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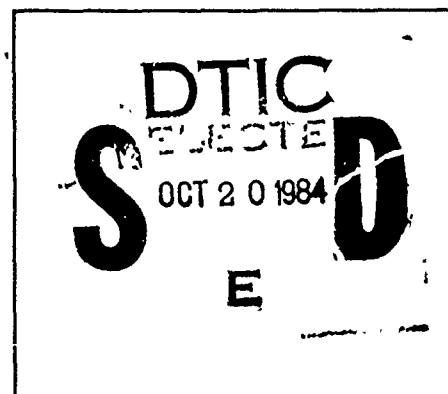
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July 28, 1923.

Report No. 5.

Light Armor Plate Development.

- A. History
- B. Heat treatment investigation.
- C. Preparation for ballistic test.
 - 1. Carburization
 - 2. Rolling
 - 3. Heat treatment
 - 4. Conclusion.

Introduction.

The above outline illustrates the order in which the various phases of this investigation will be discussed in this report.

Data compiled at the Bureau of Standards from the time of the arrival of the plates to the time of shipment will be included.

Section A. - History.

On December 23, 1921, twenty-four plates were received from Watertown Arsenal. These plates were approximately 18" x 18" and of the thickness listed in table I, which also includes the chemical analysis, the latter being rather uniform for the entire lot of plates. → next p.

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Table I.

Group	Thickness	Chemical Analysis.							
		C	Mn	P	S	Si	Cr	Ni	V
C	.710-.735	0.46	1.05	0.013	0.015	0.15	0.02	1.79	0.20
D	.870-.890	0.45	1.22	0.016	0.017	0.15	0.01	1.78	0.22
E	.270-.280	0.44	1.07	0.020	0.015	0.20	0.01	1.73	0.19

Note:- The grouping of the plates is in conformity with the method adopted with regard to former shipments of plates - i.e. serializing them in the order as received. (groups A and B comprised the 04825 and 17000 chrom-nickel plates respectively), which were received in the early part of 1921).

→ The surfaces of the plates in general were in fairly good condition having only small thin films of oxide on them. In a few cases the surfaces were marred by grooves - probably caused by rolling - but these defects prevailed on one side only.

The plates as they arrived were packed in grease and in order to remove this, a process of annealing followed by grease-solvent cleaning was applied in order to produce a surface which could readily be pickled.

The pickling bath was composed of a 10 ^{Percent} solution of sulphuric acid, the bath being equipped with an electric heating coil the purpose of which was to hasten the process of removing the oxide and to produce the desired surface for carburization.

After pickling the entire lot of plates - two of each group, namely C, D, and E, were set aside as experimental plates for → next P.

→ the heat treatment investigation and other experimental work.

The remaining eighteen plates were to be prepared for the ballistic tests. ←

Figures a and b depict the structure existing in the plates (as received).

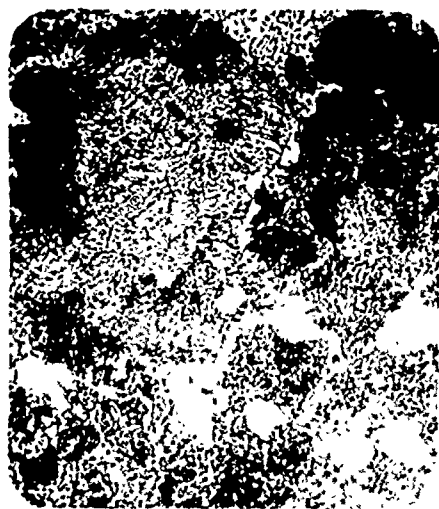


Fig. a X500
Typical structure of
0".6+ and 0".7+ armor plate.



Fig. b X500
Typical structure of
0".23+ armor plate.

Section B.

Heat-Treatment Investigation.

1. Heat treatment.

The purpose of this investigation was to produce a plate whose surface was possessed of maximum hardness, using a quench-

Table II.

