WATERTOWN ARSENAL LABORATORY

EXPERIMENTAL REPORT

NO. WAL. 710/566

ARMOR

Preliminary Metallurgical Studies of Experimental

Face Hardened Cast and Rolled Armor

BY

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DATE 13 December 1943

WATERTOWN ARSENAL
WATERTOWN, MASS.

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Watertown Arsenal Laboratory
Report No. WAL 710/566
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ARMOR

Preliminary Metallurgical Studies of Experimental

Face Hardened Cast and Rolled Armor

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OBJECT

To determine by a series of preliminary heat treatments whether a satisfactory hard case may be obtained on the surface of a 1.4" in. thick cast armor in conjunction with a sorbitic or tempered martensitic core at an approximate hardness of 270 Brinell and, if successful, to study further the ballistic possibilities of such a material.

Also to determine the metallurgical and ballistic characteristics of a 1/4" thick rolled plate which was prepared from a cast face hardened plate, produced at the same time and in the same manner as the 1.4" thick casting.

CONCLUSIONS

1. The results of this preliminary investigation indicate that this process of casting face hardened armor plate is not practical.

2. The carbon and alloy content of the face layer of the sample of the 1.4" thick cast armor and the 1/4" thick rolled armor is sufficient to produce a fairly stable austenitic alloy which cannot be transformed to martensite by various heat treatments. A sorbitic or tempered martensitic core was not obtained since a draw temperature exceeding the lower critical point was necessary to obtain an approximate 270 Brinell hardness. A microstructure consisting of ferrite and fine carbide resulted.

3. Because of the retention of large amounts of austenite upon cooling the plate from above the critical range, it was impossible to develop the desired hardness in the face alloy layers of the cast and rolled plates.

4. The relatively soft high alloy face on the cast and rolled plates was not effective in increasing the ballistic limits of the plates. The ballistic limit of the face hardened 1.4" thick cast plate was 13 f/s in excess of the specifications for homogeneous cast armor of equivalent thickness. The ballistic limit of the face

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hardened 1/4" thick rolled plate was 38 f/s below the requirements of hard rolled plate of equivalent thickness. The alloy face on the cast plate flaked and cracked badly under ballistic impact. The 1/4" thick rolled plate broke into two pieces under the impact of cal. .50 ball ammunition.

5. The unsatisfactory ballistic properties of the 1.4" thick cast plate are correlated with its poor metallurgical properties, namely, low hardness of case, pronounced cracks in the case which progress along carbide segregations in the austenitic layer and continuing into the steel base, poor diffusion between the case and core, and heterogeneous structure of the core.

6. The unsatisfactory ballistic properties of the 1/4" thick rolled plate were correlated with its poor metallurgical properties, namely, low hardness of the austenitic case, poor diffusion between case and core and heterogeneous structure of the core consisting of ferrite and carbides arranged in an acicular pattern.

7. The depth of the alloy case of the cast and rolled plates which varied considerably in thickness was somewhat less than that required on good quality face hardened plates.

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APPROVED:

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INTRODUCTION

This investigation was conducted in accordance with requests[1,2] by the Pittsburgh Ordnance District as a result of preliminary tests made on face hardened castings manufactured by the Pittsburgh Rolls Division of the Blaw-Knox Company.

Their process is briefly described below:

> The surface of that part of the mold corresponding to the face of the test plate was covered with a 1/4" thick coating of a pasty mixture consisting of equal parts by volume of 20-mesh ferro chromium, ferro-manganese and lamp black together with a small amount of ferro-silicon to prevent gas evolution. These ingredients were mixed with linseed oil to a consistency of putty, and applied to the mold by the use of a trowel, after which the mold was dried in an oven.
>
> The metal is poured at approximately 2800°F, at which temperature the ingredients in the applied coating are claimed to be dissolved into the face of the plate. The casting is slowly cooled in the mold after pouring.

A preliminary investigation was made by the Pittsburgh Rolls Division of the Blaw-Knox Company on a 36"x36"x1½" cast plate produced by the same process which developed a hardness of 500-610 Brinell at a depth of 1/4" below the surface upon spray quenching. The analysis of the case layer of the plate was 2.19% carbon, 7.75% manganese, and 5.28% chromium.

It was therefore suggested by this Arsenal[3] that a sample of the treated material be forwarded for preliminary heat treatment experiments and ballistic tests.

Accordingly, an as cast flat plate 18"x49"x1.4" in size was received at this Arsenal for further tests. This plate was cut into two equal sections, approximately 18"x24" for the investigation.

During the progress of this investigation a 18"x18"x1/4" rolled face hardened plate was submitted to this Arsenal for examination. This rolled sample was prepared from a cast, face hardened plate

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1. PIT 248.8/592, 16 July 1943, Appendix A.

2. PIT 248.8/801, 20 October 1943, Appendix A.

3. WTN 470.5/7267, July 30, 1943, Appendix A.

produced at the same time and in the same manner as the previously submitted 1.4" thick cast plate. This rolled plate was decidedly bowed, as received, the high alloy layer being on the concave side. After heat treatment, however, the curvature of the plate was nearly eliminated.

Preliminary heat treatments made on small samples of the plates, as received and also the final heat treatments of the ballistic test plates including the resulting Brinell and Vickers Brinell hardness values are given in Inclosure A, Table 1.

Preliminary Studies were made on two high carbon, high chromium steels in order to determine their merit as a satisfactory hard facing material on this type of plate.

TEST PROCEDURE

1. Visual Examination

The cast and rolled plates were examined on the high alloy surface and on the rear surface for cracks and other casting defects.

2. Ballistic Tests

a. Quenched and Drawn Cast Plate, 18x24x1.4"

This plate was tested in accordance with Spec. AXS-492, Revision 3. A ballistic limit was obtained on this plate with 37 mm. AP M74 shot when mounted for normal impact. For information purposes, the plate was subjected to a PTP test using 37 mm. AP M74 shot with a striking velocity of 2000 f/s.

b. Quenched and Drawn 18x18x1/4" Rolled Plate

This plate was tested in accordance with Spec. AXS-488, Revision 2, for hard homogeneous plate. A ballistic limit was determined on the heat treated 1/4" thick plate with Cal. .30 AP M2 ammunition when mounted for normal impact. This plate was subjected to a PTP test consisting of firing two rounds of Cal. .50 AP M2 ammunition at a velocity of about 1500 f/s, normal impact.

3. Metallurgical Examination

a. 1.4" Thick Cast Plate

The metallurgical study included chemical analyses of the high alloy face and the steel base, macroscopic and microscopic examination and Jominy hardenability test. A Brinell hardness survey was made on the high alloy surface and on the cross sections of samples, as cast, after preliminary heat treatments and also on a sample cut from the ballistic test plate after the final heat treatment. Vickers Brinell hardness surveys were also made on cross sections cut from the heat treated ballistic test plate.

b. 1/4" Thick Rolled Plate

Macroscopic and microscopic examinations were made on sections cut from the heat treated plate. Brinell hardness determinations were made on the high alloy face and on the rear face of samples cut from the rolled plate, as received, after preliminary heat treatments and on a sample cut from the ballistic test plate after the final heat treatment. Vickers Brinell determinations were also made on a cross section cut from the ballistic test plate.

4. Experimental High Carbon, High Chromium Hard Face Compositions

Studies were made on high carbon - high chromium alloys in order to determine if they would retain a suitable face hardness required for good quality face hardened plate when drawn to a temperature necessary for the proper hardness of the steel base.

Two 60 lb. ingots 4x4x10" of the compositions shown below were cast at Watertown Arsenal and homogenized at 1800°F for 5 hours followed by air cooling.

No.	C	Mn	Cr	Mo
1314	.80/.90	.40/.60	6/7	.15/.25
1315	.80/.90	.40/.60	10/11	.15/.25

Small sections of these ingots were heated to 1700°F for 4 hours, quenched in water and drawn 4 hours at 850°F, 950°F, and 1050°F.

RESULTS AND DISCUSSION

1. Visual Examination

a. 1.4" Thick Cast Plate

A crack, about 5½" in length and in the high alloy face, was observed progressing normal to the left hand edge of the plate. This crack, which was located at a position about 24" above the bottom edge, extended into the cross section of the plate to a depth of about 75% of the thickness of the plate. (See Fig. 1)

b. 1/4" Thick Rolled Plate

The plate as received was badly bowed, a deflection of about $2\frac{1}{2}$" being present in a span of 18 inches. The high alloy face was on the concave surface. After heat treatment, however, the bow in the plate was nearly eliminated.

2. Ballistic Tests

A summary of the ballistic tests made on the cast and rolled plates is given in Table 1. Photographs of the plates tested are shown in Figures 1-5 inclusive. Detailed firing records are contained in Inclosure A.

The relatively soft high alloy face on the cast and rolled plates was not effective in increasing the ballistic resistance of the plates. The ballistic limit of the face hardened cast plate was only 13 f/s in excess of the specifications for homogeneous cast armor plate of equivalent thickness. The ballistic limit of the rolled 1/4" thick plate was 38 f/s below the requirements of rolled hard homogeneous plate of equivalent thickness.

Under the impact of 37 mm. AP M74 projectiles, with a striking velocity of 979-1606 f/s, the high alloy surface of the 1.4" thick cast plate flaked and cracked badly in some areas. (See Fig. 2) Complete penetrations were obtained at velocities as low as 1027 f/s.

