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Report No. OAL 710/258

ARMOR

Metallurgical Examination of Hull Bow Casting,  
Serial No. 134 for Medium Tank M4, Manufactured by  
American Steel Foundries

by

A. HURLICH  
Asst. Metallurgist

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20 September 1943

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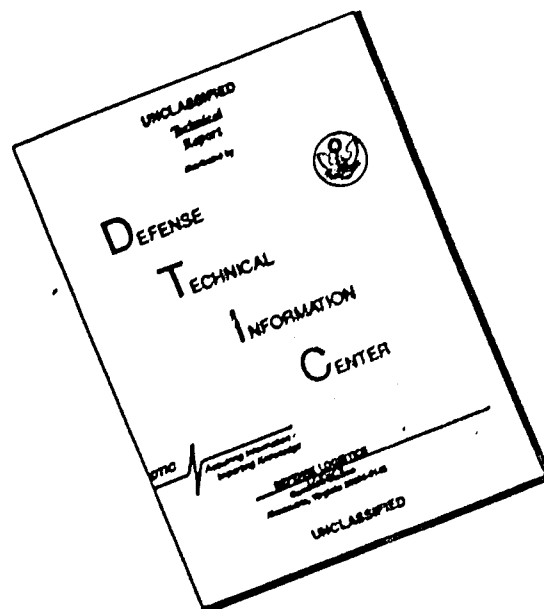
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Watertown Arsenal Laboratory  
Report No. 710/258  
Problem No. B-54

20 September 1943

## ARMOR

Metallurgical Examination of Hull Bow Casting,  
Serial No. 134 for Medium Tank M4, Manufactured by  
American Steel Foundries

## OBJECT

> To determine if the inferior ballistic properties of the <sup>casting</sup> ~~casting~~ are traceable to unsatisfactory metallurgical characteristics. *It was*

## CONCLUSIONS

- concluded that:*
- 1) The poor ballistic properties of the cast hull front section are ~~believed~~ due to a combination of low hardness and poor impact properties resulting from incomplete quench hardening.
  - 2) The incomplete quench hardening is traceable to the use of a steel of insufficient hardenability to adequately quench harden through the section thickness.
  3. The fracture test provides a definite indication of the degree of quench hardening of armor components.

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APPROVED:

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Director of Laboratory.

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## INTRODUCTION

In accordance with instructions from the Tank-Automotive Center,<sup>1</sup> three sections flame cut from a hull bow casting, serial No. 134, heat 1988, manufactured by the American Steel Foundries were forwarded to this Arsenal for metallurgical examination.

The subject casting was one of four experimental Medium Tank M4 hull front sections ballistically tested at The Proving Center, Aberdeen Proving Ground and reported upon in detail in Report No. AD-391.<sup>2</sup> The various hull front sections were fabricated by different procedures, two by welding together rolled armor components, one by welding together cast and rolled armor components, and one, the subject hull front section, was a single cast armor structure.

The ballistic tests showed that the cast section had a ballistic limit more than 400 ft/sec. lower than the rolled armor sections at approximately the same thickness and obliquity when impacted with 3" A.P.C. M62 projectiles, the thickness being 2" and the obliquity 57°. It was requested that this Arsenal conduct tests to determine if improper heat treatment was a factor in the generally poor ballistic performance of the hull bow casting.

## MATERIALS AND TEST PROCEDURE

### Armor Sections

The three flame-cut sections from the hull bow casting had stamped upon them the following numbers: Ht. 1988 Ser 134 DWG E6347, and were numbered at this Arsenal ASF1, ASF2, and ASF3 respectively.

Section ASF1 was 14"x10"x2.10" in size with a 5"x5" section cut out of one corner and a partial penetration at high obliquity of an armor piercing projectile parallel to the 10" dimension. Section ASF2 was 8"x13"x2.0" in size, with a complete penetration at high obliquity in the middle of the sample. Section ASF3 was 10"x14"x1.75" in size. It was impossible to determine in all cases precisely from which locations on the casting the samples were selected.

Sections ASF1 and ASF3 representing the thickest and thinnest portions of the casting available, were selected for metallurgical examination.

1. Teletype W.A. 472.81/27245, See Appendix A.
2. A.P.G. Report No. AD-391. "Comparative Test of Four Medium Tank M4 Hull Front Sections." February 7th to April 9th, 1943.