Non-Carburized Specimens						Single Quenching	
No.	Heat Treatment	Quenched °C	Tempered °C	Hardness		Structure	Remarks.
				Brinell	Shore Edge Interior		
3Q	775-W	---	---	---	---	E.M., (imprint in evidence)	
3	775-W	150		591	51 56	Mart. (needle struc. having begun to emulsify)	Quench cracks
2	775-W	225		550	55 63	E.M. (imprint in evidence)	Quench cracks
6	775-W	200		387	49 39	E.M. Decomposition products of mart.	Quench cracks
5Q	775-O	---	---	---	---	E.M.	
4	775-O	150		347	42 37	Mart. (needle structure but well emulsified).	
1	775-O	225		356	46 40	Same as No. 4.	
5	775-O	300		403	54 46	E.M. (slight imprint in evidence).	
10Q	850-W	---	---	---	---	E.M.	
10	850-W	150		532	54 51	Mart. (needle struc. but beginning to emulsify)	Quench cracks.
7	850-W	225		425	46 41	E.M. (imprint in evidence) - stress bands	Quench cracked badly
11	850-W	200		457	55 52	E.M. (slight imprint in evidence)	Quench cracks
9Q	850-O	---	---	---	---	Mart. (needle structure somewhat emulsified).	
9	850-O	150		354	45 41	E.M. - (imprint in evidence).	
8	850-O	225		380	46 43	E.M.	
12	850-O	300		532	60 55	E.M.	
18Q	925-W	---	---	---	---	Mart. (needle struct. somewhat emulsified).	
16	925-W	150		701	81 80	Mart. (needle struct. slightly emulsified)	Quench cracked badly
14	925-W	225		474	53 59	Same as No. 16	Quench cracked
18	925-W	300		555	66 66	E.M. (slight imprint in evidence).	

Notes: - E.M. = Emulsified martensite.

Struct. = Structure.

Mart. = Martensite (needle structure).

Imprint in evidence = Imprint of martensitic needles in evidence.

Under heat treat. 775-W; 775-O, etc. = water and oil quenching respectively.

Table II. (continued).

Non-Carburized Specimens						Single Quenching	
No.	Heat Treatment		Hardness		Structure	Remarks.	
	Quench- ed °C	Temper- ed °C	Brinell	Shore Edge Interior			
15Q	925-0	---	---	---	Mart.-(needle struct. somewhat emulsified).		
17	925-0	150	622	64	61	Mart.-(needle struct. but well emulsified).	
15	925-0	225	342	45	41	E.M.-(imprint in evi- dence).	
13	925-0	300	537	66	70	E.M.-(imprint in evi- dence).	

Notes: - E.M. = Emulsified martensite.

Struct. = Structures.

Mart. = Martensite (needle structure).

Imprint in evidence = Imprint of martensitic needles in evidence.

Under heat treat. 775-W; 775-O, etc. = water and oil quenching
respectively.

Table III.

Carburized Specimens										Single Quench		Remarks
No.	Heat Treatment	Hardness					Depth of cm. in mm.	Structure	Core			
		Brinell		Shore								
		Side A	Side B	Side A	Side B							
		A	B	Edge Inter-ior	Edge Inter-ior							
51Q	775-W	---	600	512	90	42	39	3.028	E.M.-Om (continuity broken)	E.M.- (Imprint in evidence).		
51	775-W	150	652	342	83	66	46	3.246	E.M., T and S. Om.	E.M.- (Imprint in evidence)		
45	775-W	225	327	248	66	62	42	3.028	E.M.T, S and some P. - Cm.	E.M.		
44	775-W	300	271	239	50	49	43	42	1.602	Same as # 42	E.M.	
52Q	775-0	---	---	---	---	---	---	---	P.S & T. Om.	P and S.		
54	775-0	150	336	272	59	54	47	2.990	P.S. & T. Om.	P and S.		
53	775-0	225	327	313	50	53	35	2.618	Same as # 54	Same as # 54.		
52	775-0	300	319	226	52	52	34	2.121	Same as # 54	Same as # 54.		
36Q	850-W	---	555	512	83	64			Mart. (beginning to emulsify) A, Cm. in patches	Quench struct. showing cracks		
36	850-W	150	541	505	80	82	75	68	1.655	Mart. (needle struct). Cm.	E.M. (Imprint in Quench evidence).	
35	850-W	225	567	502	80	81	71	69	2.485	Mart. (needle struct. but well emulsified), Cm. (continuity broken)	E.M.	
34	850-W	300	602	470	83	84	72	70	2.387	Same as # 35	Same as # 35.	
32Q	850-0	---	578	532	70	66				Mart.-Om (continuity broken).	E.M. (Imprint clearly in evidence).	
33	850-0	150	546	441	79	84	58	60	not measurable*	Mart. Small amt. of om. in patches - also probably A.	E.M. (Imprint in evidence).	
32	850-0	225	591	502	83	86	75	73	2.576	E.M. Cm. (continuity broken).	E.M.	

