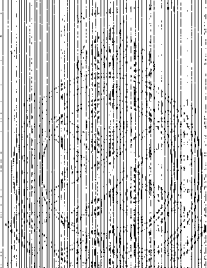


AD-A954 379



Report No. 710/497

ARMOR PLATE — CAST

Ballistic and Metallurgical Investigation
of S&W 1035 Experimental 1-3/4" Cast Armor

by

E. A. REED,
Research Metallurgist.

DTIC
ELECTE
DEC 19 1984
S
D

This document has been approved
for public release and sale; its
distribution is unlimited.

30 June 1943

WATERTOWN ARSENAL
WATERTOWN, MASS.

84 10 23 095

Handwritten: 14796

Handwritten: 1035

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

Report No. 710/497
Watertown Arsenal
Problem No. B-12

UNCLASSIFIED

30 June 1943

ARMOR PLATE — CAST

Ballistic and Metallurgical Investigation
of SAE 1035 Experimental 1-3/4" Cast Armor

↳ The OBJECT of this study

To determine the ballistic and metallurgical properties of two experimental heats of ~~SAE 1035~~ cast armor *steels for armor plate.*

CONCLUSIONS

1. Although the SAE 1035 cast steels investigated passed the resistance-to-penetration requirements as of Specification AXS-492-2, they failed with one exception to possess satisfactory ductility under the impact of 37 MM T.P. M51 projectiles.

2. The unsatisfactory shock resistance of SAE 1035 steels of this thickness is correlated with the poor metallurgical properties, namely, inadequate hardenability, unsatisfactory microstructure, and low V-notch Charpy impact resistance.

3. This SAE 1035 cast steel has a characteristic crystalline fracture which is associated with poor shock resistance.

4. With one exception, the central portions of the plates were fairly free from pronounced casting defects as revealed by macroscopic and radiographic examination.

E. L. Reed.
E. L. REED,
Research Metallurgist.

STIC
ELECTE
DEC 19 1984
D
A

APPROVED:

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

This document has been approved for public release and sale; its distribution is unlimited.

UNCLASSIFIED

RESTRICTED

UNCLASSIFIED

INTRODUCTION

In connection with a program on the conservation of alloys in cast armor initiated in February 1942 by the War Production Board, an investigation was conducted at Watertown Arsenal to determine the ballistic and metallurgical properties of SAE 1035 cast steel. This analysis is typical of Grade "B" cast steel¹ designated by the American Society for Testing Materials as A 27-42 which is used for railroad and high temperature applications.

Attention should be called to the fact that since this investigation was undertaken, it has been determined at this Arsenal² that good quality armor should possess adequate hardenability to quench out under the quenching conditions available. Hardenability studies made on SAE 1035 steel indicate that 1-3/4" castings of this type analysis have low hardenability and, therefore, cannot be quenched to the required initial hardness.

Two heats of SAE 1035 cast steel were made at Watertown Arsenal, two plates, 18"x18"x1-3/4", being vertically cast from each heat. The plates were cleaned, homogenized and quenched, two in water and two in brine, but not drawn.

The method of casting and details covering the heat treatment of the plates are given in Inclosure A.

The mold pattern for casting the 18"x18"x1-3/4" test plates is shown in Inclosure A - Figure 1.

TEST PROCEDURE

1. Ballistic Tests

Ballistic tests were conducted at Watertown Arsenal as follows:

a. First, an Army ballistic limit was obtained on each plate using the 37 MM A.P.C. M51 shot fired at normal from a 37 MM gun mounted in a 3" field piece. The ballistic limit was obtained in accordance with Specification AXS-492 Revision 2.

-
1. A.S.T.M. Part 1, Metals 1942, Page 260.
 2. Watertown Arsenal Report No. 710/500, May 17, 1943.

UNCLASSIFIED

b. Second, each plate was subjected to a shock test using one round of 37 MM T.P. M51 shot fired at normal.

2. Metallurgical Examination

After completion of the ballistic tests, the plates were sectioned for a metallurgical study which included the following tests: chemical analyses, macroscopic examination, microscopic examination, radiographic examination, Jominy hardenability tests, Brinell hardness tests and Rockwell "C" hardness surveys on cross sections of the plates.

In addition fracture tests were made on each plate. Sections approximately 1-3/4" square were cut through the thickness of the plates, nicked in the middle to a depth of approximately 1/4" and broken by a blow of a forge hammer.

Also three standard V-notch Charpy impact bars and two .357" diameter tensile bars were machined from each plate. These test bars were taken halfway between the surface and the center and parallel to the plate surfaces.

RESULTS AND DISCUSSION

1. Ballistic Tests

A summary of the ballistic tests is given in Table I. Photographs of the plates tested are shown in Figures 1-4 inclusive. Detailed firing records are contained in Appendix A.

The ballistic limits of the plates were between 62 and 115 feet per second in excess of the specified limits required in Specification AXS-492 Revision 2. On the other hand, with the exception of Plate 39, all plates were brittle under the normal impact of the 37 MM T.P. M51 projectiles.

The ballistic properties of the brine quenched plates were not superior to water quenched plates, see Table I.