## Chemical Analysis

The chemical analysis of the casting was determined at this Arsenal.

## Hardenability

A standard Jominy bar was machined from one of the cast sections, and end-quenched according to the standard procedure after austenitizing for 2 hours at 1650°F.

## Hardness Surveys

Brinell hardness traverses were made along cross-sections of samples cut from sections ASF1 and ASF3.

## Fracture Test

Approximately three-inch wide specimens were cut from sections ASF1 and ASF3, notched, and fractured under the impact blow of a 1000-pound forge hammer. The fractures were examined and rated.

## Impact Tests

Standard V-notch Charpy impact bars were machined from section ASF1 and tested both at room temperature and at -40°C (-40°F). A 1"x4"x2.10" section of sample ASF1 was reheat-treated by fully quench hardening and tempering back to the original hardness of the material. V-notch Charpy impact bars were machined from the reheat-treated specimen and tested at room temperature and at -40°C. The fractures of the Charpy bars were examined and rated.

## Macrostructure

Samples of ASF1 and ASF3 were macroetched in a hot acid solution to determine the soundness of the material.

## Microscopic Examination

Specimens for microscopic examination were taken from sections ASF1, ASF3, and from ASF1 after reheat-treatment to determine the degree of quench hardening of the material.

## DATA AND DISCUSSION

### 1. Chemical Analysis

The chemical analysis of the hull bow casting is as follows:

	<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Cr</u>	<u>Mo</u>	<u>Cu</u>	<u>Al</u>
Reported by Mfr.	.275	1.49	.48	.019	.017	.38	.14	-	-
Watertown Arsenal	.28	1.58	.52	.022	.013	.38	.16	.16	.009

This analysis represents a very low alloy content when it is considered that it is used for castings having a thickness of up to 2.10".

## 2. Hardenability

The Jominy hardenability curve was determined from a test specimen cut from section ASF3 and is shown in Figure 1. The Jominy curve shows a hardness of Rockwell C 43 (400 BHN) at a distance of 6/16" from the water quenched end. According to data published in 1942 by the Great Lakes Steel Corporation,<sup>3</sup> steel having this hardenability can be adequately quench hardened in the form of plates having a maximum thickness of not over 1.2". Since the subject casting ranges from 1.75 to 2.10" in thickness, it can readily be seen that the steel possesses insufficient hardenability to completely quench harden. Complete quench hardening in this section size can be accomplished only by increasing the hardenability through the use of additional alloys or by the use of boron-containing "needling" agents.

## 3. Hardness Surveys

Brinell hardness traverses made across the thicknesses of samples ASF1 and ASF3 gave the following results:

<u>Section Number</u>	<u>Brinell Hardness</u>
ASF1	235, 235, 235
ASF3	235, 229, 235

A hardness of 235 Brinell is on the low side for 1-3/4 to 2" thick cast armor. Well heat treated cast armor of adequate hardenability 2" in thickness has been produced which possesses an excellent combination of resistance to penetration and to shock impact at a hardness of 280 Brinell.

## 4. Fracture Tests

The fractures resulting from impact breaks of samples from ASF1 and ASF3 are rated as follows:

- 
3. "Properties and Characteristics of N-A-I 9100 Series" - Publication of the Great Lakes Steel Corporation

ASF1 (2.10" thick) - Mixed fracture, approximately half crystalline and half fibrous.

ASF3 (1.75" thick) - Mixed fracture, crystalline patches in a largely fibrous matrix.

The fractures indicate that the steel had not been fully quench hardened, but it is considered that the degree of quench hardening obtained is excellent considering the inherent low hardenability of the steel.

