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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/762

Metallurgical Examination of 2-1/2" to 6" Rolled Homogeneous Armor Manufactured by Great Lakes Steel Corp. and Heat Treated by Standard Steel Spring Co.

BY

M. Bolotsky
Asst. Metallurgist

DATE 25 June 1945

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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT NO. WAL 710/762

Final Report on Problem B-4.71

25 June 1945

Metallurgical Examination of 2½" to 6" Rolled Homogeneous Armor Manufactured by Great Lakes Steel Corp. and Heat Treated by Standard Steel Spring Co.

Abstract

Metallurgical examination, including fracture tests, Brinell hardness surveys, chemical analysis, macroscopic examination, and microscopic examination, was made on sections from 2½", 3", 4", and 6" thick ballistic test plates that had been made from the same heat and had been submitted jointly by Standard Steel Spring Company and Great Lakes Steel Corporation to Aberdeen Proving Ground for experimental and acceptance ballistic tests. The extensive spalling revealed by the ballistic tests was found to have been caused by extremely poor steel soundness. Because of the numerous laminations present in the fractures, the impact toughness of the plates could not be determined accurately. However, fractures of the 4" and 6" plates showed much crystallinity, and each plate, except the 3" plate, was revealed by Brinell hardness surveys and microscopic examination to have been incompletely quench hardened. Grain sizes were coarse (ASTM No. 2 to 4). When evaluating the ballistic limits of at least the 4" and 6" plates, their poor impact toughness as well as their poor steel soundness should be considered.

1. As requested by the Office of the Chief of Ordnance-Detroit[1], and by the Ordnance Research Center, Aberdeen[2,3], metallurgical examination has been completed on samples from four (4) rolled homogeneous plates, 2½", 3" 4" and 6" in thickness, manufactured by Great Lakes Steel Corporation and

1. Wtn. 470.5/151, OOM. 470.5/Watertown Ars.(29 Jan.'45) dated 29 Jan. 1945.
2. Wtn. 470.5/187, APG. 470.5/1358, dated 28 March 1945.
3. Wtn. 400.112/3866, APG. 470.5/1478, dated 24 April 1945.

heat-treated by Standard Steel Spring Company. This report presents the complete results of the examination. Preliminary results for the 2½" and 3" plates have been already submitted by indorsement[4].

2. The plates had all been fabricated from the same heat of steel (listed as No. 12-16953 by the Great Lakes Steel Corporation and as No. G5002 by the Ordnance Research Center, Aberdeen) and had been submitted to Aberdeen Proving Ground for acceptance and experimental ballistic tests. Results of the 45° obliquity tests and the 90 mm. AP M77 PTP tests indicated back spalling for the 2½" and the 3" plates. Back spalls resulted from complete penetrations (Navy or protection) during the tests of the 4" and 6" plates with the 155 mm. AP M112 projectile at 30° obliquity. Back spalling was further revealed by the PTP test (75 mm. AP M72 projectile at 0° obliquity) of the 4" plate and by the resistance to penetration test (90 mm. AP T33 projectile at 0° obliquity) of the 6" plate. The ballistic data are given in more detail in Appendix 1.

3. Metallurgical examination[5] consisted of the following tests:

a. Fracture tests for steel soundness and fibre characteristics.

b. Brinell hardness surveys.

c. Chemical analysis.

d. Macroscopic examination.

e. Microscopic examination.

4. The results of the above tests in detail are presented below:

a. Fracture tests for steel soundness and fibre characteristics. Fracture tests were conducted upon each Aberdeen sample, after notching in perpendicularly to the long dimension, and then upon one half of each fractured sample, after notching in parallel to the long dimension of the original Aberdeen sample. Fracture blocks of the 2½" and 3" were broken under a steam forging hammer and fracture blocks of the 4" and 6" plates were broken under a steam forging press. Fractures were rated for both steel soundness and fibre characteristics. Results of the tests are shown in Table I. Photographs of the fractures of the 2½" and 6" plates are shown in Figures 1 and 2.

Steel soundness of all the plates was revealed by the fractures to be extremely poor. Such poor quality steel has not been encountered by this arsenal since the early days of the application of the fracture test. The extensive spalling occurring during the ballistic tests was undoubtedly caused by this condition.

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4. Wtn. 470.5/187, APG 470.5/1358, 1st Ind., dated 28 April 1945.
5. Each sample had been removed as close to the center of the plate as possible. Samples from the 2½" and 3" plates were 9"x13". Samples from the 4" and 6" plates were 12"x20".

