WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/691

Metallurgical Examination of Samples of

2-1/4" Thick Rolled Homogeneous Armor Manufactured by

Carnegie-Illinois Steel Corporation

BY

E. L. REED
Research Metallurgist

DATE 30 August 1944

WATERTOWN ARSENAL
WATERTOWN, MASS.

[redacted]

WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT NO. WAL 710/691

Final Report on Problem B-4.45

30 August 1944

Metallurgical Examination of Samples of 2-1/4" Thick Rolled Homogeneous Armor Manufactured by Carnegie-Illinois Steel Corporation

ABSTRACT

Nine samples of 2-1/4" thick Carnegie-Illinois rolled homogeneous armor tested as a part of the effect of hardness program were subjected to a metallurgical examination including fracture tests, hardness surveys, macroscopic and microscopic examination, hardenability tests and chemical analysis.

With the exception of three plates which showed evidence of pronounced segregation in the fractures, transverse to the major direction of rolling, the balance of the samples were of satisfactory steel soundness. A good correlation was established between the fracture test for steel soundness and the macrostructure and nonmetallic inclusion content. All samples were satisfactorily heat treated, resulting in fibrous fractures and uniform hardnesses across the sections. The hardenability of the samples was adequate for the thickness involved.

1. As requested by the Ordnance Research Center, Aberdeen[1], metallurgical examination has been completed on nine (9) samples of 2-1/4" thick rolled homogeneous armor plate manufactured by Carnegie-Illinois Steel Corporation. Details of the samples submitted for examination are given below.

a. Size of samples 2-1/4" x 10" x 24".

b. Identification of samples -
Nos. 1A, 2, 2A, 3A, 4, 4A, 5, 5A, 6A.
(Note: Sample A, referred to in paragraph 2 of reference noted below, was marked No. 2.)

1. APG 470.5/149 - Wtn 470.5/15 dated 8 July 1944.

[redacted]

2. Metallurgical examination consisted of the following tests:

a. Chemical analyses.

b. Fracture tests for steel soundness and fibre characteristics.

c. Hardness surveys.

d. Macroscopic examination.

e. Microscopic examination.

f. Jominy hardenability tests.

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

a. Chemical Analyses. The drillings for chemical analyses were taken in a standard manner by drilling halfway through the section. The variations in chemical analysis among the several plates is interesting since it was known that all samples were from the same heat of steel (G-83355). It will be observed upon referring to Table I, that with respect to alloying elements, the individual analyses check very closely. However, large differences exist with respect to carbon and boron contents. The variation in boron content is not surprising since the percentage recovered is known to decrease in the metal poured towards the latter part of the heat when the boron is added in certain forms. The carbon variation (amounting to .06%) appears to be high among nine random samples tested.

b. Fracture Tests. The results of the fracture tests for steel soundness and fibre characteristics are given in Table II. Pronounced laminations were evident in the transverse fractures of sample Nos. 2, 2A and 4. The steel soundness was satisfactory in the remainder of the plates examined. All samples exhibited a fibrous fracture when subjected to the standard test.

c. Brinell Hardness Tests. Brinell hardness tests were made on carefully ground surfaces and cross sections. The values reported are the average of four impressions on the surface and eight impressions on the cross sections. The results are reported in Table III. Each individual plate was heat treated to a uniform hardness across the section.

d. Macrostructure. The macrostructure of the longitudinal and transverse sections after acid etching is shown in Figures 1 and 2.

Samples Nos. 1A, 3A, 5 and 6A are relatively free from segregation while samples Nos. 2, 2A, 4, 4A and 5A show the presence of varying amounts of segregation in the central area of the cross section of the plates. Generally speaking, the samples which showed the most intense segregation by the macro etch test exhibited a "D" fracture in the section, transverse to the major rolling direction.

e. Microstructure. The distribution of nonmetallic inclusions and the typical microstructures of the samples are shown in Figures 3 and 4. The two main types of nonmetallic inclusions found in the samples consisted of manganese sulphides and alumina stringers. A few scattered, fine, short manganese sulphides were present in the good quality plates Nos. 1A, 3A, 4A, 5 and 5A. Some fine alumina stringers were also found in plate No. 5A. The poorer quality plates Nos. 2 and 4 contained segregations of elongated manganese sulphide inclusions and also plate No. 2A of inferior quality contained stringers of alumina, Figure 3. Sample No. 6A which was of satisfactory quality as revealed by the fracture test but showed evidence of woodiness in the fracture contained fine manganese sulphides throughout the section. Undoubtedly, the presence of these fine elongated nonmetallic inclusions in these samples is correlated with the "woody"[1] appearance noted in the fractures, see Table II. The microstructure of all plates was characteristic of that of tempered martensite. Carbide particle size was sufficiently large to be capable of resolution at 1000X in the case of plates tempered to the lower hardnesses.