The 1/4" thick plate showed evidence of some spalling under the penetration test and when subjected to the PTP test using Cal. .50 AP projectiles, with a striking velocity of 1480 f/s, the plate broke into two pieces.

3. Metallurgical Examination

a. Chemical Analysis

Chemical analysis of the high alloy face and steel base of the 1.4" thick cast plate and the W.A. experimental high carbon, high chromium hard facing alloys are given in Table II.

TABLE I

Summary of Ballistic Tests of

1.4" Thick Cast and 1/4" Thick Rolled Face Hardened Plates

Size of Plates - 18x24x1.4" - Cast
18x18x1/4" - Rolled

Plate	Ballistic Properties: Ballistic Limit 37 mm. M74 AP f/s	Ballistic Properties: PTP Test 37 mm. M74 AP f/s	Brinell Hardness	Remarks
1.4" Thick Cast Heat Treated	1003 (+13) 1a	2000 str. vel. Exit 2-5/8x2-3/4"	341-352 Face 255-269 Back	High alloy surface layer spalled off under projectile impact. 1-3" Cracks in back face near penetrations. Back opening 1.4"x1.6".
	Ballistic Limit Cal. .30 APM2 f/s	**PTP Test Cal. .50 APM2 f/s**		
1/4" Thick Rolled Heat Treated	1231 (-38) 1b	1480 str. vel. 13/16"x5/8" B. S. Plate cracked	38[illegible]-375 Face 38[illegible]-388 Back	Plate brittle under PTP Test, broke into 2 pieces. Spall 7/16x3/8" under penetration test.

1. Number in parentheses indicate feet per second.

   a. In excess of Specification AXS-492 Revision 3 (Cast Armor).

   b. Below the requirements of Specification AXS-488 Revision 2 (Rolled Armor).

TABLE II

Chemical Analysis of the High Alloy Face and Steel Base of the 1.4" Thick Cast Plate and Experimental W.A. High Carbon, High Chromium Facing Alloys

1.4" Thick Cast Plate as received	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	Al
Face	2.40	9.20	2.14	.015	.044	2.52	8.12	.35	.85	—	—
Steel Base	.34	.77	.25	.017	.031	3.33	.06	.45	.06	.02	.015
Experimental W.A. High C High Cr Hard Facing Alloys	**C**	**Mn**	**Si**	**S**	**P**	**Ni**	**Cr**	**Mo**	**V**	**Cu**	**Al**
1314	.80	.61	.54	.019	.021	—	6.82	.20	—	—	—
1315	.76	.61	.53	.021	.018	—	9.06	.18	—	—	—

Note: The 1/4" thick rolled plate had a similar high alloy austenitic face and same type of steel base, therefore, a chemical analysis was not made on this particular plate.

The high alloy face contains sufficient carbon and manganese together with large amounts of nickel, chromium, molybdenum, and vanadium to produce a stable austenitic alloy. Both the manganese and chromium are appreciably higher than the values reported for these elements in the cast plate which when spray quenched by Pittsburgh Rolls Division reportedly developed the desired hardness. From a theoretical standpoint, the solution appears to be a reduction in the carbon content and elimination, if possible, of all the elements except chromium. It is understood from a practical point of view, that a fairly high carbon content must be present in the facing compounds to promote fusibility when cast under the recommended procedure.

b. Macroscopic Examination

The macrostructure of the 1.4" thick cast plate and the 1/4" thick rolled plate, as received and after heat treatment is shown in Fig. 6.

Five cracks were detected in the high alloy layer of the cast plate as received. These cracks were intensified by heat treatment. On the surface of the heat treated sections of the cast plate a continuous series of network cracks were detected as shown in Fig. 6.

A segregation of nonmetallic inclusions and some fine porosity was present in the center of the cross section of the cast plate. Occasionally small areas of the high alloy facing material were detected in the center of the cross section of the steel base.

No cracks were detected in the high alloy face of the 1/4" thick rolled plate.

A considerable variation was detected in the thickness of the high alloy face on the cast and rolled plates. (See Fig. 7)

c. Microscopic Examination

The microstructures of the face hardened cast and rolled plates are shown in Figures 8 and 9.

It was noted that the cracks observed in the high alloy face of the 1.4" thick plate, "as cast," progressed along segregates of complex carbides which were located in the dendritic fillings. In many cases these cracks proceeded into the steel base. (See Fig. 8) The matrix of the high alloy surface of the plate, as cast, was chiefly austenitic.

After heat treatment, which included high temperature homogenization, segregations of carbides still persisted together with a fine precipitation of very fine carbide, which developed in the austenitic matrix. (See Fig. 9) Furthermore after heat treatment, the crack systems in the high alloy face were intensified and progressed to a considerable depth into the steel base. (See Fig. 9) In some cases cracks extended into the steel base to a depth of ½".

Generally speaking there was no pronounced diffusion zone at the junction of the high alloy surface layer and the steel base of the cast 1.4" thick plate.

The microstructure of the steel base of the plate, as cast, was definitely a Widmanstatten structure consisting of ferrite and sorbite.

In some areas in the steel base, continuous films of oxide were detected around the grain boundaries, a condition which is correlated with poor steel making practice.

After heat treatment, some ferrite associated with fine carbides was observed in the steel base of the cast plate. (See Fig. 9.) Due to the fact that it was necessary to draw this plate to 1325°F, in order to arrive at a Brinell hardness of 270, it is believed that the ferrite present in the microstructure resulted from reheating to a temperature above the lower critical point. In this connection[4], the Ac_1 point of a similar steel, namely SAE 2335, is 1275°F.

Marked bands of complex carbides were detected in the austenitic matrix of the high alloy face of the 1/4" thick heat treated rolled plate. (See Fig. 9.) The microstructure of the steel base of this plate consisted of ferrite and fine carbide arranged in an acicular pattern. Failure under shock may have been due to this type of microstructure. Pronounced banding associated with segregations of nonmetallic inclusions as revealed by the Oberhoffer etch was evident in the steel base. (See Fig. 9.) A rather sharp demarcation was observed between the high alloy face and the core of this plate.

Several thickness measurements were made of the high alloy face on the cast and rolled plates and are reported below:

	Thickness of High Alloy Face				
1.4" thick cast plate	.22"	.25"	.30"	.25"	.21"
1/4" thick rolled plate	.034"	.058"	.032"	.012"	.015"

As noted above there was a noticeable variation detected in the thickness of the high alloy face on the samples examined.

The average thickness of the alloy face of the cast and rolled plates was less than the requirements for good quality face hardened plate. Good quality plate has a case thickness, approximately 20-25% of the gauge of the plate.

d. Jominy Hardenability Test

The results of the end quench hardenability test which are shown in Fig. 10 are summarized in Table III below:

4. "Approximate Critical Temperatures of SAE Steels" by M. J. R. Morris, R. Sergeson and G. W. Gable, Metal Progress, August 1935.

TABLE III

End Quench Hardenability of Steel Base of

1.4" Thick Cast Plate

C Content %	Hardness 1/16" from Quenched end Rc	Jominy Hardenability Data No. of 1/16" for a drop of 5 Rc	of 10 Rc	to 42 Rc 400 BHN	Hardness at 2-1/2" from Quenched end Rc	Thickness of Plate Quenchable in Water to 400 BHN in Center
.34	50	5.7	11	9	32	1.6"

The results of the hardenability test indicate that the steel base of the 1.4" thick cast plate has sufficient hardenability to water quench properly throughout its cross section.

e. Heat Treatment and Hardness Surveys

It was determined that the high temperature heating cycles and subsequent drawing temperatures used in this investigation failed to transform the stable high alloy austenitic face on the cast and rolled plates into a hard martensitic surface layer.

The results of the hardness determinations made on the high alloy face and the steel base of cast and rolled sections after the preliminary heat treatments and also the results of the hardness surveys made on the ballistic test plates are given in Table I, Inclosure A.

The fact that the high alloy face of the 1.4" thick cast plate remains a stable austenitic alloy after the homogenizing and subsequent heat treatments is verified by the fact that the hardness of all these heat treated samples is relatively low, varying from 293 to 352 Brinell. It should be noted that the alloy face of the plate submitted was not made martensitic by heating the plate to 1600°F and spray quenching according to the practice of the Pittsburgh Rolls Division. The steel base of the cast plate had an adequate hardenability, resulting in an as quenched hardness of 461-514 Brinell. It should be noted, however, that a relatively high drawing temperature was necessary to produce a Brinell hardness of approximately 270 in the core of this plate. A series of network cracks were detected in some areas of the high alloy surface of the heat treated 1.4" thick cast plate. This condition was not observed on the high alloy surface of the 1/4" thick rolled plate.

The hardness of the case of the 1/4" thick rolled plate, as received, varied from 401-415 Brinell. After heat treatment, the hardness of the case was 388 Brinell, and 425-455 Vickers Brinell. This relled plate had a satisfactory as quenched hardness of 461-477

Brinell and was drawn to 388 Brinell after tempering at 750°F.

A summary of the hardness determinations made on the 1.4" thick cast and 1/4" thick rolled plate is given in Table IV.