TABLE I

Summary of Ballistic Tests

of SAE 1035 Experimental 1-3/4" Cast Armor

Size of Plates - 18"x18"

Plate No.	Thickness	Ballistic Properties		Brinell Hardness	Remarks
		B.L. f/s	Shock Test		
31 Water Quenched	1.75"	1588 (+88)*	Failed	212	Poor ductility under shock.
39 Water Quenched	1.75"	1605 (+105)	O.K.	229	Acceptable under shock test applied.
32 Brine Quenched	1.75"	1615 (+115)	Failed	217	Poor ductility under shock.
40 Brine Quenched	1.69"	1514 (+62)	Failed	217	Poor ductility under shock.

* Numbers in parentheses indicate feet per second in excess of Specification AXS-492 Revision 2.

** 37 MM T.P. M51 - Target practice, soft projectiles.



Accession For	
DTIC CARD	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	<input type="checkbox"/>
Distribution/	
Availability Codes	
Dist	Special
A1 23	

2. Metallurgical Examination

a. Chemical Analyses

The chemical analyses taken from test coupons cast from the two heats investigated are given in Table II.

TABLE II
Chemical Analyses

<u>Plate No.</u>	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>
31	.39	.88	.43	.022	.007
32	.39	.88	.43	.022	.007
39	.32	.88	.49	.019	.008
40	.32	.88	.49	.019	.008

These compositions are typical plain medium carbon steels which as stated in the introduction may be classified as Grade "B" carbon cast steel.

b. Macroscopic Examination

Macroscopic examination of the plates showed in all cases the absence of pronounced dendritic segregation, see Figure 5. Varying amounts of porosity were present in the center of the cross sections of the plates from very little in Plate 40 to considerable in Plate 39.

c. Microscopic Examination

Photomicrographs illustrating the typical microstructure of the water quenched and the brine quenched plates are shown in Figure 6. In all cases, as might be expected, pronounced grain boundary ferrite which was rejected during the quench surrounded grains of fine pearlite. This type of structure is generally associated with low hardenability of the steel and poor shock-resisting properties, as verified in the plates tested. A duplex grain size, A.S.T.M. No. 4 and 7, was evident in the plates containing a relatively high carbon content while a duplex grain size, A.S.T.M. No. 6 and 8, was present in the medium carbon plates, Nos. 39 and 40, see Figure 6.

d. Radiographic Examination

The results of the radiographic examination are given in Table III.

TABLE III

Radiographic Examination

Plate No.	Defects and Their Location		
	Gate End	Center of Casting	Riser End
31	Sound metal.	Scattered gas cavities.	Spongy metal gas cavities.
32	Few scattered gas cavities.	Extensive piping.	Spongy metal.
39	Gas cavities pipe system.	Short pipe systems.	Shrinkage cavity, gas cavities.
40	Short pipe systems.	Short pipe shrinkage cavity.	Extensive shrinkage cavity - gas cavities.

More pronounced piping was observed in the central portion of Plate No. 32 than in the same location in the other plates examined. The defects noted in the gate ends and riser ends of the castings do not extend appreciably into the central areas of the plates. The other defects noted in the center of plates Nos. 31, 39, and 40 were not extensive.

e. Jominy Hardenability Test

The results of the end quench hardenability tests which are shown in Figure 7 are summarized in Table IV below.

TABLE IV

End Quench Hardenability of SAE 1035 Cast Steel

Plate Nos.	C Content %	Grain Size ASTM	Jominy Hardenability Data				Hardness at 2½" from Quenched End Rc	Thickness of Plate Quenchable to 400 BHN in Center Inches
			Hardness 1/16" from Quenched End Rc	No. of 1/16ths of an Inch for a Drop				
				of 5 Rc	of 10 Rc	to 42 Rc 400 BHN		
31	.39	4-7	53	3.5	5.0	4.5	11	7/8
32								
39	.32	6-8	50.5	3.0	3.5	3.8	9.0	11/16
40								

The following Jominy¹ hardenability data on a production heat of low alloy Mn-Mo cast armor containing 0.29% C, 1.65% Mn, and 0.32% Mo is given for comparison with the above:

21	--	--	51.5	9	13	12	29.5	1.9
----	----	----	------	---	----	----	------	-----

The thickness of plate quenchable to 400 Brinell hardness was calculated according to recent investigations conducted by Battelle Memorial Institute³ and the Great Lakes Steel Corporation.⁴

The Jominy hardenability curves Nos. 31 and 39 are similar to those obtained on Plates Nos. 32 and 40 and, therefore, only these two curves are shown to illustrate the two heats investigated. The heat containing .39% carbon has a slightly higher hardenability as compared to the heat containing 0.32% carbon due to the relatively larger grain size of the former, see Figures 6 and 7.

The marked difference in hardenability of the SAE 1035 cast steel as compared to that of a low alloy production heat of cast armor is shown in Table IV.

f. Fracture Tests

The SAE 1035 steels investigated had a characteristic crystalline⁵ fracture. Crystalline fractures in armor are, according to recent investigations at Watertown Arsenal,² associated with a micro-structure containing ferrite rejected on the quench and with poor shock resisting properties. Good quality armor, on the other hand, has been shown to possess a fibrous⁶ fracture which is associated with a micro-structure consisting of spheroidized sorbite or tempered martensite and with resultant good shock resistance.