Note: Photomicrographic work was conducted by M. Yoffa.

f. Jominy Hardenability Data. Jominy hardenability tests were made on specimens cut from the nine plates. Each Jominy bar was ground to a depth of .050" previous to making Rockwell C hardness tests and microscopic examination. The results are plotted in figures 5, 6 and 7 and summarized in Table IV. A survey of the Jominy hardenability curves shows that the hardness of samples Nos. 1A, 2, 2A, 3A, 4, 4A and 6A decreased fairly gradually from the quenched end of the bar. Microscopic examination of these bars indicated that the distances from the quenched end at which the structure was 90% martensitic (balance intermediate temperature transformation products) varied from 26-40 sixteenths. In samples Nos. 5 and 5A, however, an abrupt drop in the Jominy hardness curves occurred at 16 and 22 sixteenths respectively from the quenched end. This was associated with the fact that these samples had lower hardenability characteristics than the other plates. It was noted that martensite persisted from the quenched end of these two Jominy bars to a distance 16-17 sixteenths of an inch. The balance of the structure consisted of intermediate temperature transformation products.

There was some degree of scatter noted in the Jominy curves shown in Figures 5, 6 and 7 but this is to be expected because of alloy and carbon segregation in the plane on which hardness readings were made.

1. "Study of "Woody" Fractures in Rolled Armor Plate" - WAL Rpt. No. 710/664, dated 19 June 1944.

The results of these tests indicate that the type of composition investigated has sufficient hardenability for the thickness of plate in question.

4. The results of the metallurgical examination indicate that, with the exception of plates Nos. 2, 2A and 4 which showed pronounced segregation in the transverse direction, the balance of the plates may be considered satisfactory with respect to steel soundness. Satisfactory correlations were established between fracture tests for steel soundness and macroscopic and microscopic examination. Fibrous fractures were obtained in these samples which varied in average cross sectional Brinell hardness from 228 to 298.

E. L. Reed.

E. L. REED
Research Metallurgist

APPROVED:

N. A. Matthews

N. A. MATTHEWS
Major, Ord. Dept.
Chief, Armor Section

TABLE I

Plate No.	Chemical Composition												
	C	Mn	Si	S	P	Ni	Cr	Mo	V	B	Ti	Cu	Al
1A	.34	1.26	.21	.023	.018	.84	.80	.39	nil	.001	trace	.105	.03
2	.33	1.28	.22	.028	.020	.84	.82	.40	"	.0025	"	.10	.03
2A	.35	1.26	.21	.028	.017	.85	.80	.39	"	.0027	"	.10	.03
3A	.34	1.25	.21	.025	.020	.86	.81	.39	"	.0020	"	.10	.02
4	.33	1.26	.20	.023	.022	.81	.81	.39	"	.0019	"	.105	.03
4A	.35	1.25	.23	.024	.021	.84	.82	.39	"	.0025	"	.105	.02
5	.33	1.21	.22	.020	.017	.81	.81	.40	"	.001	"	.105	.03
5A	.29	1.21	.23	.021	.016	.77	.78	.40	"	.001	"	.105	.03
6A	.28	1.26	.21	.026	.019	.85	.82	.40	"	.001	"	.105	.02

TABLE II

Fracture Tests

(Rated in accordance with Specification AXS-488 evision 2.)

Plate No.	Steel Soundness *Longitudinal Fracture	Steel Soundness *Transverse Fracture	Fibre Fracture Test
1A	B	B	Fibrous
2	C (woody)	D	Fibrous
3A	B (trace) (woodiness)	D	Fibrous
3A	B	B	Fibrous
4	C (woody)	D	Fibrous
4A	B (trace) (woodiness)	C	Fibrous
5	B	B	Fibrous
5A	B	C	Fibrous
6A	B (trace) (woodiness)	B	Fibrous

*Longitudinal fractures - parallel to major direction of rolling.

*Transverse fractures - perpendicular to major direction of rolling.