Table III (continued).

No.	Heat Treatment Quench- ed °C	Carburized Specimens										Depth of cm. in mm.	Single-Quench		Remarks.	
		Hardness					Structure						Case (carburized zone).	Core		
		Brinell		Shore			Mart.									Quench cracks.
		Side A	Side B	Side A	Side B	Edge	Inter- ior	Inter- ior	Inter- ior	Inter- ior	Inter- ior					
31	850-0	300	569	512	N1	84	74	74	---	Mart. (passing into emulsified condition).	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Quench cracks.			
27Q	925-W	---	600	545	---	87	58	74	---	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Quench cracks.			
27	925-W	150	591	546	82	83	74	74	---	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Quench cracks.			
26	925-W	225	555	524	80	83	76	74	---	Mart. (emulsified to great extent).	Mart. (emulsified to great extent).	Mart. (emulsified to great extent).	Quench cracks.			
25	925-W	300	569	524	79	80	74	79	---	Mart. (emulsified to great extent).	Mart. (emulsified to great extent).	Mart. (emulsified to great extent).	Quench cracks.			
925-0.925-0	---	---	683	387	91	59	---	---	---	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Quench cracks.			
30	925-0	150	637	600	75	79	75	70	---	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Quench cracks.			
29	925-0	225	632	546	82	83	75	78	---	E.M.	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Quench cracks.			
28	925-0	300	573	488	80	83	75	74	---	E.M. (evidence of imprint)- S.	Mart. (slightly emulsified).	Mart. (slightly emulsified).	Quench cracks.			

- Notes:-
1. E.M. = emulsified martensite
 2. Mart. = martensite (needle structure).
 3. P = pearlite
 4. T = troostite
 5. S = sorbite
 6. Struct. = structure
 7. A = austenite.
 8. Cm = cementite.
9. Imprint in evidence = imprint of martensitic needles in evidence.
10. = 850-0 and 850-W, etc. = 850 oil quench and 850 water quench, respectively
11. Side A = carburized side and side B = non-carburized side.
- * Cm. broken and present only in small globules.

Table IV.