-
3. "Correlation of Cooling Velocity of the Standard Jominy Hardenability Test with the Cooling Velocity within the Cross Section of Plates" by John G. Kura and C. H. Lorig, Battelle Memorial Institute, Aug. 24, 1942.
 4. "Hardenability Comparisons" - Chart published by Great Lakes Steel Corporation, 1942.
 5. The crystalline fracture is characterized by a bright, silvery sheen caused by the reflections from flat crystalline facets. The crystalline structure may range from fine to coarse grained.
 6. The fibrous fracture is characterized by a nonreflecting, dark gray, pitted rough surface. In cast steel the dendritic structure is frequently revealed in a fibrous fracture.

g. Mechanical Tests

(1) Brinell Hardness Determinations and Rockwell Hardness Surveys

The results of the Brinell hardness determinations and Rockwell C hardness surveys are given in Table V.

TABLE V

Brinell Hardness and Rockwell C Hardness Surveys on the As-Quenched Test Plates

<u>Plate No.</u>	<u>Brinell Hardness Tests Made on Ground Surface</u>	<u>Average Rockwell C Hardness Surveys Made 1/16" apart on Cross Section</u>
31 Water Quenched	212	15.2
39 " "	229	13.3
32 Brine Quenched	217	17.0
40 " "	217	15.8

The low Brinell hardness determinations noted above confirm the results of the microscopic examination that plain medium carbon cast steel of this thickness cannot be quenched to a proper initial hardness.

(2) Tensile Tests and V-Notch Charpy Impact Tests

The results of the tensile tests and V-Notch Charpy impact tests are given below in Table VI.

TABLE VI

Physical Properties of SAE 1035 Cast Armor

<u>Plate No.</u>	<u>Yield Strength Lbs./Sq.In.</u>	<u>Tensile Strength Lbs./Sq. In.</u>	<u>% Elong.</u>	<u>% Red. Area</u>	<u>V-Notch* Charpy Ft./Lbs.</u>	<u>Brinell Hardness</u>
31 Water Quenched	81,000	107,100	17.9	41.4	28.3	212
39 Water Quenched	72,300	105,800	17.9	43.0	37.6	229
32 Brine Quenched	77,000	110,900	17.2	47.6	21.0	217
40 Brine Quenched	68,000	105,500	15.4	46.9	21.0	217

*V-Notch Charpy tests made at 78°F.

The quenched SAE 1035 steels have a fairly good combination of strength and ductility as noted in Table VI. No correlation can be made between the tensile and ballistic properties. On the other hand, a good relationship² has been established between the V-notch Charpy values of armor and its ballistic properties. These values given in Table VI are considered typical of poor quality armor, that is, containing ferrite on the quench and hence having poor shock properties. Recently it has been determined that good quality armor with a uniform microstructure of spheroidized sorbite had a V-notch Charpy value of approximately 75 foot pounds at these hardnesses.

GENERAL CONSIDERATIONS

The ballistic limits of the SAE 1035 cast steel were found to be satisfactory. In fact these limits obtained compared favorably with those of some of the low alloy armor now in production. These results⁷ were confirmed in the testing of several SAE 1035 rolled plate of approximately the same thickness.

