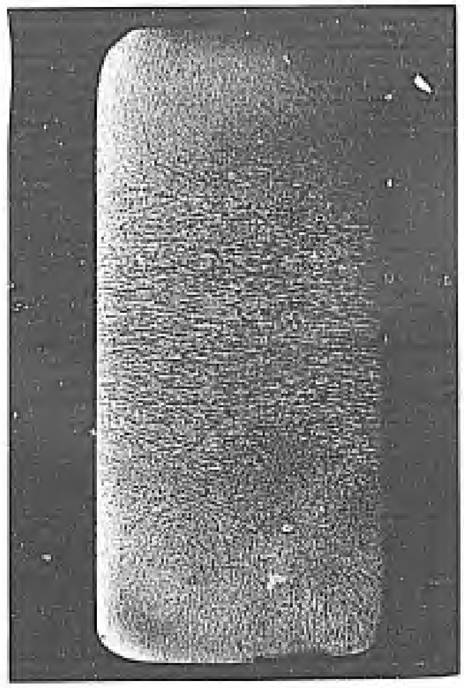
Plate 3012-H	X2	MA-3629
Plate 3013-H	X2	MA-3628
Plate 3018-H	X2	MA-3630
Plate 3024-H	X2	MA-3631

FIGURE 2.

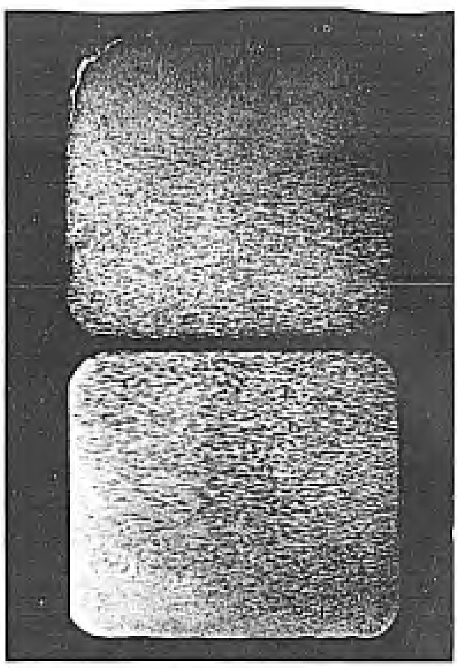
MACROSTRUCTURE OF PLATES



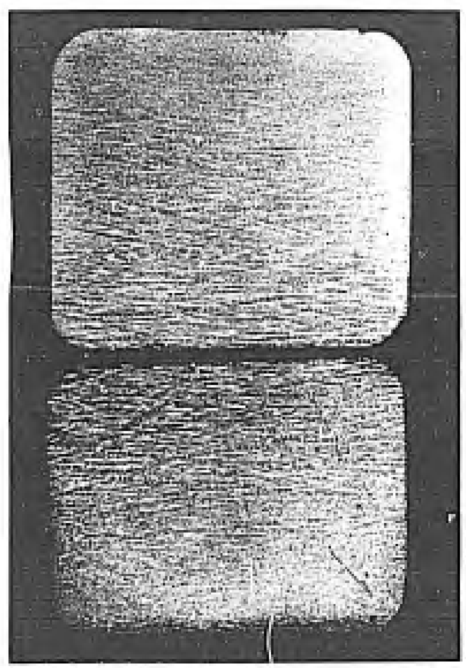
3012 X3



3013 X3



3018 X3



3024 X3

ETCHED IN OBERHOFFER'S REAGENT.

W.A.639-3649

Figure 3

Microstructure of Plates as Hot Rolled,

Annealed, and after Normalizing

a. Plate No. 3012R - Hot Rolled - Annealed

Spheroidized carbide and larger carbides located in the grain boundaries.

Etched in 1% Nital X1000 MA-3616

b. Plate No. 3012N - Hot Rolled - Annealed and after Homogenizing

Sorbite and ferrite in cleavage planes. No indication of carbides in grain boundaries.