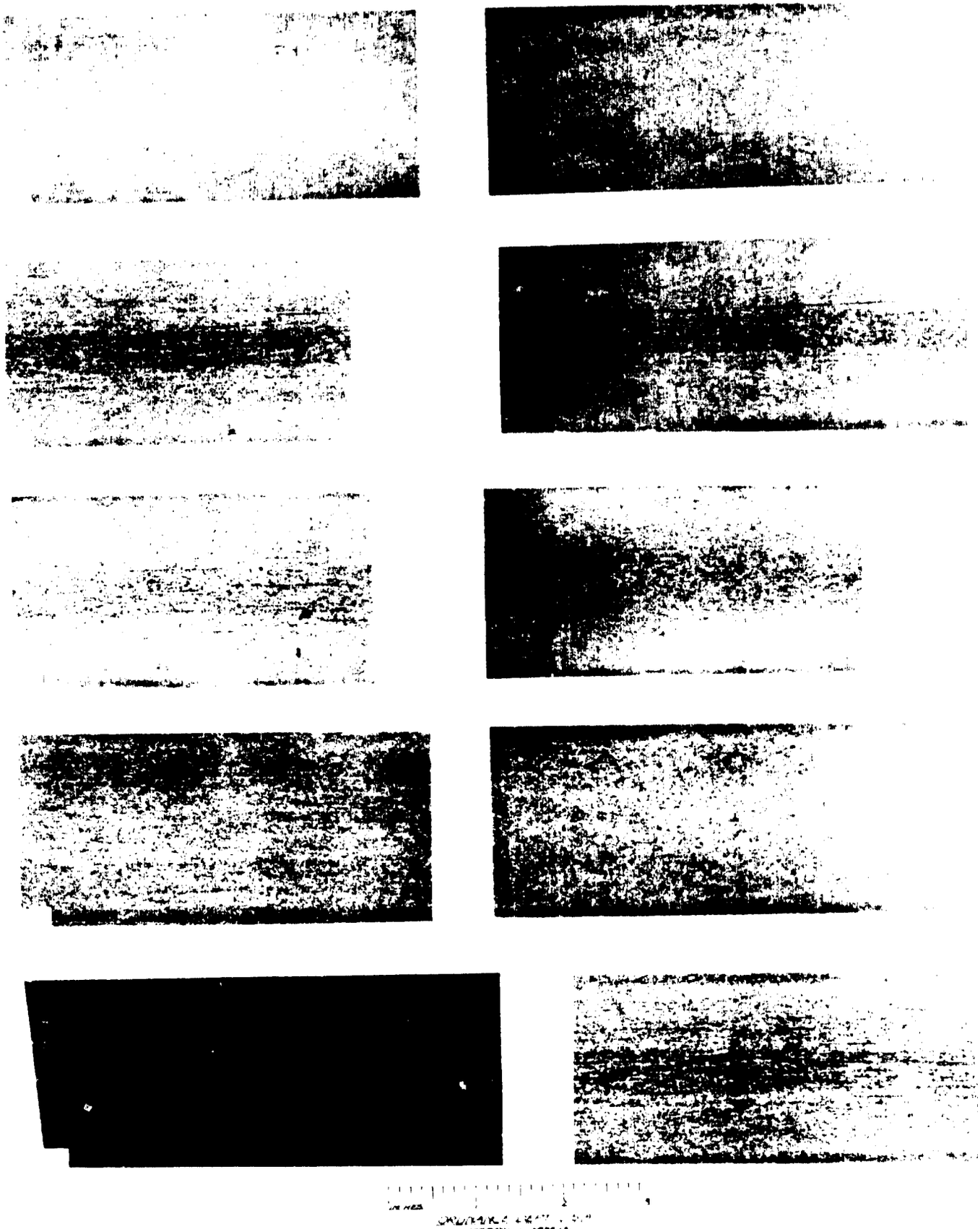
TABLE III

Brinell Hardness Tests

Sample No.	Cross Section		Surface	
	Range	Average	Range	Average
1A	293-302	298	293-293	293
2	285-293	290	277-285	279
2A	272-285	282	285-285	285
3A	262-277	271	269-269	269
4	248-262	254	248-248	248
4A	248-255	251	241-241	241
5	235-248	241	248-248	248
5A	229-248	237	248-248	248
6A	223-229	226	229-229	229