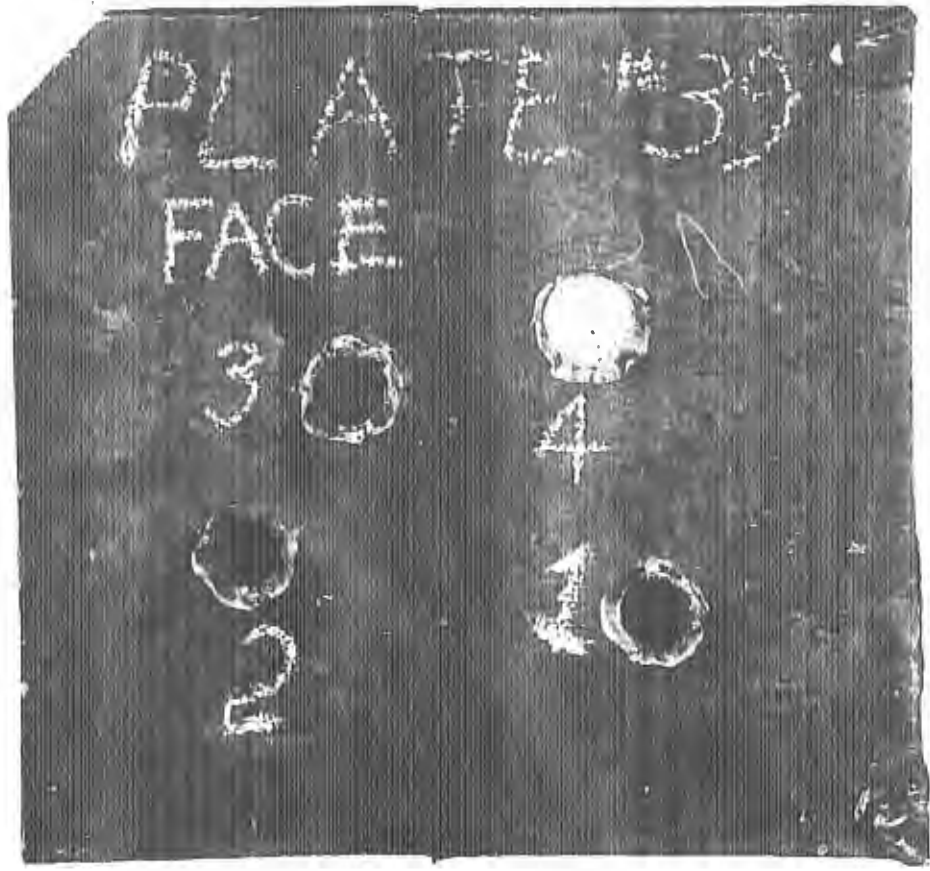
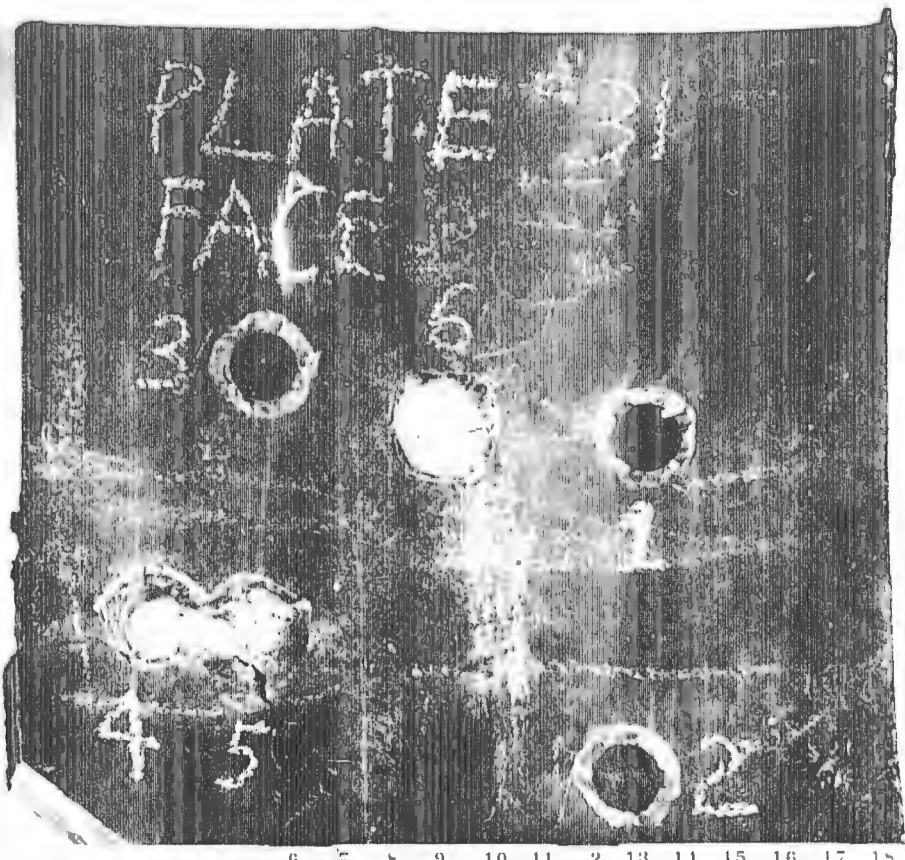
With the exception of one plate, the material was brittle under the impact of 37 MM T.P. M51 projectiles.

It is believed that stress relieving the quenched plates would not have promoted an increase in ductility under the shock test. In this connection, it has been determined that the ductility of SAE 1035 rolled plates of approximately the same thickness was not improved by stress relieving.

The SAE 1035 cast steel investigated has been found to have inadequate hardenability for good quality armor. A good correlation was obtained between unsatisfactory shock resistance of this steel and its poor metallurgical properties.

The metallographic work in this report was conducted by Miriam Yoffa.