TABLE IV

Summary of Hardness Determinations

Material	Brinell Hardness Face	Brinell Hardness Back
1.4" Cast Plate as cast	302, 302, 293	277, 277, 285
1.4" Cast Plate quenched and drawn	352, 341, 352 *421, 429, 450, 446	269, 255, 269 *270, 274, 287, 290
1.4" Cast Plate Spray quenched and drawn	352, 352, 352	269, 269, 269
1/4" Rolled Plate as rolled	415, 401, 415	293, 285, 293
1/4" Rolled Plate Quenched and Drawn	388, 388, 388 *455, 425, 429, 442	388, 375, 388 *383, 387, 394, 401

*Vickers Brinell Hardness Values

f. Experimental Watertown Arsenal High Carbon, High Chromium Hard Face Compositions

It was determined that the alloys containing .76/.80% carbon, 6.82/9.06% chromium, and .18/.20% molybdenum retained a Brinell hardness of 477/495 at a tempering temperature of 950°F. while at a tempering temperature of 1050°F, the hardness decreased to 341 Brinell.

A summary of these hardness tests is given in Table V.

TABLE V

Hardness Tests Made on Heat Treated

Watertown Arsenal Experimental High Carbon

High Chromium Hard Face Compositions

W.A. Experimental High C, High Cr, Hard Face Compositions	Brinell Hardness: Quenched from 1700°F into Water	Drawn 4 hrs. at 850°F	Drawn 4 hrs. at 950°F	Drawn 4 hrs. at 1050°F
1314 C .80 Cr 6.82 Mo .20	601	477	477	341
1315 C .76 Cr 9.06 Mo .18	601	495	495	341

4. General

It is evident that the face layer on the plates submitted contained a greater percentage of alloy than the face composition prepared by the Pittsburgh Rolls Division of the Blaw-Knox Company. The face layers on the cast and rolled plate tested at this arsenal remained austenitic after various heat treatments including spray quenching and hence offered no resistance to the penetration test. Furthermore, due to poor diffusion between the case and core of the cast plate, the high alloy face flaked and cracked badly under ballistic impact. A face hardness of 600 Vickers was reported by the Pittsburgh Rolls Division of the Blaw-Knox Company on a sample spray quenched by them.

In selecting compositions for a good quality face hardened cast plate, the following factors should be considered:

a. The compositions of face and back should be so selected with respect to coefficients of expansion and critical points that upon final quenching, excess warping would be eliminated.

b. A proper diffusion between case and core should be evident, thereby eliminating excessive face spalling.

c. The composition of face and core should be so selected that after heat treatment, the case should have a uniform martensitic structure (500-600 Brinell hardness) with a sorbitic or tempered martensitic core (about 270 Brinell hardness for cast armor, 1½" in thickness).

These combinations of factors are difficult to meet in the manufacture of the type of face hardened plate described herein both from the practical and theoretical point of view.

For example, it is understood that at least 2% carbon is necessary in the face hardening mixture of the alloy face to promote fluidity during the melting procedure. Such a high carbon content in combination with an element such as chromium forms considerable carbide, which requires a high solution temperature, about 1800-1900°F. Although this alloy steel retains a hardness of about Rockwell C 62 at a drawing temperature of 1000°F, the high solution temperature recommended will cause objectionable grain growth in the steel base. It is believed that hard alloy facing compositions containing such a high carbon content will be brittle under ballistic impact. In fact several materials such as a laminated plowshare steel with a high carbon face showed evidence of brittleness when subjected to a ballistic test.

An attempt was made at this arsenal to prepare a hard face composition containing a lower carbon content, high chromium, and low molybdenum which would retain the proper face hardness at a drawing temperature of about 1050-1150°F or better (a temperature range necessary for a core hardness of about 270 Brinell hardness required for cast armor 1½" in thickness).

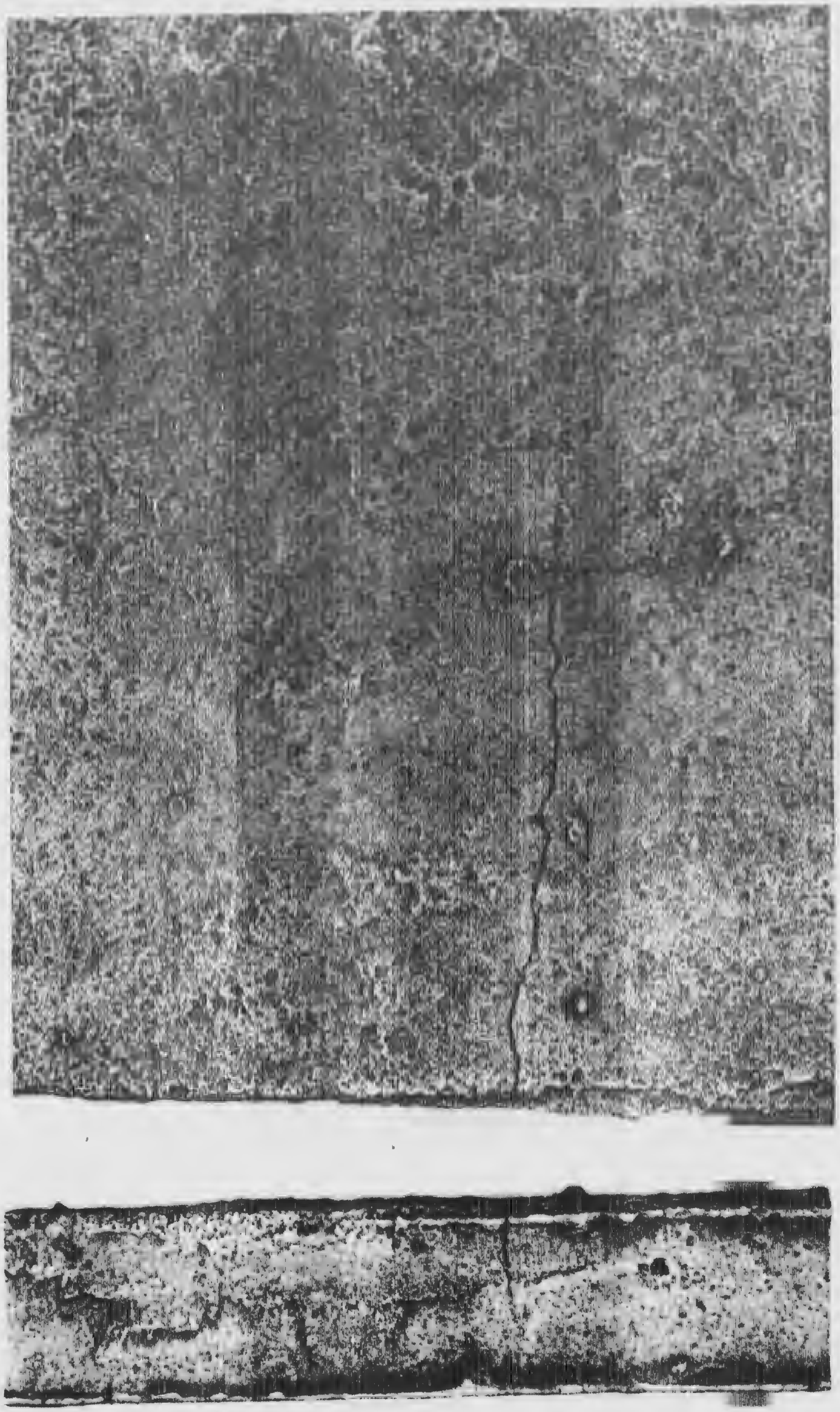
It was determined that these quenched alloys containing 0.76/0.80% carbon, 6.82/9.06% chromium, and 0.18/0.20% molybdenum retained a Brinell hardness of 495 at a maximum drawing temperature of 950°F and at a draw of 1050°F, a Brinell hardness of 341 Brinell was obtained. It is evident that this type of an alloy fails to fulfill the above requirements. No ballistic tests were made in this composition.

The face hardened 1/4" thick plate which was rolled from a heavy face hardened cast plate, cast in the same manner as the 1.4" thick plate submitted had poor metallurgical and ballistic properties as described herein.

It has been determined that a too high chromium content cannot be used in the alloy surface of rolled duplex plate, since difficulties arise in flame cutting the material. Furthermore, face spalls were prevalent under ballistic impact due to carbide segregations in the case of the various types of this rolled light duplex plate tested and examined.

The most promising duplex plate produced is made up of a low carbon, nickel molybdenum base with a medium high carbon, nickel molybdenum face.

The results of this preliminary investigation indicate that this process of casting face hardened armor plate is not practical.