### 5. Impact Tests

Standard V-notch Charpy impact bars taken from section ASF1 in the as-received condition gave the following results:

<u>Temperature</u>		<u>Impact Strength</u>	<u>Fracture Rating</u>
<u>°C</u>	<u>°F</u>	<u>Ft. Lbs.</u>	
+21	+70	44.9	Half fibrous, half crystalline
+21	+70	47.8	Half fibrous, half crystalline
-40	-40	20.8	Completely crystalline
-40	-40	14.0	Completely crystalline

An average V-notch Charpy impact value of 46.4 ft.lbs. for cast steel at a hardness of 235 BHN is approximately 15-20 ft.lbs. lower than that generally obtained with well heat-treated material. The great decrease in impact strength at reduced temperatures is typical of incompletely quench hardened materials.<sup>4</sup>

A 4"x2"x1" thick section of sample ASF1 was reheat-treated as follows:

<u>Temperature</u>	<u>Time at Temp.</u>	<u>Coolant</u>	<u>Brinell Hardness</u>
1600°F	2 hrs.	Water	444
1175°F	2 hrs.	Air	262
1225°F	2 hrs.	Air	229

It is noteworthy that the manufacturer of the casting tempered the material at 1090°F to produce a hardness of 235 BHN whereas, at this Arsenal, a small section, completely quenched out, required a temperature of 1225°F (135°F higher) to produce approximately the same hardness.

Standard V-notch Charpy impact bars were machined from the reheat-treated section and the results follow:

4. W.A. Report 710/532 "Armor, Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels Upon Quenching", A. Hurlich.

Temperature		Impact Strength	Fracture Rating
$^{\circ}\text{C}$	$^{\circ}\text{F}$	Ft. Lbs.	
+21	+70	56.0	Fibrous
+21	+70	73.4	Fibrous
-40	-40	53.1	Mixed, crystalline patches in fibrous matrix.
-40	-40	49.1	Mixed, crystalline patches in fibrous matrix.

The room temperature impact strength of the reheat-treated material in the fully tempered martensitic condition now averages 64.7 ft.lbs., an increase of almost 20 ft.lbs. over the material in the as-received condition. The fact that satisfactory impact properties are maintained down to  $-40^{\circ}\text{C}$  indicates that the steel had been well quench hardened and that the inherent quality of the steel is satisfactory.

Referring to A.P.G. Report No. AD-391, it is noted that the rolled armor components of the experimental hull front sections varied in hardness from 250 to 293 Brinell, which is considerably harder than the subject casting, namely 235 Brinell. It is believed that if cast armor is completely quench hardened it can be tempered back to higher hardnesses and still have good impact strength and satisfactory shock resistance and, at the same time, will have better resistance to penetration than incompletely quench hardened material at lower hardness levels. This is probably particularly true of high obliquity conditions wherein the penetration is invariably effected by the formation of a punching. It has been shown<sup>5</sup> that the resistance to the punching type of failure will decrease with increasing hardness. On the other hand, the effect of increased hardness is to increase the deflection of the projectile from its incident angle, producing longer, more shallow scooped out penetrations. The increase in the resistance to penetration produced by the latter effect may more than overcome the adverse effect of the decrease in the resistance to punching, and the net result may be an increase in the resistance to complete penetration resulting from an increase in hardness.

It is believed that the inferior ballistic properties of the cast hull section are the result of a combination of its low hardness in conjunction with the poor impact properties resulting from incomplete quench hardening. The utilization of a steel of sufficient hardenability combined with good heat treating procedure will allow the use of higher hardnesses and should materially improve the ballistic properties of the hull front section.

5. W.A. Report No. 710/492 "Mechanism of Armor Penetration - Second Partial Report". C. Zener and R. E. Peterson.



## 6. Macrostructure

Photographs of the hot acid etched sections of ASF1 and ASF3 are shown in Figure 2. Section ASF1 contains a considerable amount of shrinkage porosity while section ASF3 appears materially superior.

## 7. Microscopic Examination

Microscopic examination of sections ASF1 and ASF3 showed both to possess the same microstructure. The steel evidences considerable dendritic segregation with large amounts of rejected ferrite in the dendritic axes, see Figure 3A. Ferrite and pearlite have been rejected at elevated temperatures resulting from the hardenability being insufficient to prevent transformation from occurring at 1000-1200°F, see Figures 3B and C.

After reheat-treatment, section ASF1 has a homogeneous microstructure of tempered martensite with no high temperature transformation products present, see Figures 3D and E.

## SUMMARY

Insufficient hardenability to completely quench harden through the section was found responsible for the poor metallurgical characteristics of the cast hull front section. The comparatively low resistance to ballistic impact resulted from a combination of low hardness and poor impact properties. The use of a steel of higher hardenability is clearly indicated for this application.