7. A.P.G. Firing Record No. A5740, January 27, 1943.



WATERTOWN ARSENAL

SAE 1035 EXPERIMENTAL 1 3/4" CAST ARMOR PLATE WATER QUENCHED
 NO TEMPER. JAN 1 1943 WTN.710-1983

REPRODUCED AT GOVERNMENT EXPENSE

FIGURE 1



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

WATERTOWN ARSENAL

SAE 1035 EXPERIMENTAL 1 3/4" CAST ARMOR PLATE WATER QUENCHED
 NO TEMPER. JAN 1 1943 VTN.710-1984

REPRODUCED AT GOVERNMENT EXPENSE

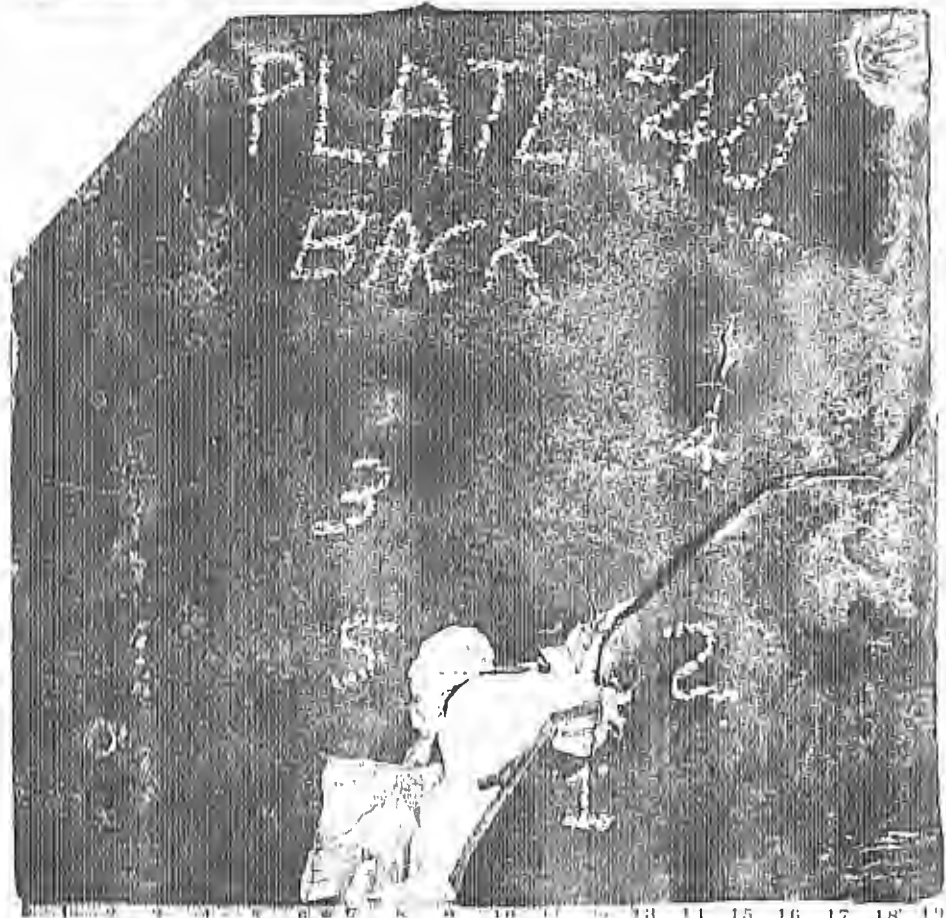
FIGURE 2



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

SAE 1035 EXPERIMENTAL 1 3/4 CAST ARMOR
 PLATE. BRINE QUENCHED - NO TEMPER
 JANUARY 9 1914
 REPRODUCED AT GOVERNMENT EXPENSE