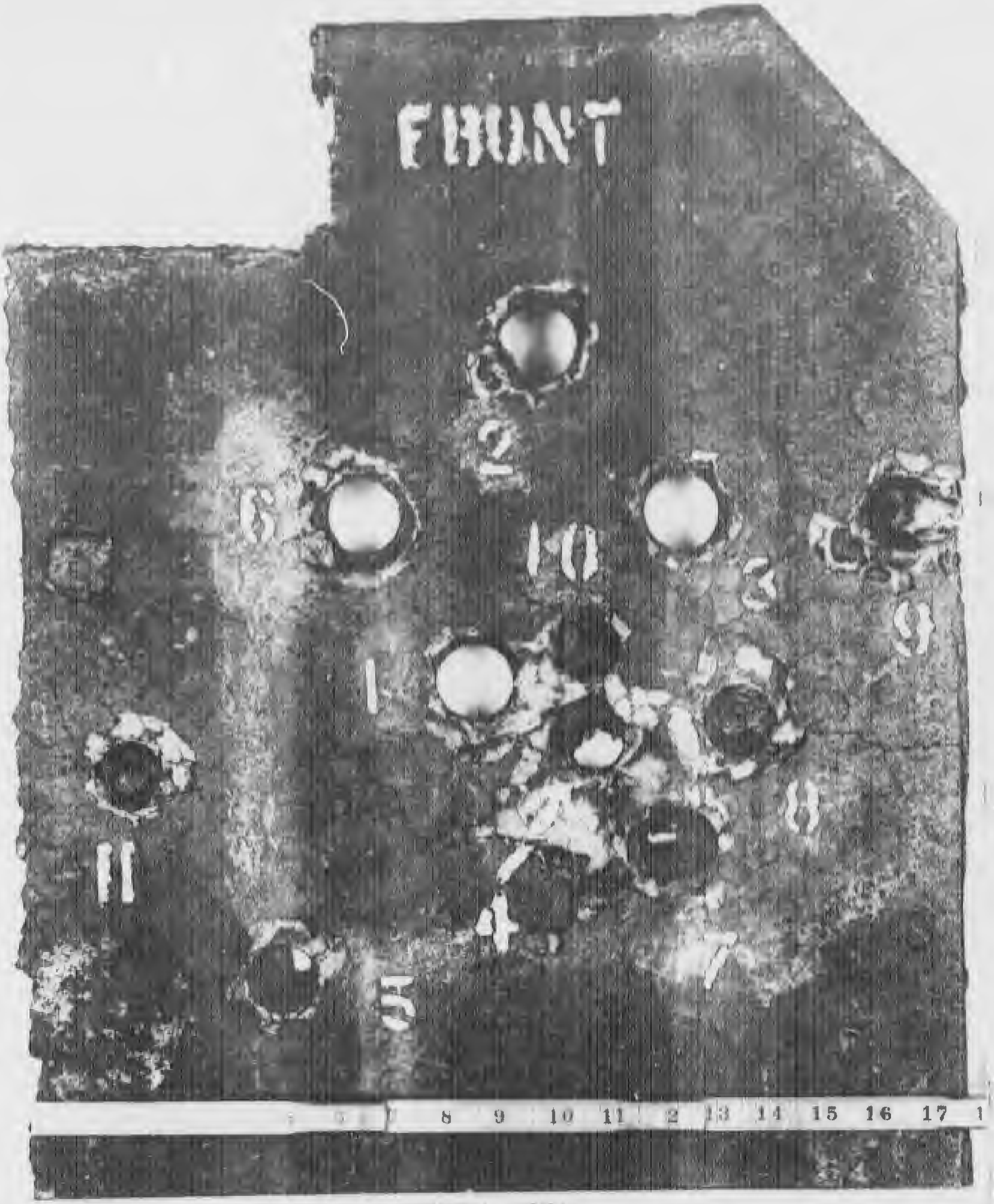


WATERTOWN ARSENAL

CRACK IN HIGH ALLOY SURFACE, EXTENDING INTO STEEL BASE

29 SEPTEMBER 1943 WTN.710-2150

FIG. 1



WATERTOWN ARSENAL

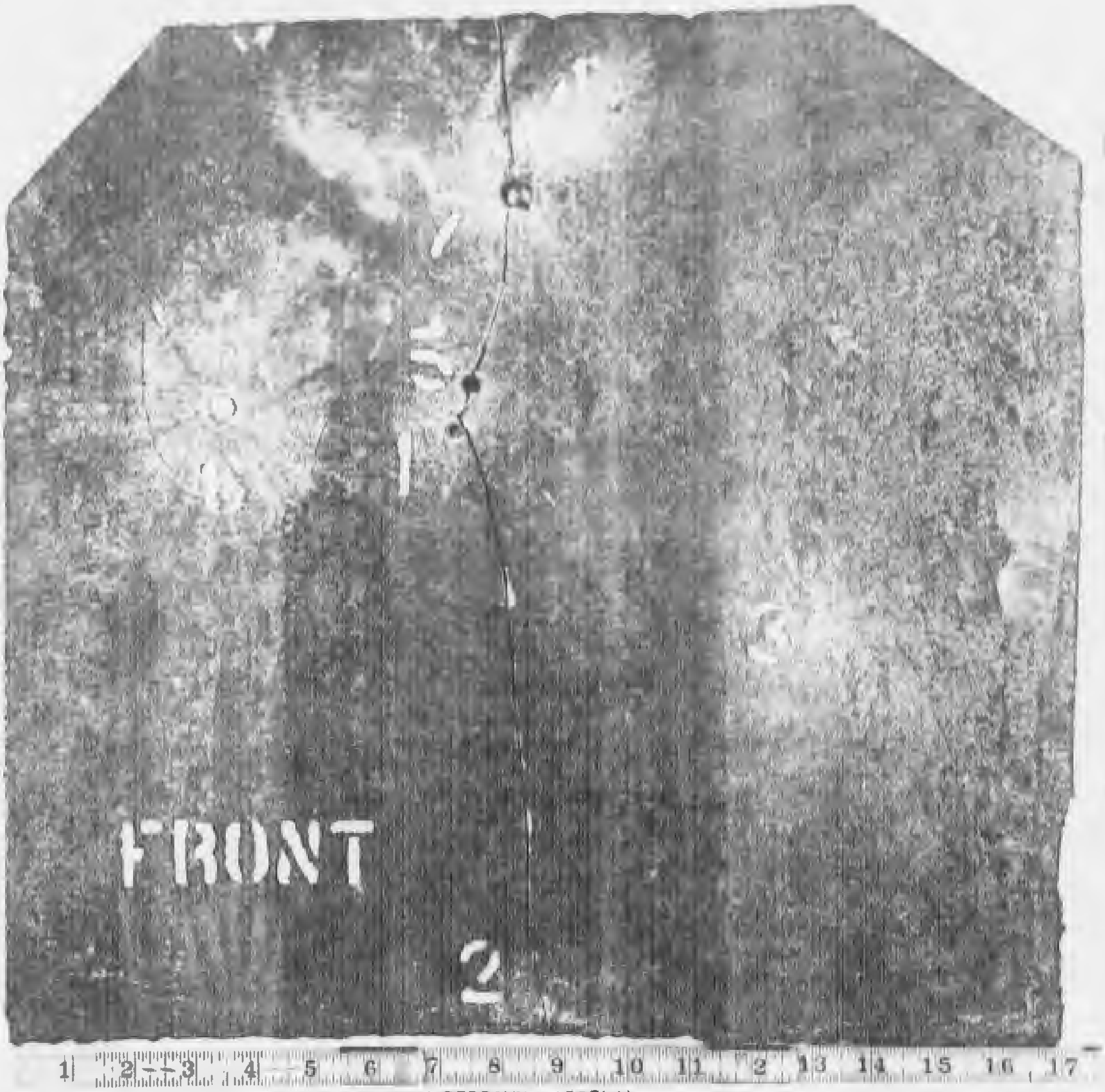
1.4" THICK FACE HARDENED CAST ARMOR
16 NOVEMBER 1943 FRONT WTN.71C-2194

FIG. 2

WATERTOWN ARSENAL

1.4" THICK FACE HARDENED CAST ARMOR
16 NOVEMBER 1943 BACK WTN.710-2195

FIG. 3



WATERTOWN ARSENAL

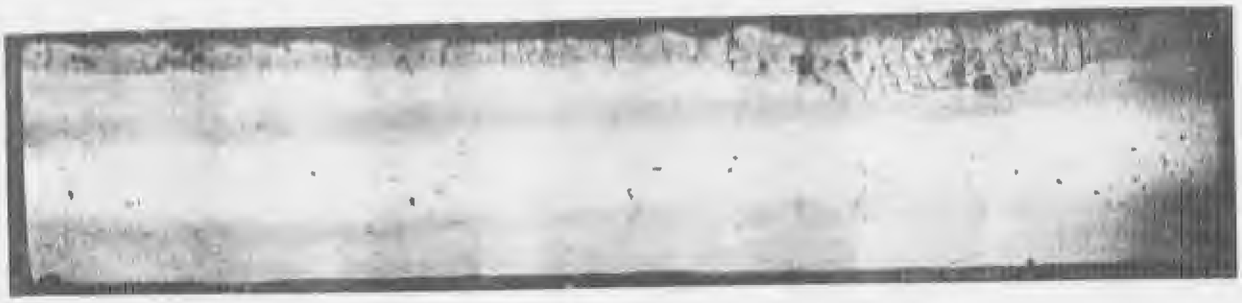
1/4" FACE HARDENED ROLLED ARMOR
16 NOVEMBER 1943 WTN.710-2196