LONGITUDINAL

TRANSVERSE

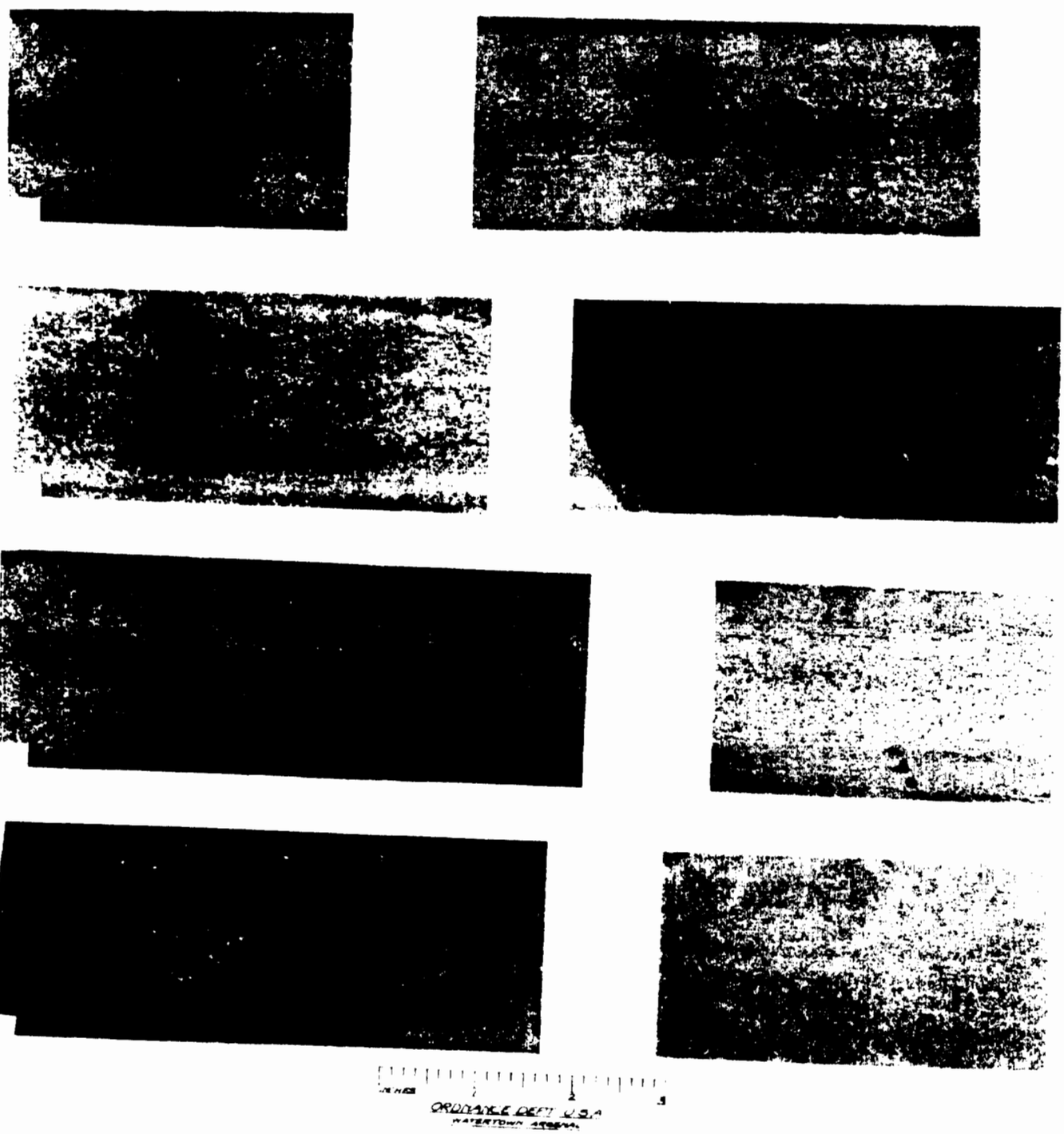


MACROSTRUCTURE OF 2 ½" THICK ROLLED CARNEGIE ILLINOIS ARMOR PLATE
11 AUGUST 1944
WTN. 710-2425

FIGURE 1

LONGITUDINAL

TRANSVERSE



MACROSTRUCTURE OF 2 $\frac{1}{4}$" THICK ROLLED CARNEGIE ILLINOIS ARMOR PLATE
11 AUGUST 1944
WTN. 710-2426

FIGURE 2

Nonmetallic Inclusions in 2-1/4" Thick
Rolled Homogeneous Carnegie-Illinois Armor Plate

No. 1A
Few scattered fine short manganese-sulphide inclusions. Typical of sample Nos. 3A, 4A, 5, and 5A.

No. 2A
Occasional alumina streak found in center of section.