FIGURE 3



SAE 1035 EXPERIMENTAL 1 3/4 CAST ARMOR
PLATE. BRINE QUENCHED - NO TEMPER
JANUARY 9 1943 WTN.710-1097

REPRODUCED AT GOVERNMENT EXPENSE

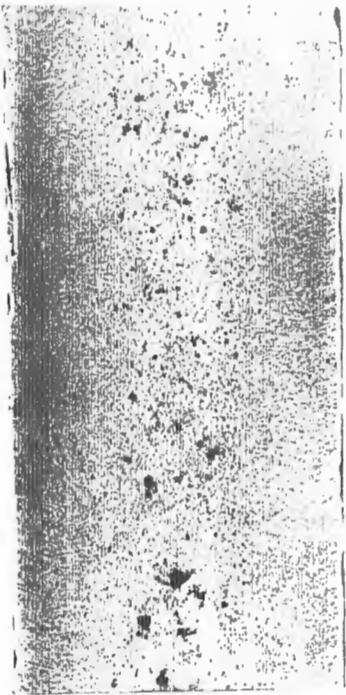


PLATE 39
WATER QUENCHED NO TEMPER

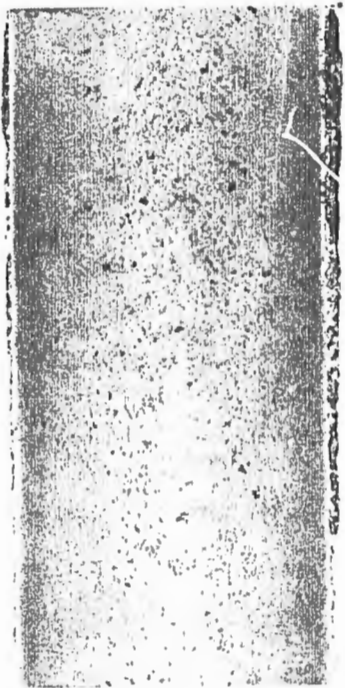


PLATE 31
WATER QUENCHED NO TEMPER

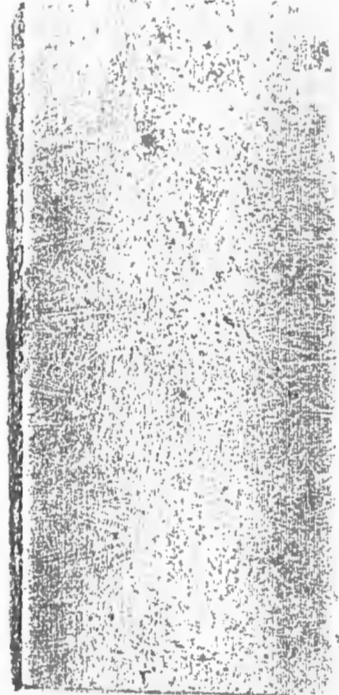


PLATE 40
BRINE QUENCHED NO TEMPER



PLATE 32
BRINE QUENCHED NO TEMPER

MACRO STRUCTURE OF SAE 1035 EXPERIMENTAL 1 3/4" CAST ARMOR PLATE
WTN.71C-2100

SAE 1035 Experimental 1-3/4" Cast Armor Plate

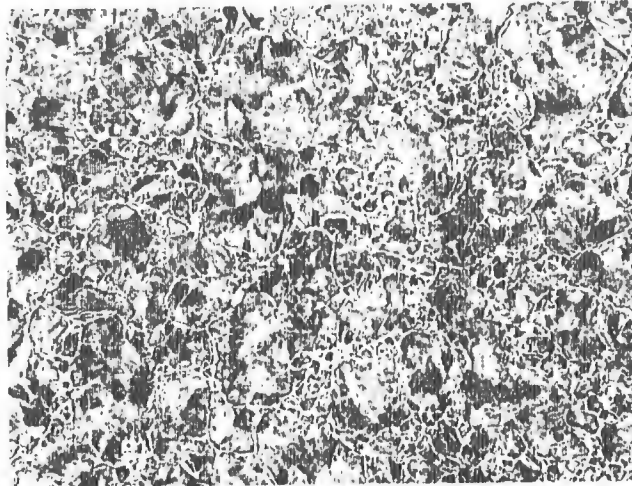


Plate 31 -A- X100
Duplex grain size - ASTM #4 and #7.

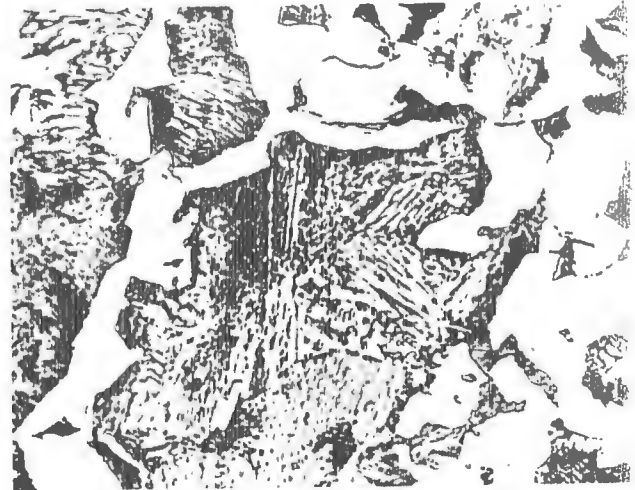


Plate 31 -B- X100
Ferrite and fine pearlite.

Water Quenched - No Draw

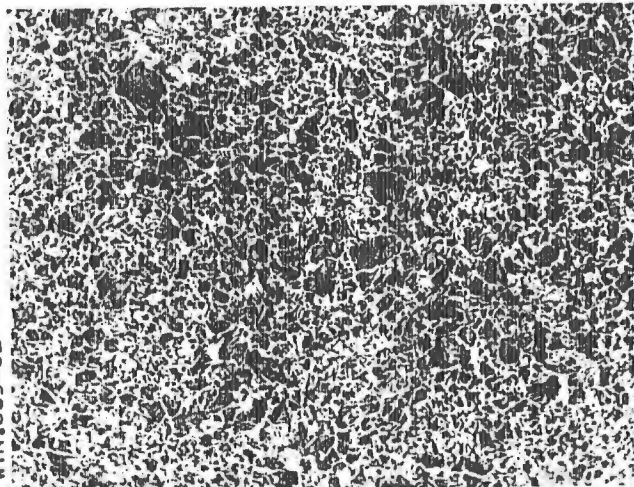


Plate 39 -C- X100
Duplex grain size - ASTM #6 and #8.



Plate 39 -D- X100
Ferrite and fine pearlite.