Etched in 1% Nital X1000 MA-3615

c. Plate No. 3013A - Hot Rolled - Annealed and re-annealed in order to determine if graphite could be retained in solution. Annealing did not retain any appreciable amount of graphite in solution,

Temper carbon and carbides in cleavage.

Etched in 1% Nital X250 MA-3602

d. Plate No. 3013R - Hot Rolled - Annealed

Some evidence of grain boundary carbide.

Etched in 1% Nital X1000 MA-2089

e. Plate No. 3018R - Hot Rolled - Annealed

Sorbite and ferrite.

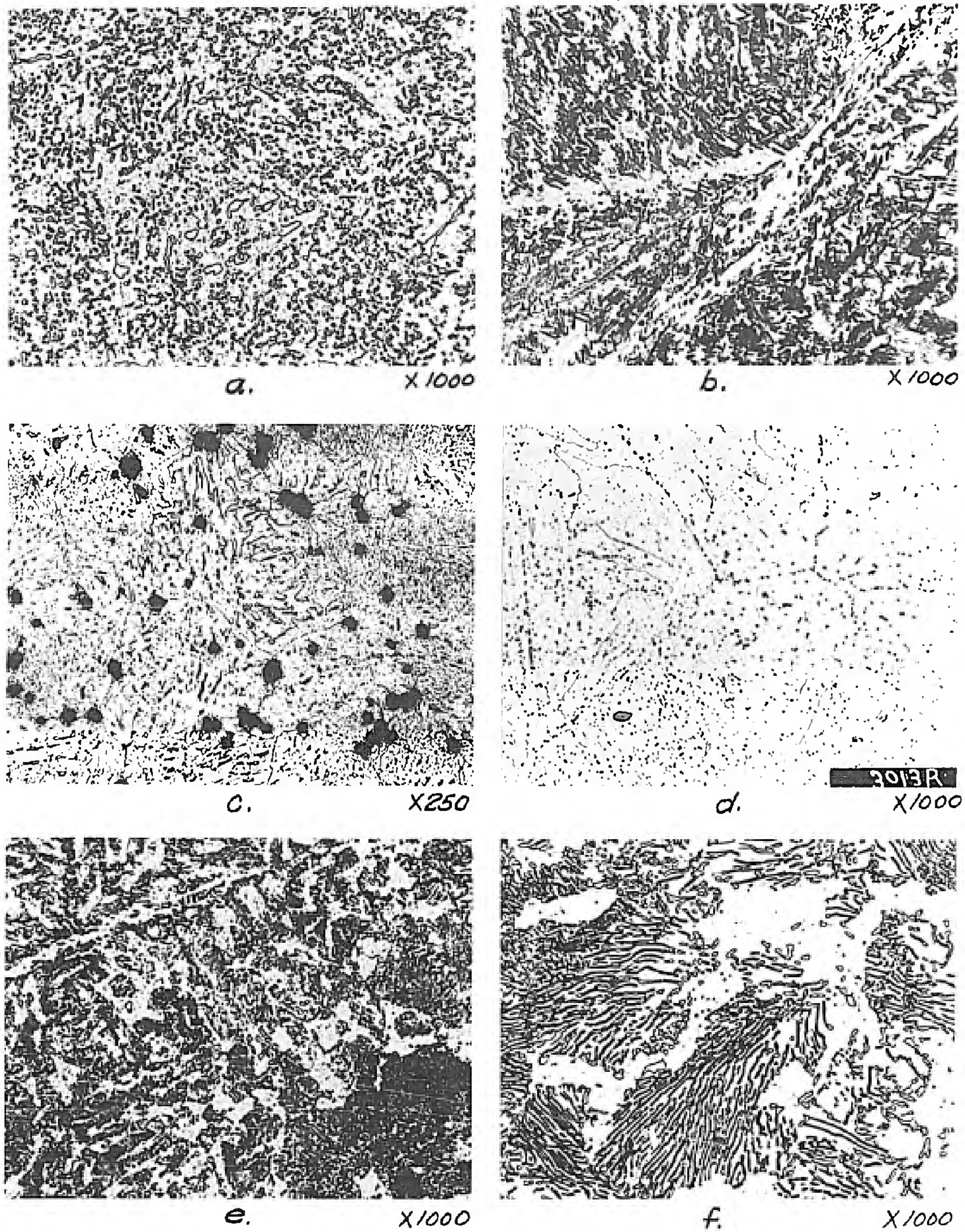
Etched in 1% Nital X1000 MA-3617

f. Plate No. 3024R - Hot Rolled - Annealed

Lamellar pearlite and areas of ferrite.

Etched in 1% Nital X1000 MA-3618

FIGURE 3.
MICROSTRUCTURE OF PLATES AS HOT-ROLLED, ANNEALED, AND AFTER NORMALIZING.



ETCHED IN 1% NITAL.

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Figure 4

Non-Metallics

a. Plate 3012

Average distribution of non-metallics in plate. Relatively large amount of non-metallic inclusions.

X25 MA-3590

b. Plate 3012

Typical elongated stringers in middle of cross section of plate.

X25 MA-3589

c. Plate 3013

Average distribution of non-metallic inclusions and temper carbon in the plate. (Graphitic carbon - .33%, total carbon .39%.)

X25 MA-3588

d. Plate 3018

Very clean steel throughout the cross section.