Ballistic tests have shown that at high obliquities, hardness assumes a very important role. Relatively small increases in hardness produce a correspondingly large increase in resistance to ballistic impact of armor piercing projectiles at high obliquities. The fact that the subject casting at a hardness of 235 Brinell had a resistance to impact 400 ft./sec. lower than the rolled armor structures at 250-290 Brinell at an obliquity of 57° is largely traceable to the differences in hardness.

APPENDIX A

Correspondence

C O P Y

TELETYPE

TAC CENTER ENGR DEV BR DE113 MAY 5-43 2202Z ML

WATERTOWN ARSENAL

SPECIAL

WATERTOWN ARSENAL

SPECIMENS OF HULL BOW CASTINGS MANUFACTURED BY AMERICAN STEEL FOUNDRIES  
ARE BEING SENT TO YOUR STATION FROM A.P.G. FOR FRACTURE TESTS, HARDNESS  
TRAVERSE, MACROETCH, AND, IF THE HARDNESS TRAVERSE AND PHOTOMICROGRAPHS  
SHOW INSUFFICIENT QUENCH, FOR REQUENCH OF THE PIECES. END. IN REPLY  
CITE SPOME-EP WBREED/TT8477

CUMMINGS

TANK AUTOMOTIVE CENTER

FISHER BLDG.

W.A. 472.81/27245

C O P Y

COOLING RATE, DEG. F PER SECOND AT 1300°F.

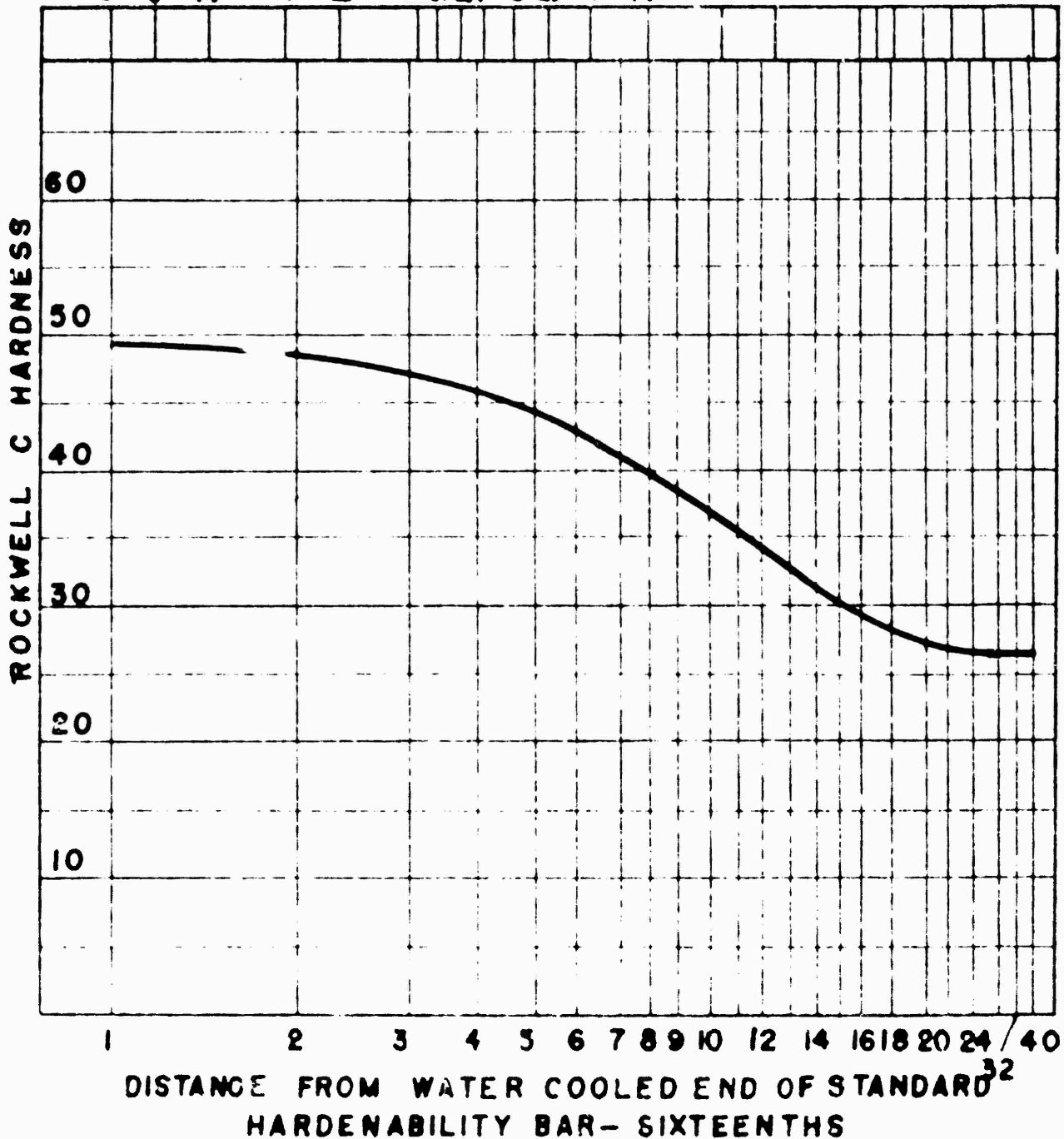
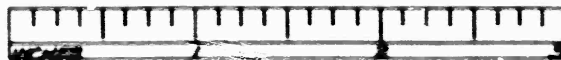