FIG. 4

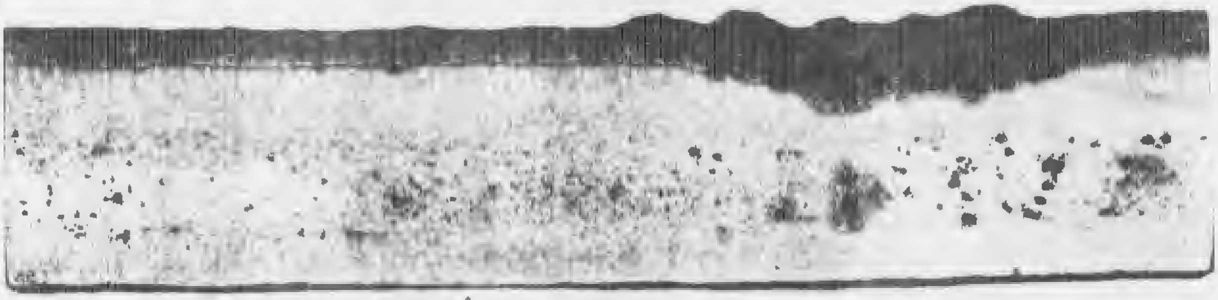
WATERTOWN ARSENAL

1/4" FACE HARDENED ROLLED ARMOR
16 NOVEMBER 1943 WTN.710-2197

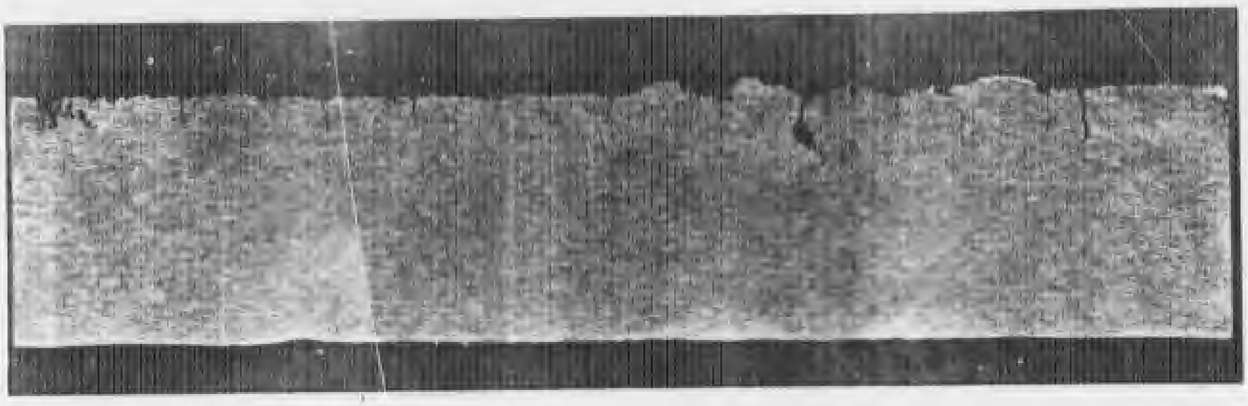
FIG. 5



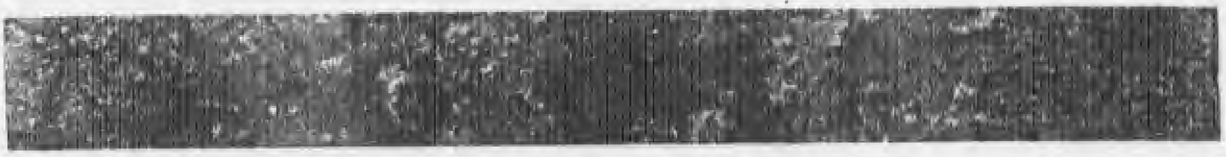
CROSS SECTION – AS RECEIVED – UNETCHED
CRACKS IN SURFACE LAYER



CROSS SECTION – AS RECEIVED – MACROETCHED



CROSS SECTION – AFTER HEAT TREATMENT – UNETCHED
PRONOUNCED CRACKS IN CASE

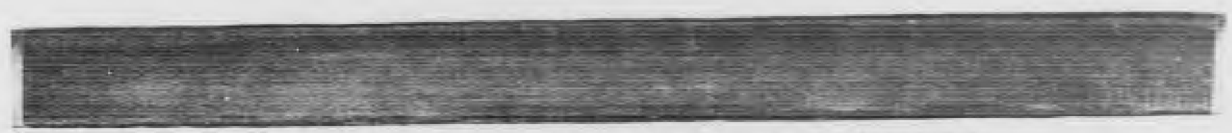


SHOWING CRACKS IN SURFACE LAYER AFTER HEAT TREATMENT

18 OCTOBER 1943 FACE HARDENED ARMOR WTN.639-5727

FIG. 6

NEAR EDGE OF PLATE AS ROLLED



NEAR CENTER OF PLATE AFTER HEAT TREATMENT

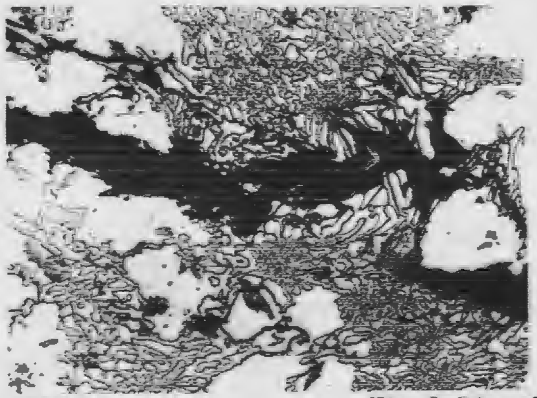
WATERTOWN ARSENAL

MACROSTRUCTURE OF HOT ROLLED 1/4" THICK FACE HARDENED PLATE
18 NOVEMBER 1943 WTN.710-2199

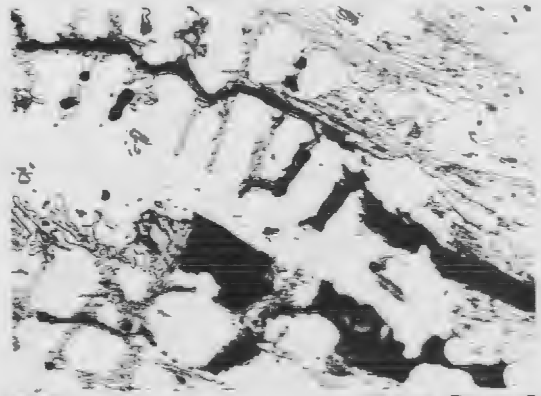
FIG. 7

WTN.639-5942

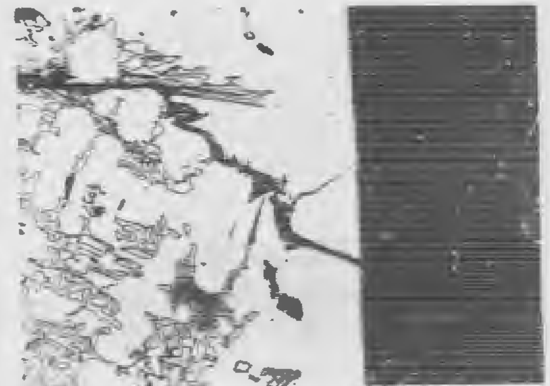
FACE HARDENED 1.4" THICK CAST ARMOR
AS CAST



X100 Nital Picral
Near surface of high alloy face. Crack following carbides in austenitic matrix.

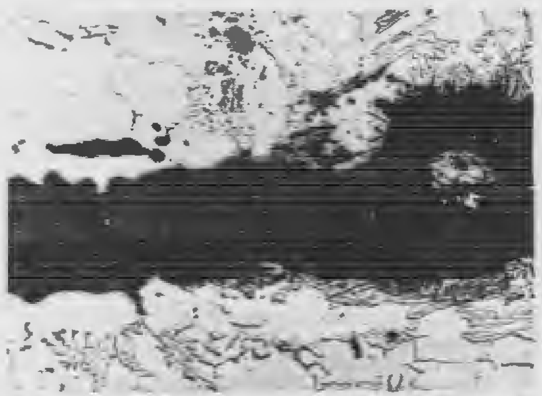


X100 Nital Picral
Center of high alloy face. Cracks following carbides in austenitic matrix.

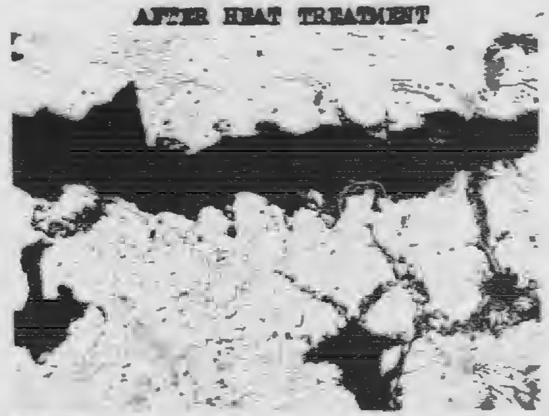


X100 Nital Picral
Junction of high alloy face and steel base. Crack in high alloy face progressing into steel base.

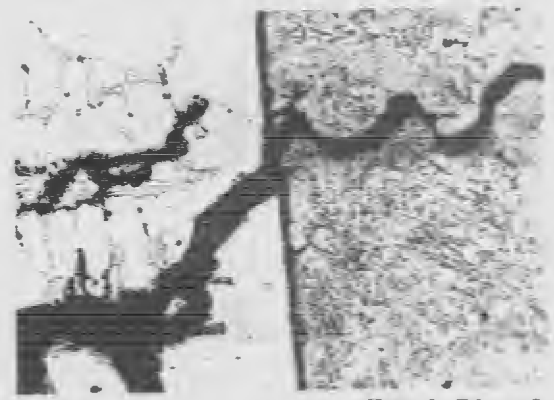
AFTER HEAT TREATMENT



X100 Nital Picral
Near surface of high alloy face. Large crack following carbides in austenitic matrix.