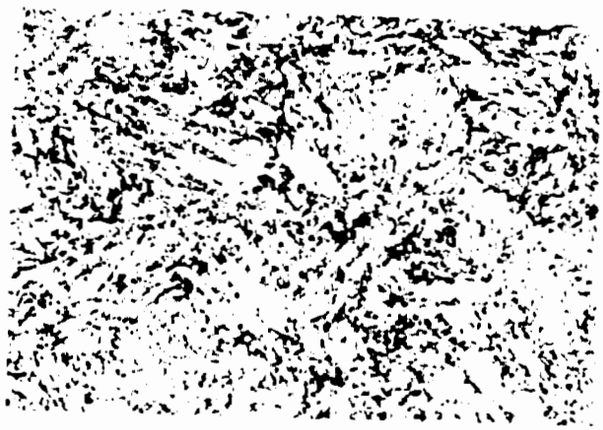
No. 4
Segregation of fine elongated manganese-sulphide inclusions in center of section. Typical of sample No. 2.

No. 6A
Typical group of fine short manganese-sulphide inclusions present throughout section.

Photomicrographs taken at X1000. Samples unetched.

FIGURE 3

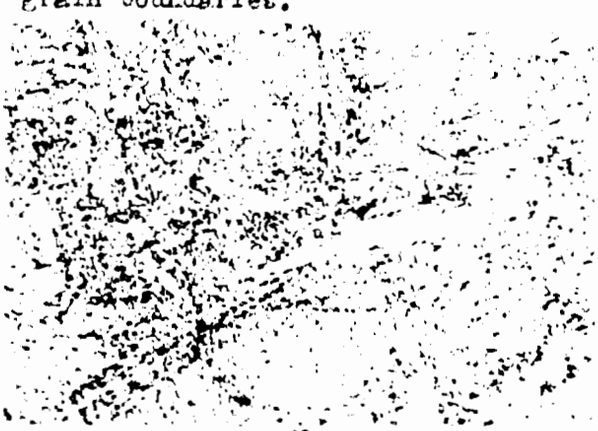
Microstructure of 2-1/4" Thick
Rolled Homogeneous Carnegie-Illinois Armor Plates



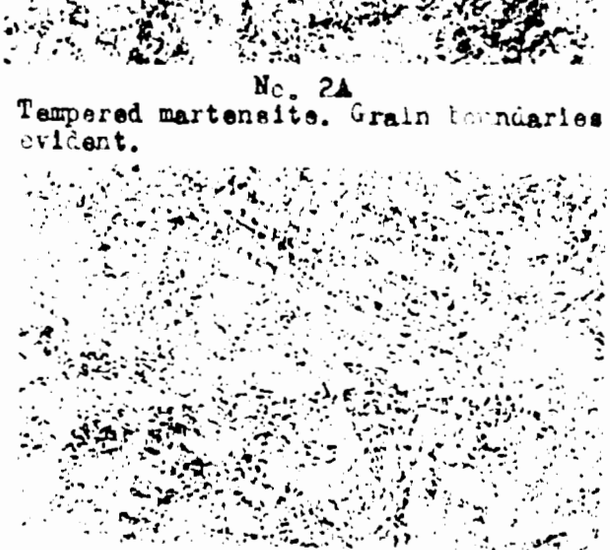
No. 1A
Fairly coarse tempered martensite.

No. 2
Tempered martensite. Evidence of grain boundaries.

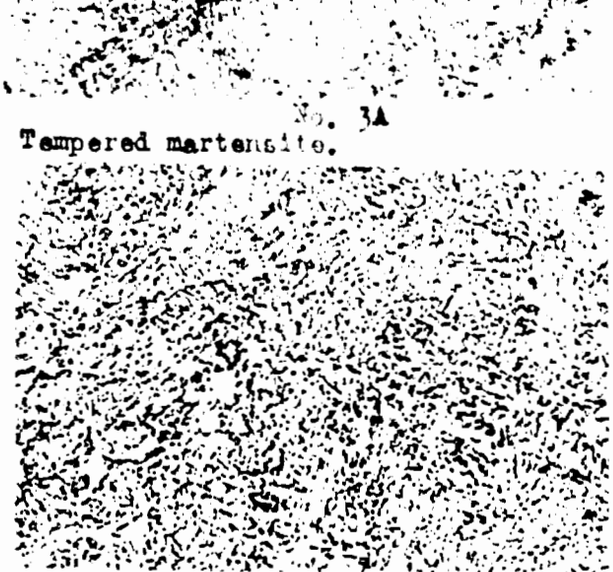
No. 2A
Tempered martensite. Grain boundaries evident.



No. 3A
Tempered martensite.



No. 5
Fine carbides, tempered martensite similar to samples Nos. 4, 4A and 5A.



No. 6A
Fine carbides, tempered martensite. Some of the carbides are of a larger particle size then those in sample Nos. 4, 4A, 5, and 5A.

Photomicrographs taken at X1000. Samples etched in picral.