Because of the deep and numerous shelves in the fractures, it was not possible to accurately evaluate the fibre characteristics of the plates. Laminations tend to prevent a material of poor impact toughness from breaking brittlely, and, therefore, when a fibrous or partially crystalline fracture contains one or more deep laminations, the possibility always exists that the fracture might have contained more crystallinity had the steel been of good quality. Nevertheless, much crystallinity appeared in some of the fractures of the 4" and 6" plates, indicating that the impact toughness of these plates is indeed poor. It is apparent that had laminations not been present, their fractures would have been entirely crystalline. The fractures of the 2½" and 3" plates presented a fibrous appearance (except for the effect of the brightly shiny shelving surfaces), but in view of the steel soundness, the fibre characteristics of these plates must be considered indeterminate. When evaluating the ballistic limits of at least the 4" and 6" plates, their poor impact toughness as well as their poor steel soundness should be considered.

Because of the effect of laminations upon the fibre rating of a fracture, V-notch tests could not be performed. Hence it was not possible, first, to learn the extent and variation of impact toughness within the sections and, second, to determine the factors responsible for the lack of good toughness in the 4" and 6" plates (and in the other plates also if this were the case).

b. Brinell hardness surveys. On carefully ground cross sections, Brinell hardness surveys were made in duplicate for each plate. The surveys, shown in Table II, reveal that hardness was significantly lower at the center than at the surface in the case of the 2½", 4", and 6" plates. This means that these plates had been incompletely quench hardened.

c. Chemical analysis. Chemical analysis was made of only the 2½" plate. The Watertown Arsenal determination and the heat analysis reported by Great Lakes Steel Corporation are given below.

	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	Al	B	Zr	Ti
Watertown	.28	1.94	.43	.017	.024	.17	.80	.52	tr	.055	.01	.0009	.11	tr
Great Lakes	.29	1.98	.45	.019	.019		.72	.56					.06	

d. Macroscopic examination. Cross sectional samples in both rolling directions were cut from each plate, surface ground, and then hot acid etched. Macrostructures correlated excellently with the fractures, as many inclusion stringers were evident throughout the section of each sample. Stringers were much longer in the longitudinal direction than in the transverse direction in the 2½" and 3" plates, indicating (as did the fractures) that these plates had been rolled predominantly in one direction. The macrostructures of the 4" and 6" plates showed that these plates had been well cross rolled.

e. Microscopic examination. Photomicrographs illustrating the inclusions and microstructures at the centers of the sections are shown in Figure 3.

Figure 3A illustrates the typical stringers composed of oxide inclusions that were detected in varying amounts in the microspecimens of all of the plates. Figure 3B shows a severe condition detected in the 4" plate microspecimen and which is undoubtedly also present in the other plates (judging from the fractures and macrostructure) but did not happen to occur in the particular microspecimens examined.

Ferritic non-martensitic transformation products were found in all of the plates in varying amounts at the centers of the sections. Microstructure of the 2½" plate showed a substantial amount of these products (Figure 3C) while that of the 3" plate had the appearance of being largely tempered martensite. Microstructures of the 4" and 6" plates (Figures 3D and 3E) consisted almost entirely of these products. If it can be assumed that the plates had been quenched efficiently, then microscopic examination indicates that this heat of steel is unsuitable for proper quench hardening of heavy armor.

Grain sizes were coarse, being as follows: 2½" plate, No. 3-4; 3" plate, No. 4; 4" plate, No. 2; and 6" plate, No. 2.

5. The results of the investigation can be summarized as follows:

a. Steel soundness of all plates was extremely poor and the ballistic test back spalling is attributed to this cause.

b. Impact toughness of at least the 4" and 6" plates is quite poor. Because of the laminated condition of the plates, this physical property could not be accurately determined. Poor impact toughness should be taken into account when reviewing the ballistic limits of at least the 4" and 6" plates.

c. At least the 2½", 4", and 6" plates had been incompletely quench hardened, but whether this or temper brittleness or both of these factors caused the brittle behavior of the 4" and 6" plates could not be determined because V-notch Charpy tests cannot be conducted upon steel which is badly laminated. Grain sizes were coarse and ranged from 4 to 2.

6. It is apparent from the investigation that the data derived from ballistic tests conducted upon this heat of steel cannot be considered the performance of normal heavy rolled homogeneous plate. Had proper fracture tests been conducted prior to the initiation of the firing programs, then judgment would have dictated that the ballistic tests be cancelled and the heat scrapped. The quality of the steel is "E" and, therefore, rejectable according to the proposed draft of rolled homogeneous armor, 4 to 12 inches in thickness, dated 24 April 1945.