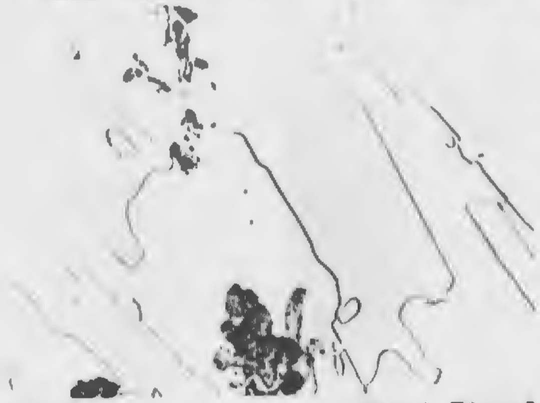
X100 Nital Picral
Center of high alloy face. Cracks following carbides in austenitic matrix.



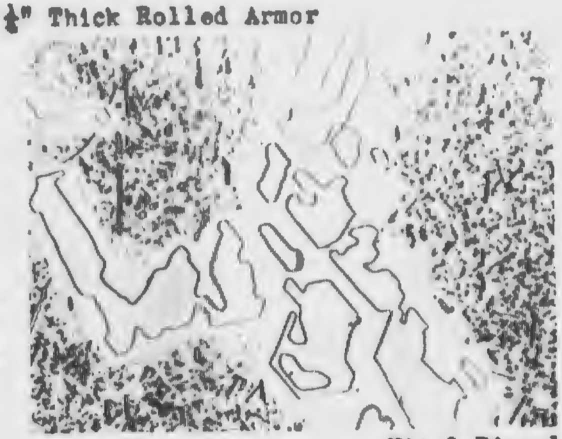
X100 Nital Picral
Junction of high alloy face and steel base. Crack in high alloy face progressing deeply into the steel base.

FIG. 8

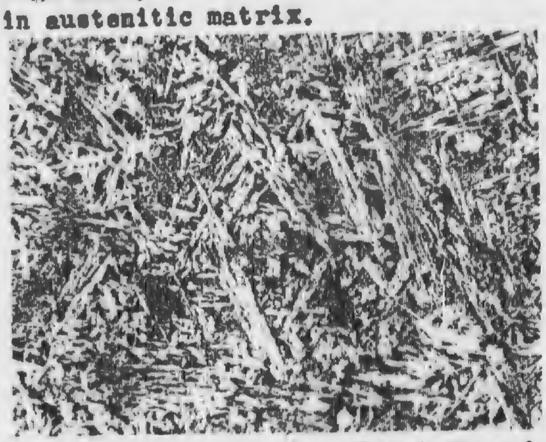
Face Hardened 1.4" Thick Cast and ¼" Thick Rolled Armor



X1000 Nital Picral
1.4" thick plate as cast. Center of high alloy face. Massive carbides in austenitic matrix.



X1000 Nital Picral
1.4" thick plate after heat treatment. Center of high alloy face. Massive carbides in austenite matrix.



X100 Nital Picral
1.4" thick plate as cast. Center of steel base. Widmanstatten structure sorbite and ferrite.

X1000 Nital Picral
1.4" thick plate after heat treatment. Typical structure after drawing at 1325 F.

WTN.639-5943

X100 Nital Picral
¼" thick rolled plate after heat treatment. High alloy face and core. Note bands of carbides in case.

X50 Oberhoffer
¼" thick rolled plate after heat treatment. Banding in core.

X1000 Nital Picral
¼" thick rolled plate after heat treatment. Tempered martensite in core.

FIG. 9

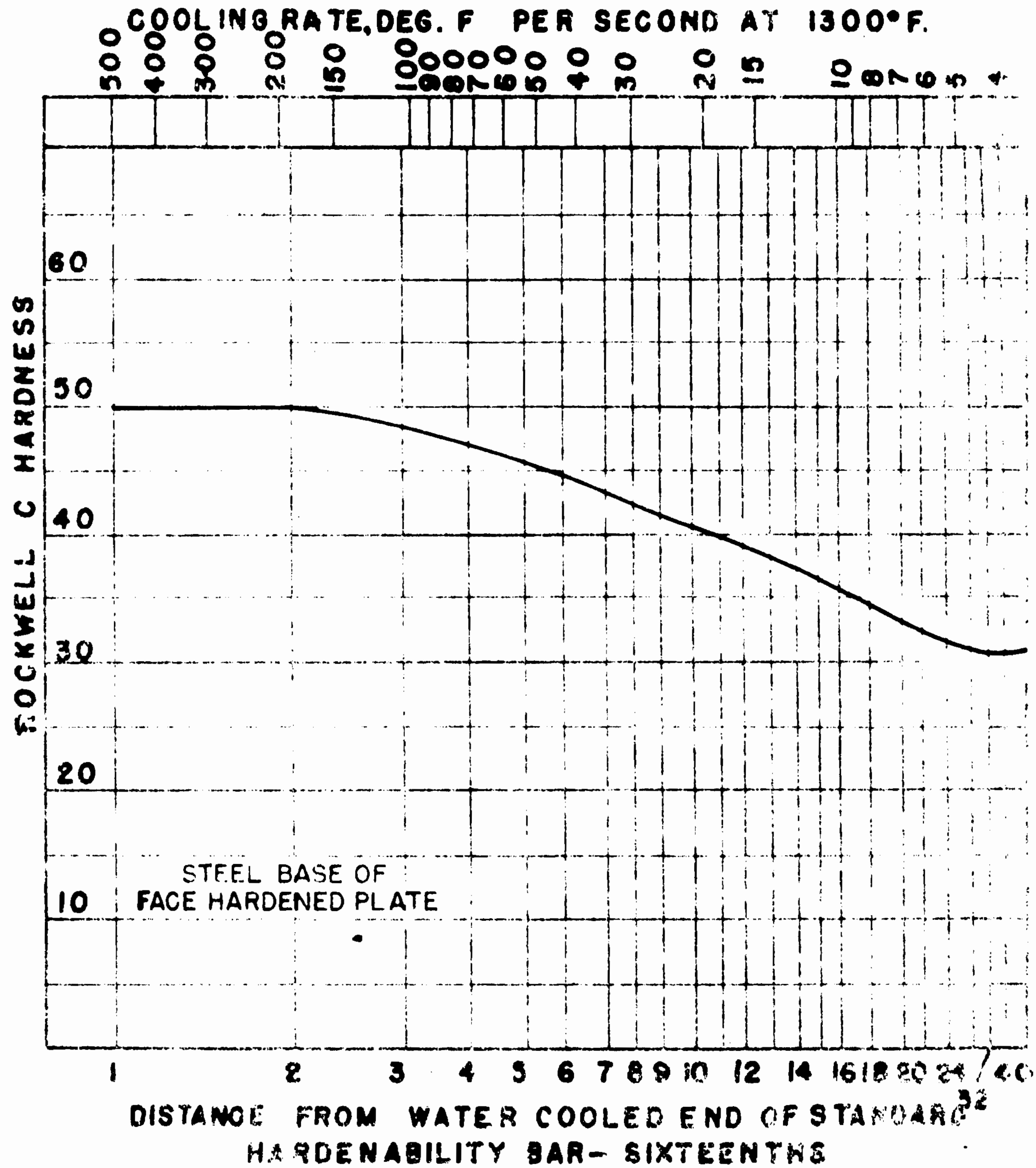


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	V	QUENCH TEMP	TIME	G.S.
.207		.34	.77	.25	.017	.031	3.33	.06	.45	.02	.06	1500	2 hrs.	

FIGURE 10

INCLOSURE A

Preliminary and Final Heat Treatments of

Face Hardened 1.4" Thick Cast and

1/4" Thick Rolled Plate

1. Series of Samples for Preliminary Heat Treatments

Small sections approximately 3"x3/4"x1.4" were cut from the central portions of the cast plate and heat treated in an attempt to produce a hard martensitic face together with a tempered martensitic or a sorbitic core at a hardness of approximately 270 Brinell.

Also small sections, approximately 2"x1"x1/4" were cut from the edge of the 1/4" thick rolled plate for the purpose of determining its proper quenching and drawing temperature.

The series of preliminary heat treatments are listed below:

a. 1.4" Thick Cast Plate

(1) One sample heated to 1700°F for 6 hrs., air cooled.

(2) One sample of a.(1) heated to 1500°F, water quenched.

(3) Five samples of a.(1) heated to 1500°F, water quenched and drawn 4 hrs., at 1000°F, 1100°F, 1200°F, 1275°F, and 1325°F until a core hardness of approximately 270 Brinell was obtained.

(4) One sample heated to 1900°F for 6 hrs., air cooled.

(5) One sample heated to 1900°F for 6 hrs., quenched in water.

b. 1/4" Thick Rolled Plate

(1) One sample heated to 1650°F for 2 hrs., air cooled.

(2) One sample of b.(1) heated to 1500°F for 1 hr., quenched in water.

(3) Two samples of b.(1) heated to 1500°F for 1 hr., quenched in water drawn 2 hrs., at 900°F and 750°F until a core hardness of approximately 380 Brinell was obtained.