FIGURE 4

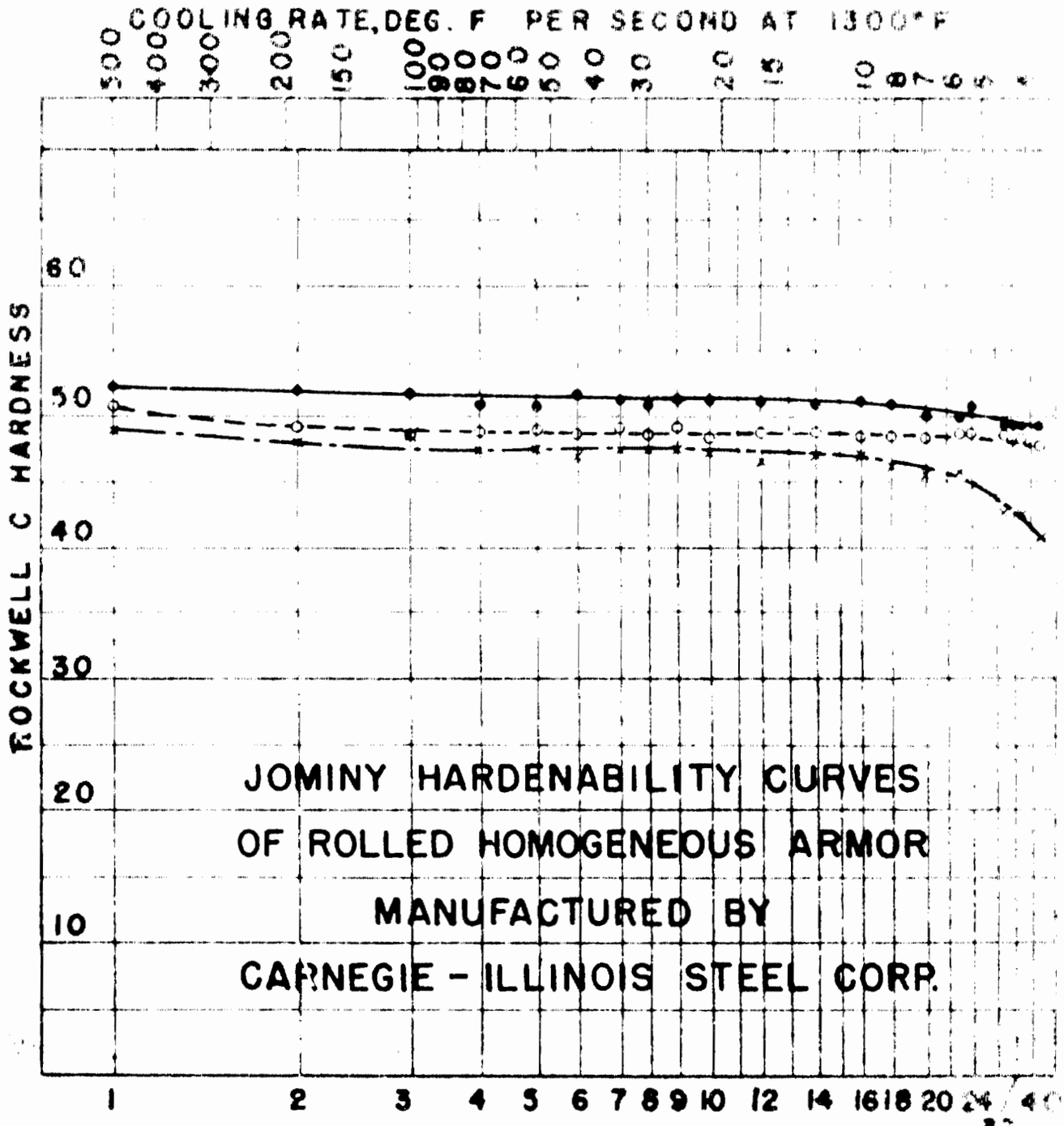


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	B	CU	AL	QUENCH TEMP	QUENCH TIME	G.S.
2	•——	.33	1.28	.22	.028	.020	.84	.82	.40	.0025	.10	.03	1600°F	2 HRS. 1 HR. AT	RISE TEMP
4	o— — —	.33	1.26	.20	.023	.022	.81	.81	.39	.0019	.105	.03	1600°F	2 HRS. 1 HR. AT	RISE TEMP
5	x—— —	.33	1.21	.22	.020	.017	.81	.81	.40	.001	.105	.03	1600°F	2 HRS. 1 HR. AT	RISE TEMP