M. Bolotsky

M. Bolotsky
Asst. Metallurgist

APPROVED:

E. L. Reed

E. L. REED
Research Metallurgist
Chief, Armor Section

TABLE I

Results of Fracture Tests

Plate	Direction of Fracture*	Steel Soundness**	Fibre Characteristics
2½" Plate No. 1M1	Longitudinal	E - Pronounced shelving throughout the section.	Indeterminate because of laminations - No crystallinity revealed.
	Transverse	E - Deep pronounced shelving throughout the section.	Same as above.
3" Plate No. 2T1	Longitudinal	E - Pronounced shelving throughout the section.	Same as above.
	Transverse	E - Deep pronounced shelving throughout the section.	Same as above.
4" Plate No. 3B1	90° to long dimension of Aberdeen sample.	Indeterminate because of crystallinity - Laminations present adjacent to surfaces.	Crystalline in most of the section.
	Parallel to long dimension of Aberdeen sample.	E - Pronounced shelving throughout the section.	Indeterminate because of laminations - 25% scattered crystallinity throughout the section.
6" Plate No. 5T1	90° to long dimension of Aberdeen sample.	E - Deep pronounced shelving throughout the section.	Indeterminate because of laminations - 50% crystallinity revealed.
	Parallel to long dimension of Aberdeen sample.	E - Deep pronounced shelving throughout the section.	Indeterminate because of laminations.

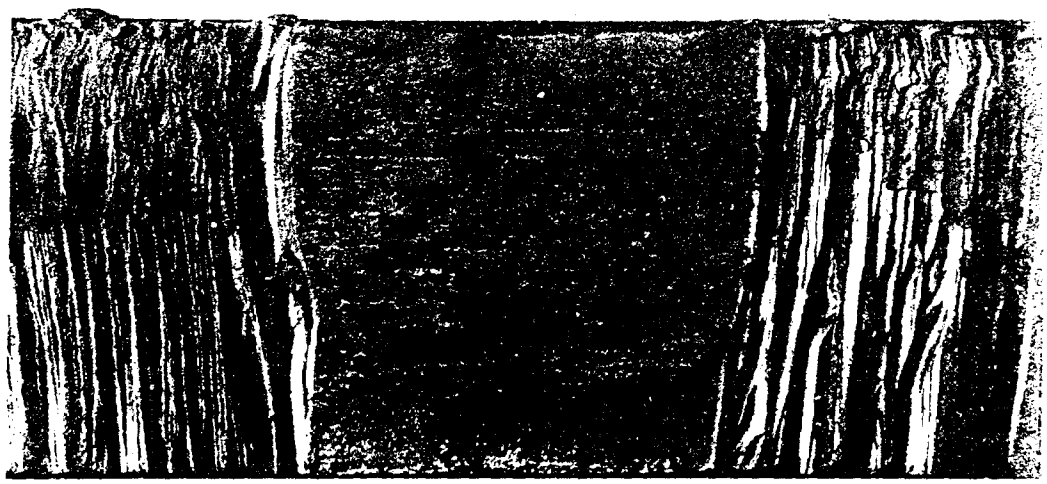
*The fractures indicate that the 2½" and 3" had been rolled essentially in one direction whereas the 4" and 6" plates had been well cross rolled.

**The surfaces of the laminations in all the fractures of the four plates were shiny.

TABLE II

Brinell Hardness Surveys Across the Sections

2½" Plate, No. 1M1		3" Plate, No. 2T1		4" Plate, No. 3B1		6" Plate, No. 5T1	
1	2	1	2	1	2	1	2
285	285	285	285	262	262	293	293
269	277	293	285	248	248	285	285
255	262	285	285	235	235	285	285
277	269	293	293	255	255	262	262
285	285	285	285	262	262	285	285
						302	302
Range, 255-285 Average, 275		Range, 285-293 Average, 287		Range, 235-262 Average, 252		Range, 262-302 Average, 283	