Brine Quenched - No Draw

MTN. 639-5244

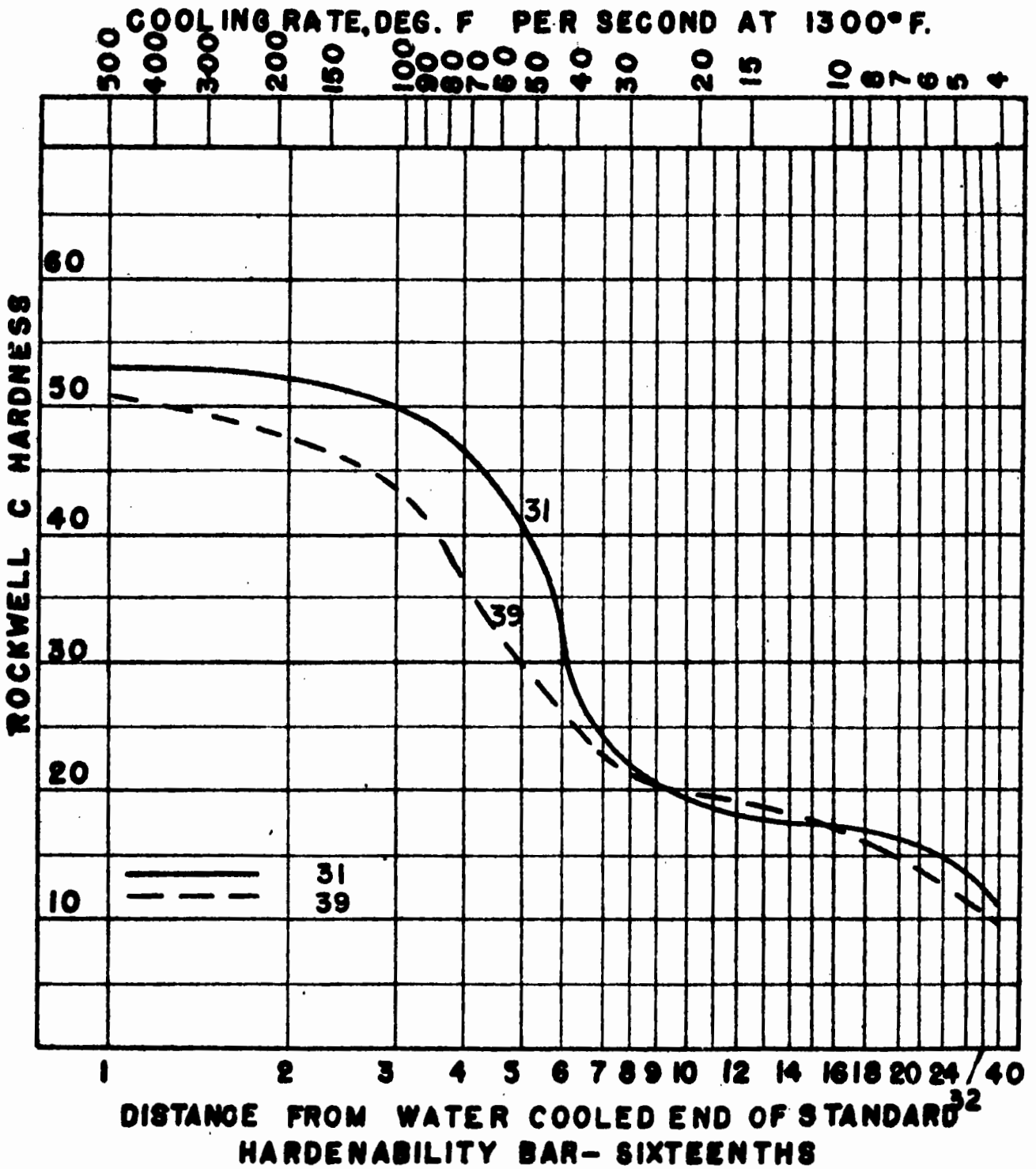


PLATE HEAT										QUENCH		
NO.	NO.	C	MN	SI	S	P	NI	CR	MO	TEMP	TIME	G.S.
31		.39	.88	.43	.022	.007				1625	2 HRS	4-7
39		.32	.88	.49	.019	.008				1625	2 "	6-8

FIGURE 7

INCLOSURE A

INCLOSURE A

Melting Procedure

Two heats of SAE 1035 steel were melted in an acid lined induction furnace and deoxidized with two pounds of aluminum per ton. The plates which were cast vertically from each heat were bottom poured. The position of the gate and risers is shown in Figure 1.

Preparation of Plates for Heat Treatment

When the plates reached a temperature, approximately 1000°F, they were removed from the mold and the gate and runners were torch cut from the plates.

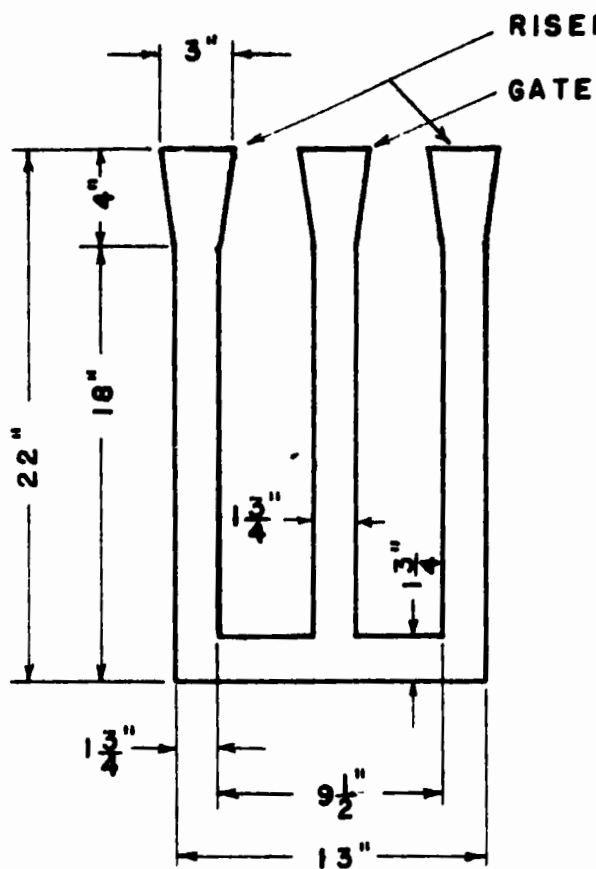
The castings were subsequently shot blasted and reheated to about 300°F at which time the risers were removed by flame cutting.