FIGURE 5

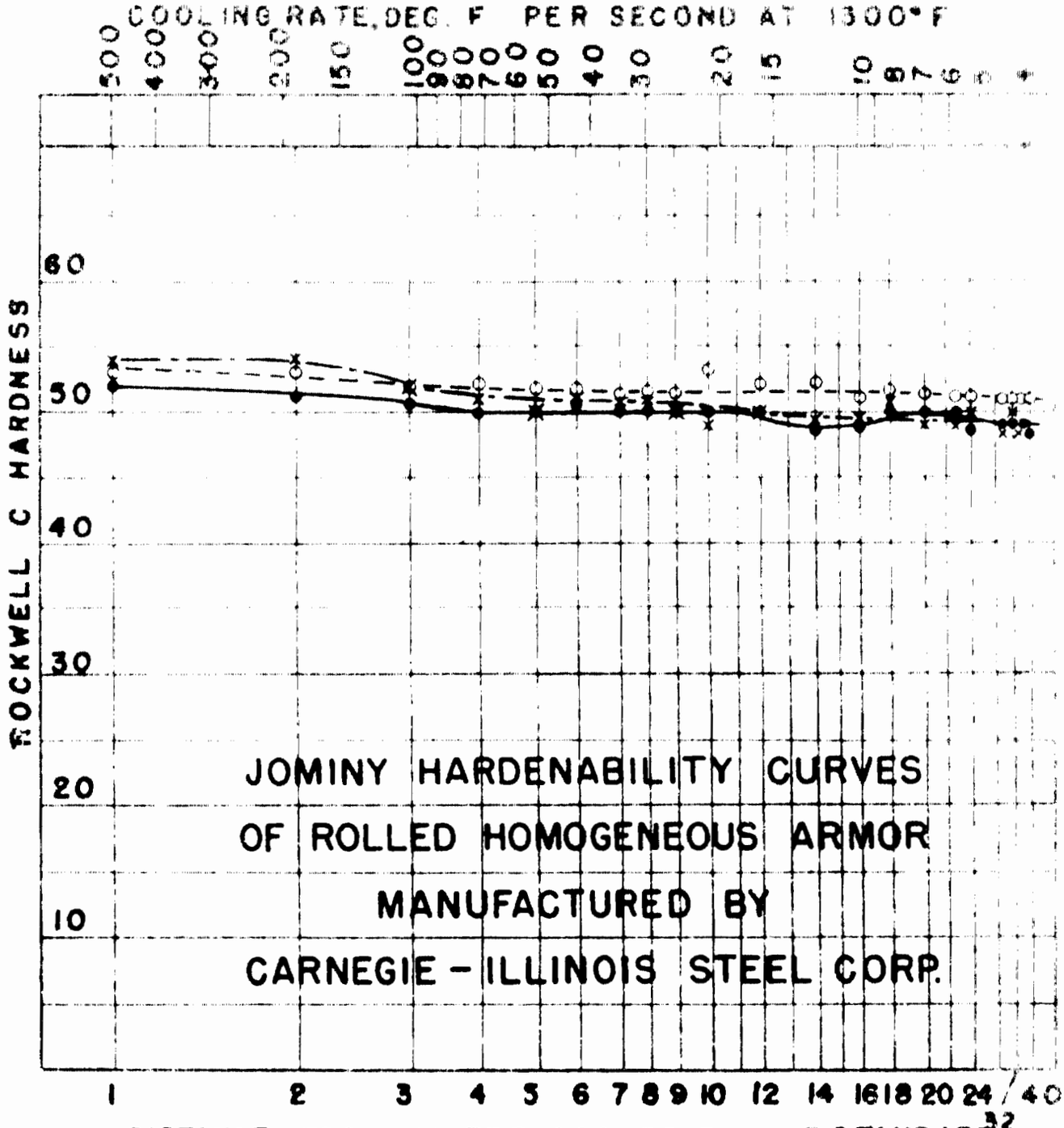


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	B	CU	AL	QUENCH TEMP	QUENCH TIME	G.S.
2A	●———	.35	1.26	.21	.028	.017	.85	.80	39	.0027	.10	.03	1600°F.	2 HRS. RISE 1 HR. AT TEMP.	
4A	o— — —	.35	1.25	.23	.024	.021	.84	.82	.39	.0025	.105	.02	1600°F.	2 HRS. RISE 1 HR. AT TEMP.	
6A	x— - —	.28	1.26	.21	.026	.019	.85	.82	.40	.001	.105	.02	1600°F	2 HRS. RISE 1 HR AT TEMP.	