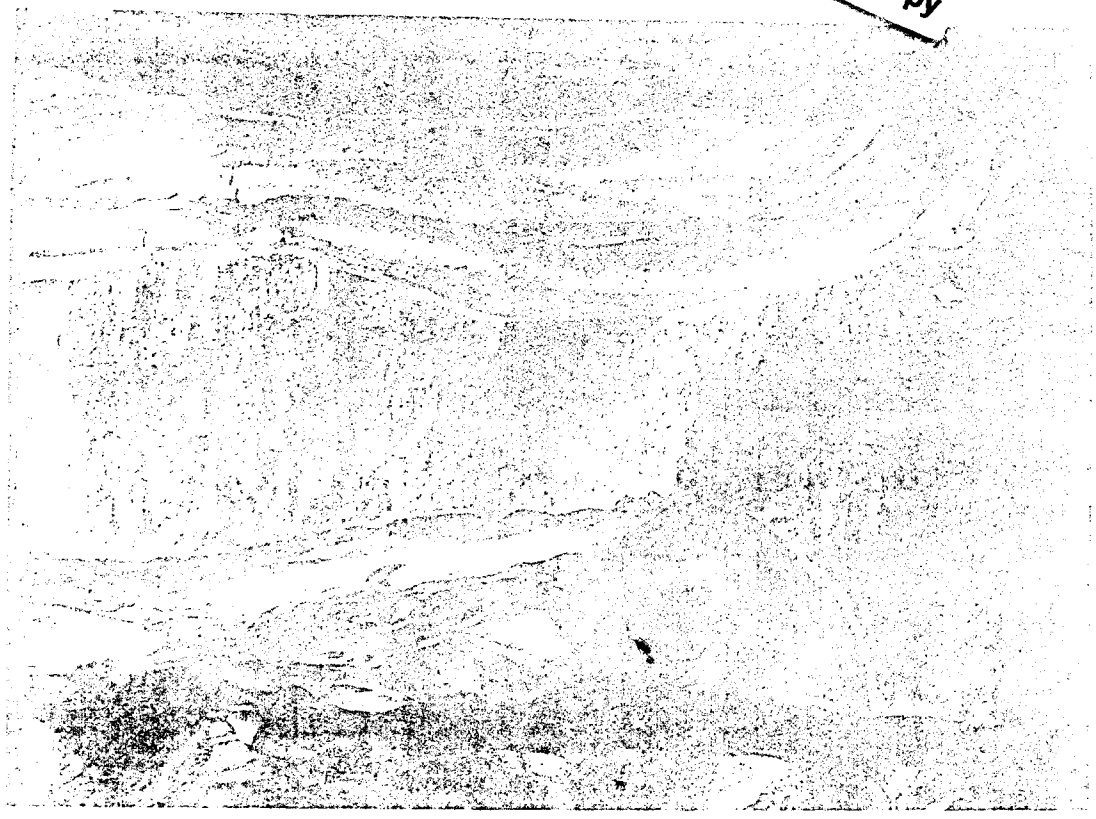
LONGITUDINAL

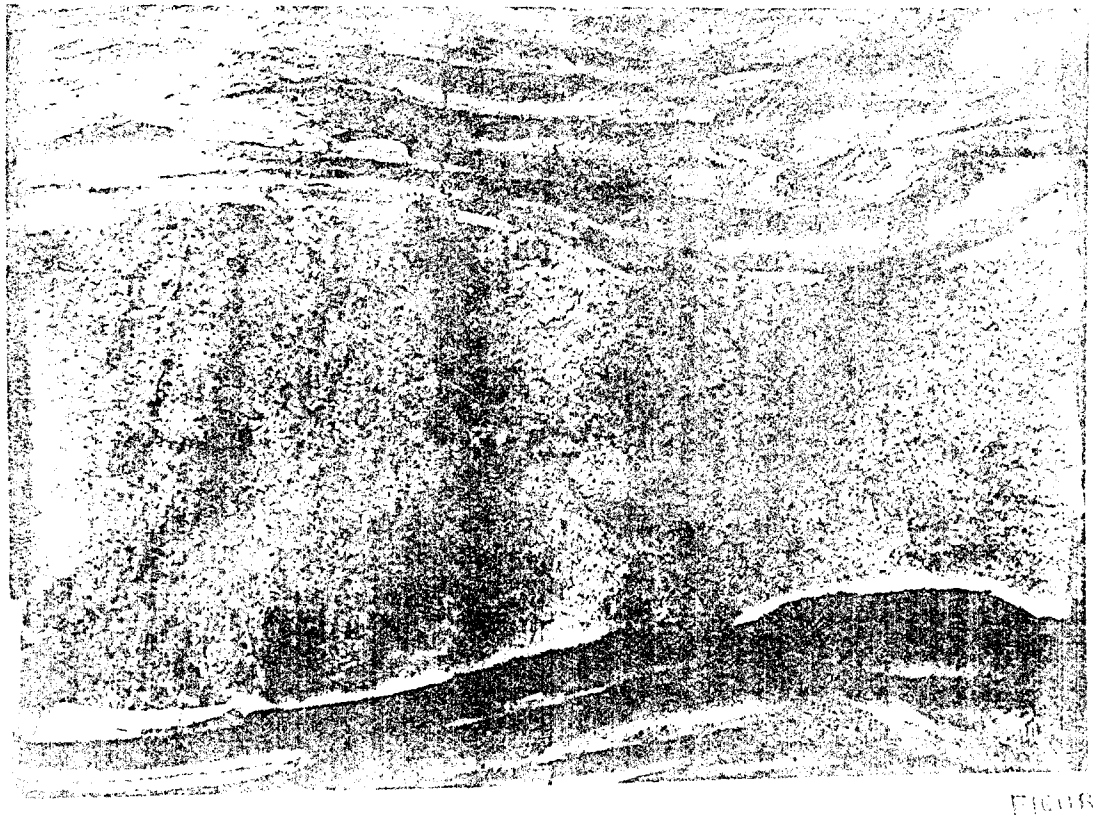
TRANSVERSE

WATERTOWN ARSENAL

FRACTURES OF HEAVY ROLLED HOMOGENEOUS PLATE MANUFACTURED BY GREAT LAKES STEEL CORPORATION AND HEAT TREATED BY STANDARD STEEL SPRING COMPANY. 2½" THICK PLATE NO. 1M1, HEAT NO. G5002. 7 APR 1945 WTN.710-237

FIGURE 1





Results of the Microscopic Examination

All Photographs Taken at Centers of the Sections

2½" Plate -A- Unetched
Typical stringers of oxide inclusions found in varying amounts in all the plates.

4" Plate -B- Unetched
Severe condition detected in this plate.

2½" Plate -C- Picral
Tempered martensite plus tempered non-martensitic transformation products. Grain size No. 3-4.

4" Plate -D- Picral
Predominantly ferritic tempered non-martensitic transformation products. Grain size No. 2.

6" Plate -E- Picral
Predominantly ferritic tempered non-martensitic transformation products. Grain size No. 2.

FIGURE 3

APPENDIX A

Ballistic Data

BALLISTIC DATA

1. 2½" Thick Plate No. 1M1, Heat No. G5002 (Data from Wtn. 470.5/187, APG 470.5/1358, dated 28 March 1945)

This plate was tested as follows:

3" APC M62 projectiles at 45° obliquity.
57 mm. AP M70 projectiles at 0° obliquity.
90 mm. AP M77 projectiles at 0° obliquity.

The results of the 45° oblique test and the 90 mm. AP M77 PTP test indicated large back spalling.

2. 3" Thick Plate No. 2T1, Heat No. G5002 (Data from Wtn. 470.5/187, APG 470.5/1358, dated 28 March 1945)