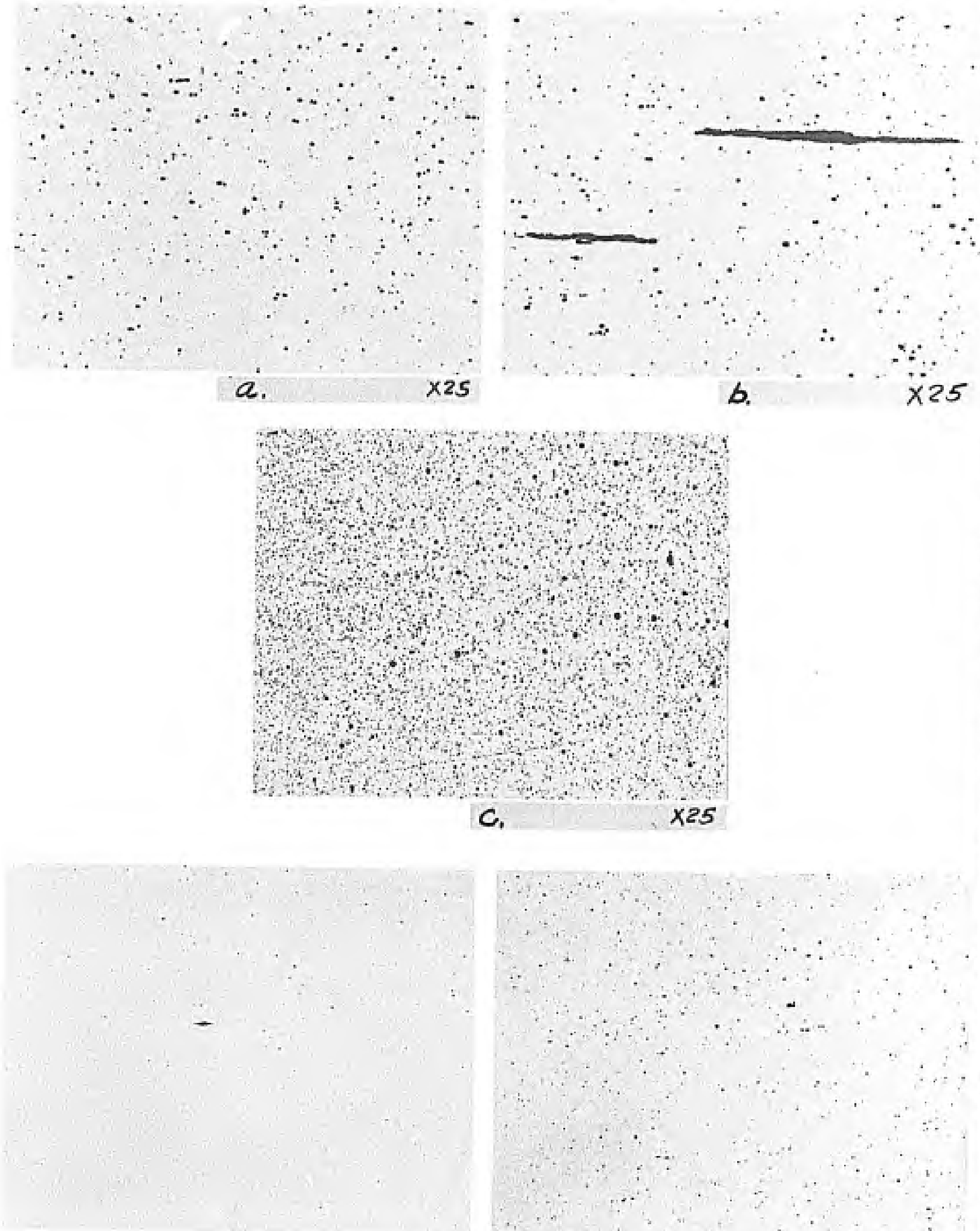
X25 MA-3592

e. Plate 3024

Fairly clean metal. Very fine non-metallic inclusions distributed throughout the cross section.

X25 MA-3591

FIGURE 4.
DISTRIBUTION OF NON-METALLIC INCLUSIONS.



a. X25

b. X25

c. X25

d. X25

e. X25

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Figure 5

Microstructure of Plates after Heat Treatment

a. Plate 3012-H

Fairly uniform sorbite with traces of ferrite.

Etched in 1% Nital X250 MA-3600

b. Plate 3013-H

Heat treatment has caused a solution of most of the temper carbon sorbitic matrix showing cleavage structure.

Etched in 1% Nital X250 MA-3601

c. Plate 3018-H

Pronounced banded structure, sorbite and cleavage ferrite. No non-metallics evident, see Figure 4d.

Etched in 1% Nital X250 MA-3599

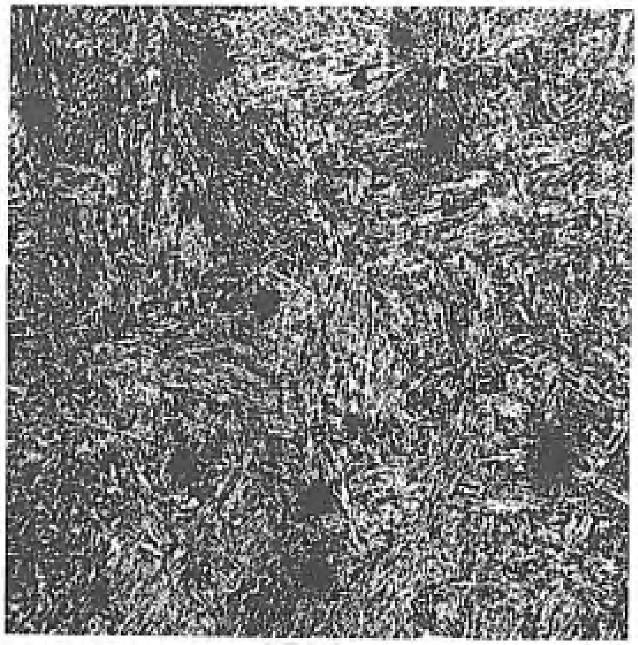
d. Plate 3024-H

Sorbite with considerable ferrite in cleavage planes and occasional patches of troostite and ferrite patches.