FIGURE 6

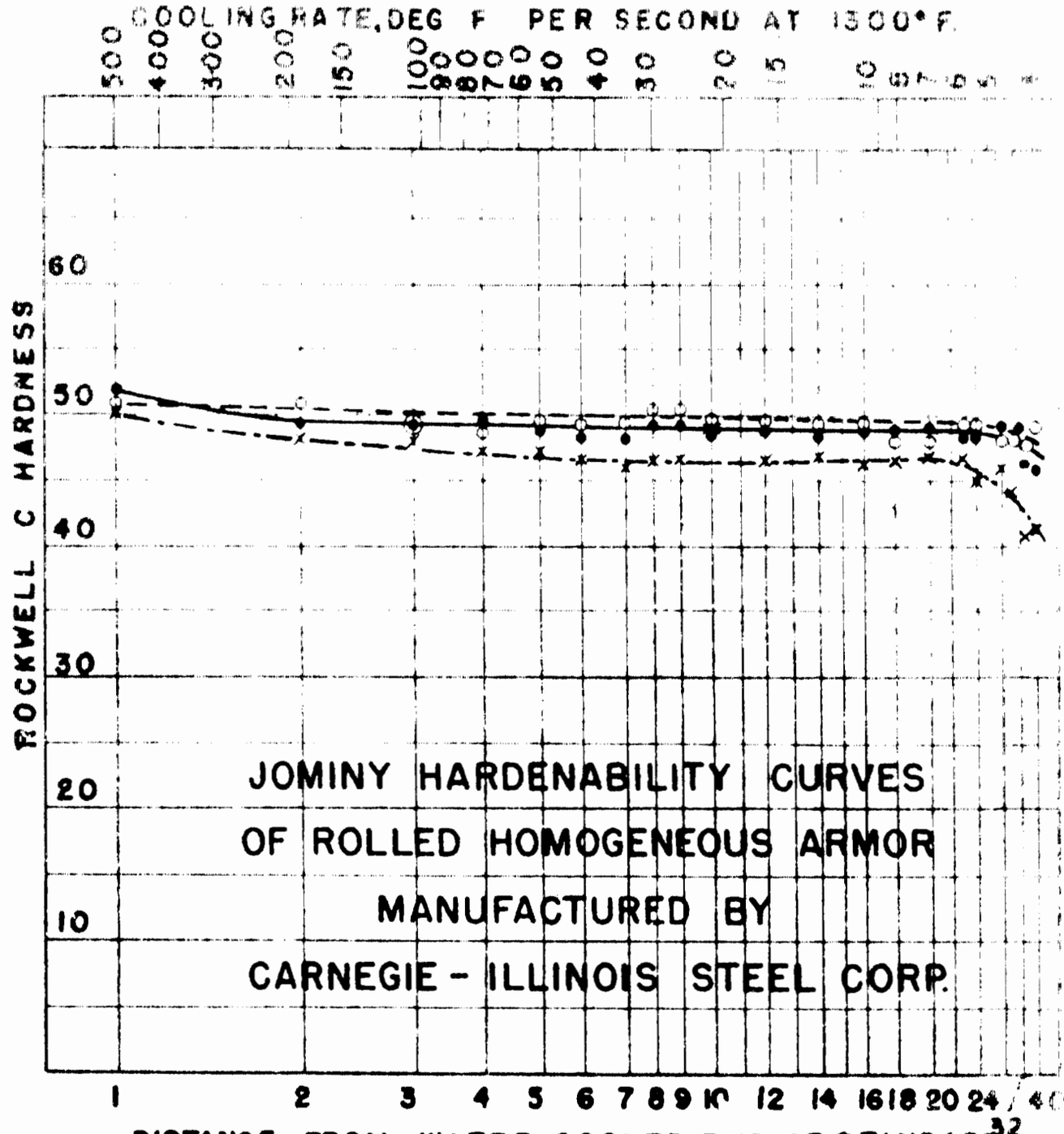


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	B	CU	AL	QUENCH TEMP	QUENCH TIME	G.S
1A	●———	.34	1.26	.21	.023	.018	.84	.80	.39	.001	.105	.03	1600°F	2 HRS 1 HR. AT TEMP.	RISE
3A	O- - -	.34	1.25	.21	.025	.020	.86	.81	.39	.002	.10	.02	1600°F.	2 HRS. 1 HR. AT TEMP.	RISE
5A	x— · —	.29	1.21	.23	.021	.016	.77	.78	.40	.001	.105	.03	1600°F	2 HRS 1 HR. AT TEMP.	RISE

FIGURE 7