2. Final Heat Treatments

a. 1.4" Thick Cast Plate

One section of the cast plate 18"x24" was heated to 1700°F for 6 hrs., air cooled, reheated to 1500°F for 2 hrs., water quenched and drawn at 1325°F for 4 hrs., followed by air cooling.

One section of the cast plate 18"x24" was heated to 1600°F for 8 hrs., spray quenched, and drawn to 1325°F for 4 hrs., followed by air cooling.

b. 1/4" Thick Rolled Plate

The plate was heated to 1650°F for 2 hrs., air cooled, reheated to 1500°F for 1 hr., water quenched and drawn at 750°F for 2 hrs., followed by air cooling.

TABLE I

Hardness Determinations Made on The High Alloy Face and on The Steel Base of Cast and Rolled Sections after Preliminary and Final Heat Treatments

Sample	Brinell Hardness: High Alloy Face - Surface			(Vickers Brinell Nos. are given in Samples Nos. 11 & 17): Cross Section of Steel Base		
Sections 3"x3/4"x1.4" Cast Plate Preliminary Heat Treatments						
1. As cast	302	302	293	277	277	285
2. Heated to 1900°F, 6 hrs., air cooled.	262*	262	293	293	321	302
3. Heated to 1900°F, 6 hrs., water quenched.	302	311	302	514	477	461
4. Heated to 1700°F, 6 hrs., air cooled.	321	311	311	321	302	311
5. Heated to 1700°F, 6 hrs., air cooled. Reheated to 1500°F, 2 hrs., water quenched.	321*	341	341	534	495	514
6. Sample heat treated as of 5 and tempered at 1000°F, 4 hrs., air cooled.	277*	352	341	341	363	363
7. Sample heat treated as of 5 and tempered at 1100°F, 4 hrs., air cooled.	311*	341	341	352	363	352
8. Sample heat treated as of 5 and tempered at 1200°F, 4 hrs., air cooled.	341	311*	341	311	341	341
9. Sample heat treated as of 5 and tempered at 1275°F, 4 hrs., air cooled	311	352	311	285	293	311
10. Sample heat treated as of 5 and tempered at 1325°F, 4 hrs., air cooled.	341	331	311	277	277	285

* Cracks developed during Brinell Hardness Test.

TABLE I (CONT'D)

Sample	Brinell Hardness — High Alloy Face Surface	(Vickers Brinell* Nos. are given in Samples Nos. 11 & 17) — Cross Section of Steel Base
Sections 18"x24"x1.4" Cast Plate Final Heat Treatment		
11. Heated to 1700°F, 6 hrs., air cooled. Reheated to 1500°F, 2 hrs., water quenched. Drawn 4 hrs., at 1325°F, air cooled.	352 341 352 421 429 450 446*	269 255 269 270 274 287 290*
12. Heated to 1600°F, 8 hrs., spray quenched.	352 352 352	401 401 415
13. Same as 12, drawn at 1325°F, 4 hrs., air cooled.	352 352 352	269 269 269
Sample Sections 2"x1"x1/4" Rolled Plate Preliminary Heat Treatments		
14. As rolled.	415 401 415	293 285 293
15. Heated to 1650°F, 2 hrs., air cooled.	514 514 495	477 461 477
16. Same as 2, drawn at 750°F, 2 hrs. air cooled.	388 375 388	388 388 388
Sample Sections 18"x18"x1/4" Rolled Plate Final Heat Treatment		
17. Heated to 1650°F, 2 hrs., air cooled. Reheated to 1500°F, 1 hr. water quenched, drawn 750°F, 2 hrs., air cooled.	388 388 388 455 425 429 442*	388 375 388 383 387 394 401*

TABLE II

Ballistic Tests on Cast Plate - 18"x24"x1.4"

Hardness

Cast Plate 1.4" Thick — Face - 341-352 Brinell; Back - 255-269 Brinell

Round Number	Striking Velocity f/s 37 mm. M74 AP	Result
1	1606	PTP - Exit 2-1/4"x2-7/16".
2	1438	PTP - Exit 2-1/4"x2-1/4".
3	1345	PTP - Exit 2-7/8x2".
4	1142	CP - Back opening 1-1/2"x1-1/4".
5	1028	CP - Back opening partially backed by support.
6	2000 App.	PTP - Exit 2-5/8"x2-3/4".
7	1134	CP - BS 1.4"x1.6".
8	1027[a]	CP - Punching started 2"x1.4" crack to edge of plate 2.9" long.
9	936	PP - Edge of plate.
10	930 App.	PP - SB, cracks on back 1.1"x.7" long.
11	979[a]	PP - SB

[a] ballistic limit, 1003 f/s.

High alloy face flaked and cracked under ballistic test, see Fig. 2.

TABLE III

Ballistic Tests on Rolled Plate - 18"x18"x1/4"

Hardness Rolled Plate 1/4" Thick	Face - 429-455 Vickers Brinell Back - 383-401 Vickers Brinell

Round Number	Striking Velocity f/s Cal. .30 APM2	Result
1	Velocity Lost	CP - Pinhole 1/16"x1/16".
2	1060	PP - No bulge.
3	1210[a]	PP - No bulge.
4	1190	CP - Pinhole, backed by support
5	1252[a]	PTP - 7/16"x3/8" BS.
	Cal. .50 APM2	
6	1480	PTP - 13/16"x5/8", 12"crack.
7	1480	PTP - 9/16"x5/8", plate broke into 2 pieces.

[a] ballistic limit 1231 f/s.

APPENDIX A

COPY

WAR DEPARTMENT
PITTSBURGH ORDNANCE DISTRICT
1202 CHAMBER OF COMMERCE BUILDING
PITTSBURGH, PA.

PIT. 248.8/592
Attn: of
Industrial Division
Engineering
Wtn 470.5/7267

16 July 1943

Knode/vlm

Subject: Experiments on Face-Hardened Armor at Pittsburgh Rolls Division, Blaw-Knox Company.

To: Office Chief of Ordnance
Pentagon Building
Washington, D. C.

Attn: S P O T R

1. For many years, the steel casting manufacturers in this district have been face hardening castings, particularly for rolls and surfaces which are subject to wear. This office has worked with the Pittsburgh Rolls Division of the Blaw-Knox Company to determine if this same principle could be applied to armor castings and thus improve the ballistic properties.

2. In order to determine the depth of penetration of the face-hardened surface, a standard ballistic test plate 36 x 36 x 1½" in thickness was cast as follows:

a. The mould was prepared in the usual manner except that the surface of that part of the mould corresponding to the face of the test plate which was to be hardened, was covered with a ¼" coating of a pastey mixture consisting of equal parts by volume of 20-mesh Ferro chrome, Ferro manganese and lamp black and a small amount of Ferro silicon to prevent blowing. These ingredients were mixed with linseed oil to a consistency of putty, and applied to the mould by the use of a trowel. The mould was then dried very slowly in an oven.

b. The casting was bottom poured in order that the metal would not wash the applied mixture from the sides of the mould. The metal was poured at 2875°F at which temperature it absorbed the metal in the applied coating. The casting was allowed to cool slowly in the sand.

c. This casting was made from a heat of metal which they used in the manufacture of their rolls, the chemical composition of which follows:

Analysis

Si	S	P	Mn	Tc	Ni	Cr	Mo	V
.22	.026	.043	.72	.54	---	.92	.48	.05

COPY

Subject: Experiments on Face Hardened Armor.
To: OCO - SPOTR 16 July 1943 Knode/vlm

d. After cooling in sand, the casting was heat treated in the following manner:

Heat to 1625°F - Hold 3 hours
Cool slowly to 1000°F
Heat to 1625°F - Hold 2 hours
Spray the alloyed face with water
Heat to 1050°F - Hold 2 hours
Furnace Cool

3. (a) It is to be emphasized that the casting of this test plate was done only to demonstrate the possibility of obtaining an alloyed surface in the initial casting which differs from the composition of the parent metal. No attempt has been made to determine the most suitable alloy for either the surface or the parent metal, nor what depth of penetration is most desirable. This casting was made from a heat of steel from the regular foundry practice and does not represent any steel which they would propose to use as a parent metal but was merely cast to determine the depth of the penetration that could be expected.

(b) It will be noted on Figure No. 1, that a hardness of over 600 Vickers, was obtained on the surface and extends to a depth of ¼", and then the hardness apparently graduates back to that of the parent structure. In this first trial, the thickness of the coating of ¼" gave a penetration of approximately ¼". This office believes that the same depth of penetration may be obtained if the thickness of the coating were reduced to approximately 1/8". Photomicrograph #1, #2, and #3 verify the results of the hardness values and show that a very hard surface is obtained. Chemical analysis of the hardened surface showed the following percentages of alloying elements: - Manganese 7.75%. Chromium 5.28%. Carbon 2.19%.

4. As a result of this preliminary investigation, it would appear to this office that castings can be made with a hardened surface. However, considerable more experimental work would have to be done in order to determine the proper analysis for the parent metal, the composition of the mixture to be applied to the mould, the thickness of coating and how it should be applied, and also the proper heat treatment that should be used for such casting.

It is suggested that his office give this suggestion serious consideration and advise this office of his recommendations concerning the composition of steel and heat treatment that should be used to obtain the most effective ballistic properties.

5. It is requested that his office arrange for a research and development contract to the Pittsburgh Rolls Division of Blaw-Knox Company to furnish castings as required in the development of a satisfactory armor plate by this method in accordance with a program to be outlined by his office.