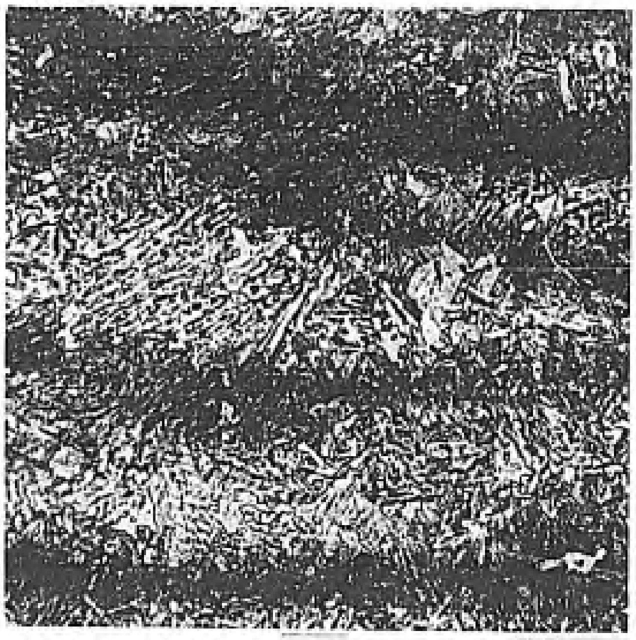
Etched in 1% Nital X250 MA-3632

FIGURE 5.
MICROSTRUCTURE OF PLATES AFTER HEAT-TREATMENT.

a. X250



b. X250



c. X250

d. X250

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Figure 6

Microstructure of Plates

after Heat Treatment

a. Plate 3012-H

Sorbite with traces of cleavage ferrite. Tendency towards spheroidized carbide.

Etched in 1% Nital X1000 MA-3594

b. Plate 3024-H

Patches of troostite and sorbite with ferrite in cleavage planes.