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	CU	AL	QUENCH TEMP OF	TIME HRS	G.S.
ASF3		.28	1.58	.52	.022	.013	-	.38	.16	.16	.009	1650	2	
AMERICAN STEEL FOUNDRIES										HULL CASTING # 134.				
HEAT 1988										DING. E 6347.				
JCMIXY HARDENABILITY CURVE										AH 9/17/43				

FIGURE 1



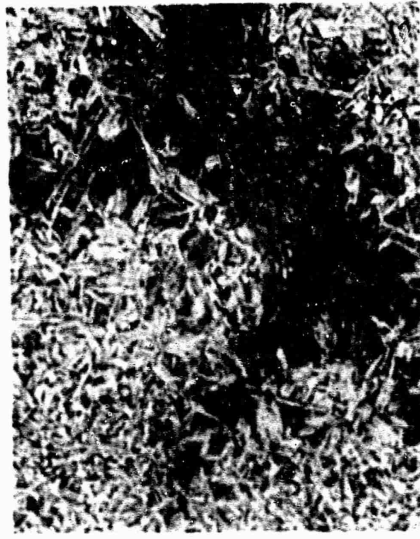
ORDNANCE DEPT U.S.A.  
MEYERTOWN ARSENAL

MACROETCHED SECTIONS OF AMERICAN STEEL FOUNDRIES HULL BOW CASTING HEAT 1980  
SER. NO. 134 DWG. E6347 ASFI-2.10" THICK SECTION ASF3-1.75" THICK SECTION  
WTN. 710-2130

FIGURE 2

American Steel Foundries - Hull Casting #134.

Nital-Picral Etch



-A- X200  
Section ASF1. As received. Dendritic segregation with rejected ferrite in dendrite axes.



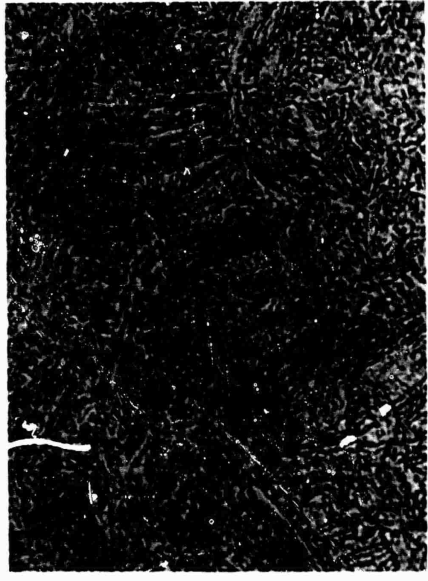
-B- X1000  
Section ASF1. As received. Outer third of section. Incompletely quenched hardened. Rejected ferrite and pearlite.



-C- X1000  
Section ASF1. As received. Middle of section. Rejected ferrite and pearlite.



-D- X200  
Section ASF1. Reheat-treated. Homogeneous structure.



-E- X1000  
Section ASF1. Reheat-treated. Tempered martensite. No rejected ferrite or pearlite.