Encl: 1 graph
3 Photomicrographs

F. B. BALL
District Chief

COPY

Wtn 470.5/7267
O.O. 470.5/14686
PIT 248.8/592
SPOTB

1st Ind.

Ballistic Steel and Welding Section, Special Service, Technical Division, 24 July 1943

To: Commanding Officer, Watertown Arsenal, Watertown, Mass., Attention: Laboratory.

1. It is requested that an opinion be rendered as to whether or not there is enough merit in the basic subject to make arrangements as requested in paragraph five.

2. Tc in the analysis means total carbon content. It is noted that the metal is drawn at nearly high enough temperature for armor and that casing is about the right percentage depth for case-hardened armor of about $1\frac{1}{2}$" in thickness.

3. Furthermore, it has been reported that a Bend test on the casing indicates toughness.

By order of the Chief of Ordnance:

(S/T)G. Elkins Knable
Colonel, Ord. Dept.
Assistant.

Encl: 1 graph
3 Photomicrographs.

COPY

Wtn. 470.5/7267
O.O. 470.5/14686
PIT 248.8/592 — 2nd Ind. — Matthews/amv

C.O., Watertown Arsenal, Watertown 72, Massachusetts, 30 July 1943.

To: Chief of Ordnance, U.S.A., Pentagon Building, Washington, D. C.
Attn: SPOTB

1. Reference process described in basic correspondence, and the request for an opinion as to the merit of the process as stated in paragraph 1 of the 1st Indorsement, the following comments are offered:

a. The process has interesting possibilities because it is apparently possible to treat the base metal to the optimum strength-ductility characteristics while at the same time retaining an extremely hard face.

b. It is considered that the case would be brittle under projectile impact and probably considerable face spalling and cracking in the face layer would occur. These tendencies could probably be minimized by adjusting the carbon content of the hardened layer to a value of approximately 1.00%.

c. Obviously, a casting produced by this process could not be welded from the face-hardened side.

d. Such castings could not be machined after final heat treatment; and if machining were performed before final heat treatment, subsequent distortion in the quenching and drawing operations would produce difficulties.

e. It is felt that such a process could undoubtedly increase the ballistic efficiency of cast armor but only at a sacrifice with respect to back spalling and cracking tendencies. It is further believed, however, that with the control of base metal properties that should be possible; it would be expected that improved ballistic limit characteristics could be obtained without jeopardizing shock and projectile-through-plate properties to a damaging extent.

2. It is suggested that two (2) sections of the cast 1½" plate 12" x12" in size be furnished this Arsenal for heat treating and metallurgical studies before additional experiments by the facility are conducted.

For the Commanding Officer:

H. H. ZORNIG,
Colonel, Ord. Dept.,
Assistant.

4 Incls.
Graph
3 Photomicrographs
4 Incls. w/d
Dup. Copy of Graph
Dup. Copies of 3 Photomicrographs

COPY

O.O. 470.5/14686
Wtn. 470.5/7267
PIT. 248.8/592
SPOTB 3rd Ind.

Ballistic Steel and Welding Section, Special Service, Technical Division, 3 August 1943

To: Pittsburgh Ordnance District 1202 Chamber of Commerce Building, Pittsburgh, Pennsylvania

1. It is requested that compliance with paragraph two of second indorsement be made by direct transmittal to Watertown Arsenal.

By order of the Chief of Ordnance:

(S/T) G. Elkins Knable
Colonel, Ord. Dept.
Assistant.

4 Incls. -
1 Graph
3 Photomicrographs

1 Incl. w/d
Dup. Copy of Graph
Dup. Copies of 3 Photomicrographs.

COPY

PIT No. 248.8/592
Industrial Div.
Engineering
O.O. 470.5/14686
Wtn. 470.5/7267
SPOTB

4th Ind.

Knode/WRJ/ma

Pittsburgh Ordnance District, 1202 Chamber of Commerce Building, Pittsburgh, (19) Pennsylvania. To: The Commanding Officer, Watertown Arsenal, Watertown, (72) Mass. 17 August 1943. Attn: Col. H. H. Zornig.

1. In response to action requested by his Arsenal in 2nd Indorsement to basic letter, and as directed to this office through 3rd Indorsement, a sample of cast armor face-hardened by subject process is being shipped, marked for attention of Colonel H. H. Zornig.

2. The section is 1½" thick, 36" x 18" in size, in the as-cast condition and of the following ladle analysis:

C.	S.	P.	Mn.	Si.	Ni.	Mo.	V.
.36	.021	.033	.66	.21	3.19	.44	.064

The alloy concentration in the surface layer was obtained by coating the mold according to the method given in the basic letter from this office date 16 July.

3. Since no appropriation has been made available for this project, the submitted sample was cast from steel which happened to be available at the foundry. It serves only to illustrate the metallurgical possibilities of the method, but is not necessarily possessed of potential ballistic qualities. Obviously, these can only be obtained by selection of the parent metal and by development of the process to produce a ballistically satisfactory surface.

4. The objections raised in comments (c), (d) and (e) of 2nd Ind. are not necessarily applicable to subject process. It should be understood that, by its very nature, the treatment may be selectively applied, omitting it from areas requiring machining or welding. It is also not obvious why the addition of the hardened surface should increase the tendency of the base metal to back-spall or crack beyond any tendency now existing, since no alteration of this underlying metal is contemplated.

5. It is suggested that the experience of his Arsenal be made available in stating specifications for further development of the process. The depth, hardness, and analysis of the "case" and the physical properties and composition of the parent metal, as might appear desirable upon the basis of previous experience, will aid in directing the continuing study of this office.

For the District Chief:

GEORGE H. KNODE
Major, Ord. Dept.
Assistant

Incls,-4

COPY

WAR DEPARTMENT
PITTSBURGH ORDNANCE DISTRICT
1202 CHAMBER OF COMMERCE BUILDING
PITTSBURGH, PA.

Knode/WRJ/ma

7 September 1943

PIT 248.8/718
Attn: of
Industrial Div.
Engineering

O.O. 470.5/14686
Wtn. 470.5/7267
SPOTB

Subject: Experiments on Face Hardened Armor at Pittsburgh Rolls Division of Blaw-Knox Company

To: The Commanding Officer
Watertown Arsenal
Watertown (72) Massachusetts

ATTN: Colonel H. H. Zornig

1. Reference is made to Paragraph 1 of 4th Indorsement dated 17 August 1943.

2. Sample of cast face-hardened armor is being shipped today as described therein.

For the District Chief:

(S/T)GEORGE H. KNODE
Major, Ord. Dept.
Assistant

COPY

WAR DEPARTMENT
Pittsburgh Ordnance District
1202 Chamber of Commerce Building
Pittsburgh 19, Pa.

Knode/WRJ/ma

20 October 1943

Wtn 470.5/7371
PIT 248.8/801
Attn: Ind. Div. - Eng.

Subject: Experiments on Face Hardened Armor at Pittsburgh Rolls Division of Blaw Knox Company

To: The Commanding Officer
Watertown Arsenal
Watertown (72) Massachusetts

Attn: Col. H. H. Zornig

1. Reference PIT 248.8/592 dated 7 September 1943 upon subject. This office desires information obtained from examination and test of cast armor sample submitted at that time.

2. Rolling experiments conducted by the facility have produced a plate 1/4-inch in thickness. A sample about 18 inches square is being shipped today, marked for his attention. This rolled specimen was prepared from a cast, face hardened plate produced at the same time and in the same manner as the previously submitted casting. No preparation preceded rolling other than heating to rolling temperature and no effort was made to straighten the rolled piece.

3. This office will be interested to learn the results of further tests as may be suggested by the potential ability of this product to be reduced in thickness by rolling without destroying the identity or adherence of the hardened surface.

For the District Chief:

(S/T) GEORGE H. KNODE
Major, Ord. Dept.
Assistant

COPY

Wtn 470.5/7371
PIT 248.8/801
Attn: Ind. Div., Eng. 1st Ind. Reed/NAM/amv

C.O., Army Service Forces, Ordnance Department, Watertown Arsenal, Watertown 72, Massachusetts, 19 November 1943.

To: District Chief, Pittsburgh Ordnance District, 1202 Chamber of Commerce Building, Pittsburgh, Pa. Attn: Industrial Div. - Engineering.

1. The face hardened cast plate which was submitted with letter file No. PIT 248.8/718, dated 7 September 1943, has been examined and the following preliminary report submitted:

a. The material is ballistically unsatisfactory as compared with homogeneous cast armor.

b. The carbon and alloy content of the face layer of the sample submitted is sufficient to produce a fairly stable austenitic alloy which cannot be transformed to martensite by various heat treatments.

c. Because of the retention of large amounts of austenite upon cooling from above the critical range, it was impossible to develop the desired high hardness in the face layer.

2. Considerable thought is being given to the idea of arriving at a suitable composition of the face and core which when heat treated will result in a martensitic case having a Brinell hardness of about 600 and a tempered martensitic core having a Brinell hardness of about 270. In this connection, tests are being made on several promising hard face compositions.

3. A report covering the tests of the cast plate and the ¼" rolled plate submitted with letter file No. PIT 248.8/801 is being prepared and will be forwarded to his office when completed.

For the Commanding Officer:

G. L. COX
Lt. Col., Ord. Dept.
Assistant.