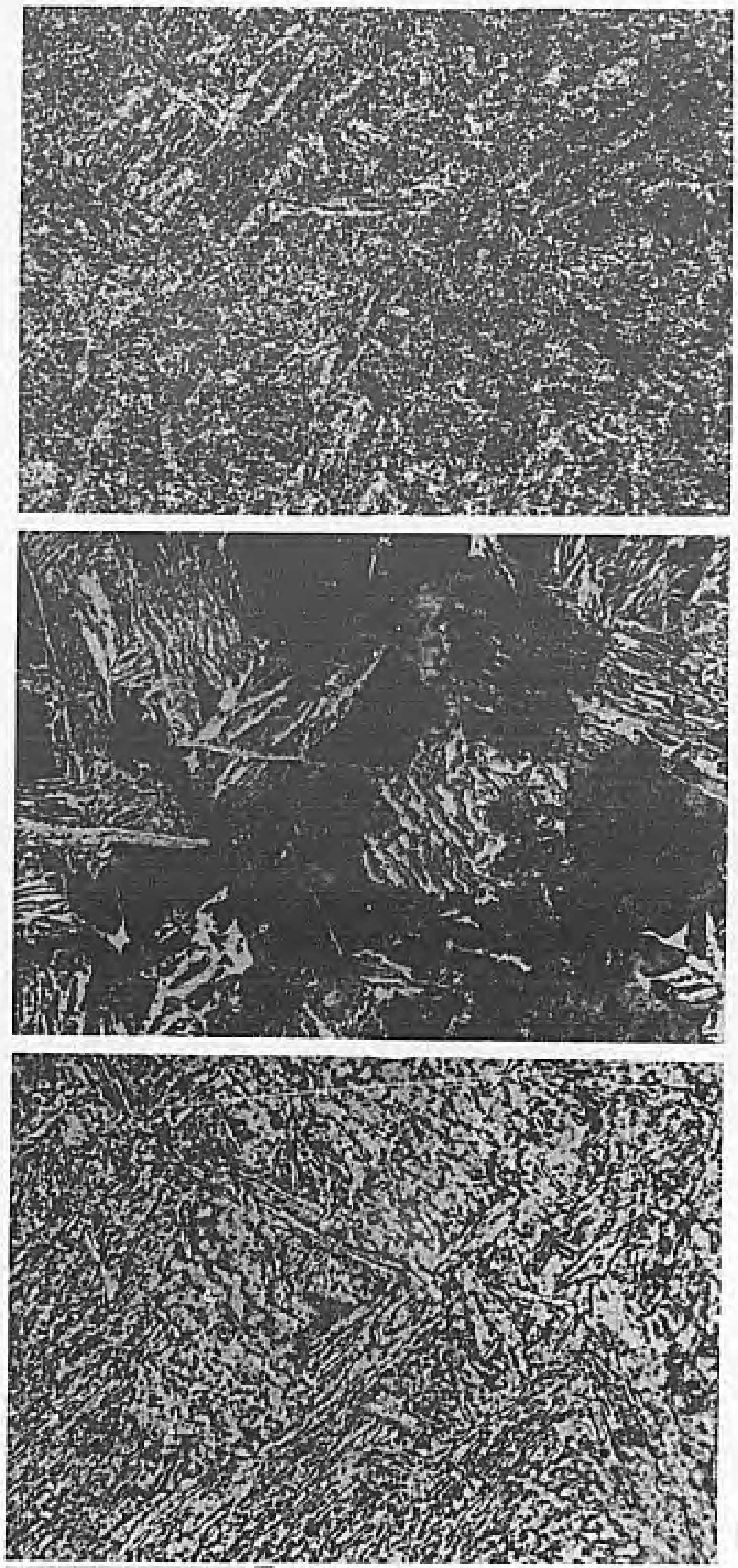
Etched in 1% Nital X1000 MA-3596

c. Plate 3013-H

Fine spheroidized carbide in cleavage planes.

Etched in 1% Nital X1000 MA-3593

FIGURE 6.
MICROSTRUCTURE OF PLATES AFTER HEAT-TREATMENT.



a.

b.

c.

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ETCHED IN 1% NITAL. MAGNIFICATION X1000