This plate was tested as follows:

90 mm. APC M82 projectiles at 45° obliquity.
90 mm. AP M77 projectiles at 0° obliquity.
57 mm. AP M70 projectiles at 0° obliquity.

The results of the 45° oblique test and the 90 mm. AP M77 PTP test indicated large back spalling.

3. 4" Thick Plate No. 3B1, Heat No. G5002 (Data from APG Report No. Ar-16232)

This plate was given the tests outlined in Spec. AXS-488-1 and Tent. Spec. AXS-488-3, as follows:

Ballistic Limit Tests			PTP Test
155 mm. AP M112 at 30°			
Velocity	Back of Plate	75 mm. AP M72 at 0°	75 mm. AP M72 at 0°, 2000 f/s
1239 f/s, PP(A)	11" crack punch. st.	No spalling from any impact.	E.D. is 7x8" w/bs.
1281 f/s, CP(N)	11½"x14½" w/bs.		
1309 f/s, CP(N)	11"x11½" w/bs.		
B.L. (P&N) is 1260 f/s.		B.L. (A) is 1691 f/s.	

Note: The plate appeared to be crystalline.

4. 6" Thick Plate No. 5T1, Heat No. G5002 (Data from APG Report No. Ar-16232)

This plate was given development tests, as follows:

Ballistic Limit Tests

155 mm. AP M112 at 30°		90 mm. AP T33 at 0°	
Velocity	Back of Plate	Velocity	Back of Plate
2054f/s, CP(A)	Punch. st.	Partial Penetrations	No spalling.
2085f/s, CP(P)	22"x25" w/bs.	2001 f/s, CP(P)	E.D. 9"x10" w/bs.
B. L. (P) is 2070 f/s.		2191 f/s, CP(N)	E.D. 9½"x9½" w/bs.
		B.L. (A&P) is 1995 f/s.	

Note: A companion plate, No. 5B1, broke in two at 2026f/s, CP(N). Both plates appeared to be crystalline.