Homogenizing and Heat Treatment

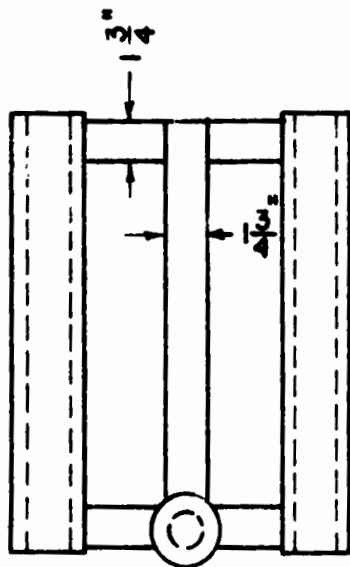
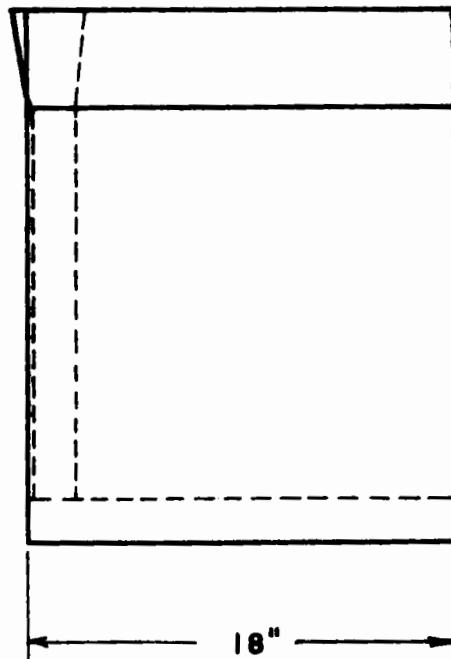
The homogenizing treatment consisted of heating to 1700°F for 6 hours and air cooling. All plates were shot blasted to remove excessive scale. The heat treatment of plates Nos. 31 and 39 consisted of heating to 1625°F for 6 hours and quenching in water followed by no draw.

Plates Nos. 32 and 40 were heated to 1625°F for 6 hours and quenched in 8% brine followed by no draw.

All plates were agitated during the quench.



RISERS
GATE



MOLD PATTERN FOR CASTING $18 \times 18 \times 1\frac{3}{4}$
TEST PLATE

APPENDIX A

BALLISTIC DATA SHEET NO. 1

Cast Plate No. 31 - 18x18x1-3/4"

Water Quenched - No Draw

<u>Plate</u> <u>Rd.</u> <u>No.</u>	<u>Powder</u> <u>Charge</u>	<u>Str.</u> <u>Vel.</u>	<u>Results</u>
<u>37 MM APC M51 Firings:</u>			
1	2.4 oz.	1550	PP, LB - Star cracks on bulge.
2	2.6 oz.	1608 ^a	CP - Pinhole 9" crack to edge of plate.
3	2.5 oz.	1568 ^a	PP, LB - Star cracks on bulge.
<u>37 MM TP M51 Firings:</u>			
4	6.25 oz.	2505	CP, PTP - 1½"x1½".
5	6.25 oz.	2520	CP, PTP - Struck Rd. 4.
6	6.25 oz.	2510	PP - Crack 21" across plate connecting Rounds 1, 4, 5, and 6.

^a.Ballistic limit - 1588 f/s.

BALLISTIC DATA SHEET NO. 2

Cast Plate No. 39 - 18x18x1-3/4"

Water Quenched - No Draw

<u>Plate</u>	<u>Rd.</u>	<u>Powder</u>	<u>Str.</u>	<u>Results</u>
<u>No.</u>	<u>Charge</u>	<u>Vel.</u>		
<u>37 MM APC M51 Firings:</u>				
1	2.6 oz.	1629	CP, 1/4" opening, star cracks 1-3/4".	
2	2.4 oz.	1541	PP, LB. Small star cracks.	
3	2.5 oz.	1580 ^a	PP, LB. Star cracks on bulge 2 1/2".	
<u>37 MM TP M51 Firings:</u>				
4	6.25oz.	2505	PP, LB. 1 1/2" cracks on bulge.	

^a. Ballistic limit - 1605 f/s.

BALLISTIC DATA SHEET NO. 3

Cast Plate No. 32 - 18x18x1-3/4"

Brine Quenched - No Draw

<u>Plate</u>	<u>Rd.</u>	<u>Powder</u>	<u>Str.</u>	<u>Results</u>
<u>No.</u>	<u>Charge</u>	<u>Vel.</u>		
<u>37 MM APC M51 Firings:</u>				
1	2.40 oz.	1544	PP, LB	- star cracks.
2	2.55 oz.	1590 ^a	PP, LB	- star cracks.
3	2.70 oz.	1640 ^a	CP,	small opening.
<u>37 MM TP M51 Firings:</u>				
4	6.40 oz.	2490	PP - LB.	Star cracks. 18" crack extending across plate, connecting Rounds 3 and 4.

^a. Ballistic limit - 1615 f/s.

BALLISTIC DATA SHEET NO. 4

Cast Plate No. 40 - 18x18x1-5/8"

Brine Quenched - No Draw

<u>Plate</u> <u>Rd.</u> <u>No.</u>	<u>Powder</u> <u>Charge</u>	<u>Str.</u> <u>Vel.</u>	<u>Results</u>
<u>37 MM APC M51 Firings:</u>			
1	2.65 oz.	1608	CP - 1/8" x 3/4" crack.
2	2.40 oz.	1560	Struck Round No. 1.
3	2.35 oz.	1503 ^a	PP, LB. No cracks.
4	2.45 oz.	1525 ^a	CP, pinhole. Cracking.
<u>37 MM TP M51 Firings:</u>			
5	6.8 oz.	2551	Plate shattered.

^aBallistic limit - 1514 f/s.