Figure 7

Microstructure of Heat Treated Plate

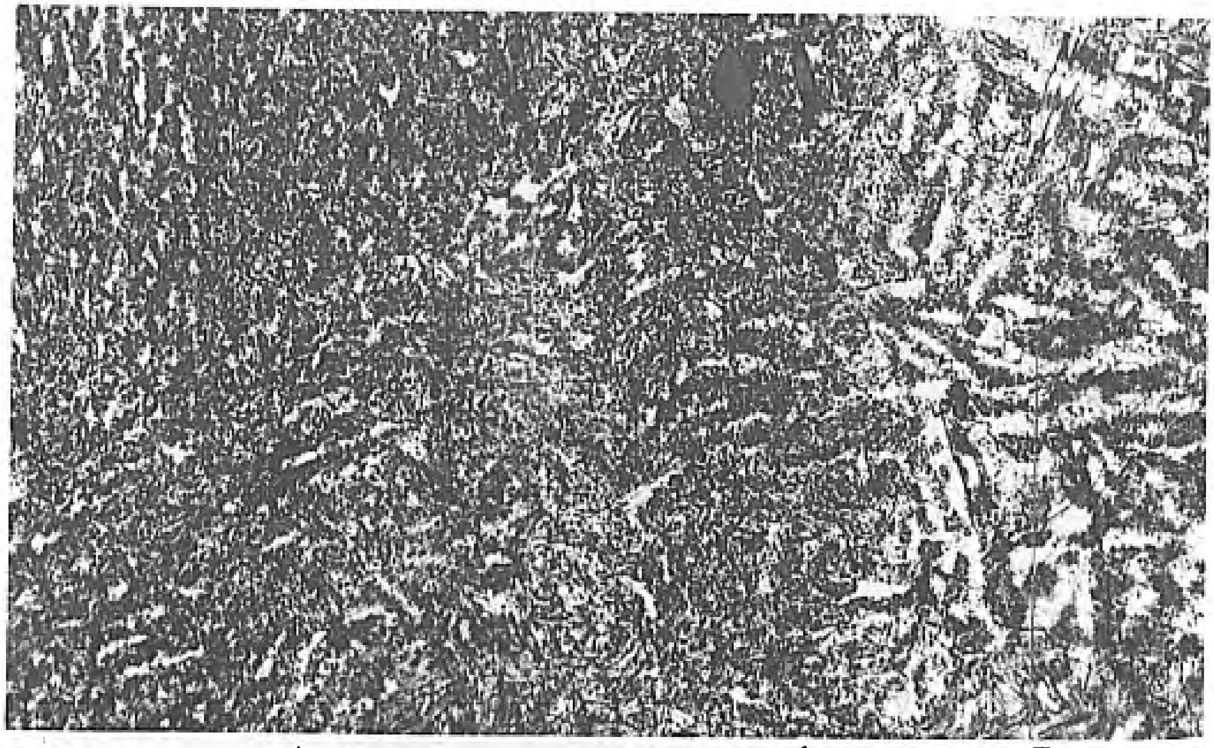
Plate 3018-H

Showing microstructure of a typical banded area in the plate.

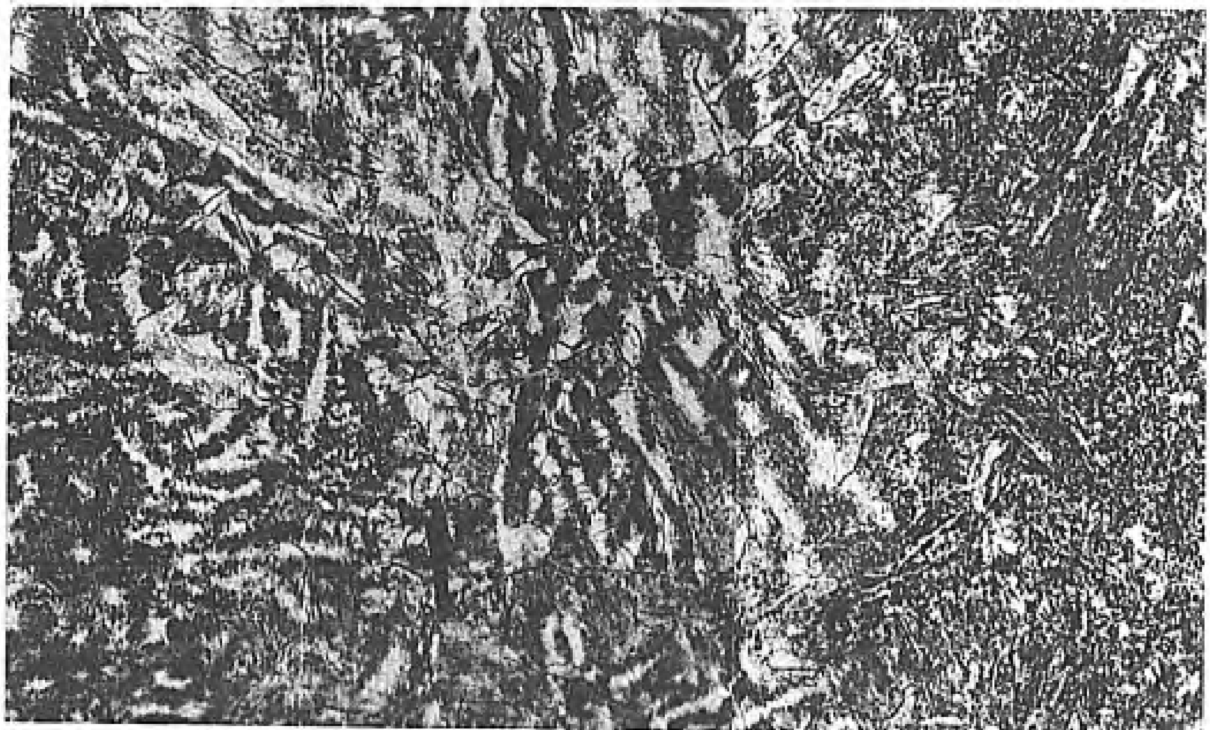
Etched in 1% Nital X1000 MA-3595a, b, c, d, e

Note: The lower photomicrograph is a continuation of the microstructure of the right hand area of the upper photomicrograph. Sections AA represent adjacent areas.

FIGURE 7.
MICROSTRUCTURE OF HEAT-TREATED PLATE #3018 H. A



A DIRECTION OF ROLLING SECTION A



SECTION A

W.A.639-3654

ETCHED IN 1% NITAL.
MAGNIFICATION - X1000.

APPENDIX A

COPY

SBR/gmm

WAR DEPARTMENT

WATERTOWN ARSENAL

WATERTOWN, MASS.

April 13, 1940

Subject: Research and Development Program of Armor Plate.

To: Chief of Ordnance, U.S.A.
War Department
Munitions Building
Washington, D. C.

1. As a result of discussions between the personnel of this arsenal and representatives of the Office, Chief of Ordnance, the following general program for further research and development work on armor plate is submitted for consideration:

a. Watertown Arsenal is to act as the center and coördinating agency for research and development work. This is not, however, to interfere with procurement of armor plate, as now carried out by Rock Island Arsenal, in any way.

b. The program will parallel development of both cast and rolled plate. The present objective on cast plate will be to obtain performance as nearly that of rolled plate as may be practicable.

c. Both face hardened (to include flame hardening) and homogeneous plate are to be investigated. This will involve thicknesses of:

(1) 1/8" - 3/16" which may have special application to aircraft

(2) continue study and development of 1/4" - 1-1/2" plate

(3) develop plate and prepare specifications for thicknesses from 1-1/2" to 3".

This should be paralleled by development of a suitable 75 mm. armor piercing projectile for use against 3" plates.

COPY

d. Welded structures are to be made as approved by the Ordnance Office and tested from plate (cast or rolled) which offers most promise.

e. Continue study of welding of plate to determine weldability and practicability of maintenance and repair by welding of damaged plate in the field.

f. Investigate fastening of plates by rivets and bolts to obviate possibility of penetration at these points.

2. As has been the procedure in research and development during the past year, the work outlined above would be carried out in full coöperation with manufacturers qualified to make armor plate. The services of certain industrial research laboratories could also be obtained gratis on some phases of the work, as is now being done on similar problems. This arsenal has, at present, close cooperative contact with Henry Disston & Sons, Lebanon Steel Foundry, International Nickel Co., American Steel Foundries, American Car and Foundry Co., Wehr Steel Co., Allegheny-Ludlum Steel Co., Carnegie-Illinois Steel Co. and others. It is proposed to tie-in such firms more closely in the Research and Development Program. Much assistance can be obtained gratis, although in some cases small orders for experimental plate may have to be placed. For certain compositions it may be found advantageous to make small heats at this arsenal, for experimental castings or for ingots.

3. Preliminary ballistic tests with plate to resist the .50 Calibre Gun can be carried out at this arsenal. It may also be practical to conduct such tests at this post on heavier plate with the 37 mm. Gun. Shipment of a .50 Calibre Gun has been requested in other correspondence. Recommendations pertaining to the 37 mm. Gun may be submitted later.

4. It is believed that consideration should be given to the development of a specification for homogeneous plate which would authorize use of such plate at a ballistic limit somewhat below that of the corresponding face-hardened plate. Possibly a bonus should be offered on homogeneous plate with a view to improving its efficiency and availability, as capacity for face-hardened plate may be inadequate in time of emergency.

5. Directions are requested with indication of priority to be followed on the program outlined.

R. W. Case,
Colonel, Ordnance Dept.,
Commanding.

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