No.	Heat Treatment Quench- ed °C	Temper- ed °C	Carburized Specimens				Depth of cm. in mm.	Double Quench	Remarks.		
			Hardness		Shore	Structure.					
			Brinell	Shore							
			Side A	Side B.	Case (carburized zone).	Core					
			A	B	Edge Inter- ior	Edge Inter- ior					
47Q	775-W	---	652	555	91	59	---	E.M.-Cm. (conti- nuity broken).	E.M. (evidence of imprint).	Quench cracks.	
48	775-W	150	600	327	82	80	74	53	2.308	E.M.-T.-S. Cm. E.M.	
46	775-W	225	564	512	71	82	75	50	---	(continuity broken). Same as # 48 ex- cept only small patches of cm.	Quench cracks.
47	775-W	300	587	484	80	82	72	70	2.548	Same as # 48	Quench cracks.
49Q	775-0	---	622	552	90	70	---	E.M.-Cm. (conti- nuity broken).	Mart. (slightly emulsified).	Quench cracks.	
43	775-0	150	622	591	83	81	76	67	---	E.M. (imprint in evidence).	Quench cracks.
50	775-0	225	623	462	88	87	73	64	2.870	E.M. Cm.	Quench cracks.
49	775-0	300	611	424	84	83	73	66	2.429	Same as # 50	Quench cracks.
41Q	850-W	---	713	652	92	88	---	E.M.	---	E.M. (imprint in evidence).	Quench cracked badly.
42	850-W	150	664	602	89	87	83	83	---	E.M. (imprint in evidence).	Quench cracked badly.
41	850-W	225	587	415	80	77	75	68	---	E.M.	Quench cracked badly.
40	850-W	300	578	502	85	84	76	76	---	E.M.	Quench cracked badly.
38Q	850-0	---	637	578	84	82	79	71	---	E.M.-Small amt. Cu. in globular form.	Quench cracks.
39	850-0	150	627	560	80	82	79	71	---	E.M. (slight evi- dence of imprint).	Quench cracks.

Table IV. (continued).

No.	Heat Treatment	Carburized Specimens						Double Quench.		Remarks.
		Quench- ed °C		Temper- ed °C		Hardness		Shore	Depth of cm. in mm.	
		Side A	Side B	Side A	Side B	Edge Inter- for	Edge Inter- for			
36	850-0 775-0	225	622 477	83	86	75	73	1.365	E.M. (slight evi- dence of imprint. imprint Cm.	E.M. (evidence of imprint)
37	850-0 775-0	300	587 450	77	79	71	65	1.845	E.M.-Decomposi- tion products of martensite. Cm.	E.M.
22Q	925-W 775-W	---	652 600	89	82	82	---	---	E.M.	Quench cracked badly
24	925-W 775-W	150	622 340	89	80	66	62	---	E.M.	E.M. (slight evi- dence of imprint). Quench cracks.
23	925-W 775-W	225	591 327	82	80	55	46	---	E.M.	Quench cracked badly.
22	925-W 775-W	300	564 433	81	82	68	61	---	E.M.	Quench cracks.
20Q	925-0 775-0	---	713 555	77	65	65	---	---	Mart. (slightly emulsified). E.M.	Quench cracks.
21	925-0 775-0	150	585 370	80	79	61	52	---	E.M.	Quench cracks.
19	925-0 775-0	225	637 532	83	86	74	72	---	E.M.	Quench cracks.
20	925-0 775-0	300	622 447	82	84	75	65	---	E.M.	Quench cracks.

- Notes: 1. E.M. = emulsified martensite
 2. Mart. = martensite (needle structure).
 3. P = pearlite
 4. T = troostite.
 5. S = sorbite
 6. Struct. = structure.
 7. A = austenite.
 8. Cm = Cementite.
9. Imprint in evidence = imprint of martensitic needles in evidence.
 10. 850-0 and 850-W, etc. = 850 oil quench and 850 water quench, respectively.
 11. Side A = carburized side and side B = non-carburized side.
 * Cm. broken and present only in small globules.

ing temperature whose destructive effect (cracking) would be a minimum, and producing a microstructure approaching a fine or emulsified martensitic texture.

The absence of free cementite, a constituent which being brittle might cause spalling, due to impact of bullet, was desired. It was proposed to drive the cementite into solution. Cementite had been originally precipitated by the slow cooling (after carburization), following the long heating (during carburization). In the case where the non-carburized plate was used (Specimens 1 to 18 - Table II), it was also desired to produce a fine or emulsified martensite. However, the problem of driving the free cementite into solution did not occur.

In carrying out this portion of the problem, 54 specimens (approximately 2" x 2") of the group "C" (.7"+) stock were prepared and surface ground on one side.

Thirty-six of these specimens were carburized for 72 hours at a temperature of 925° C, thus producing, on one side, a case of approximately 1/4 inch. The opposite side was protected by a coating mixture of plastic fire clay and water glass.

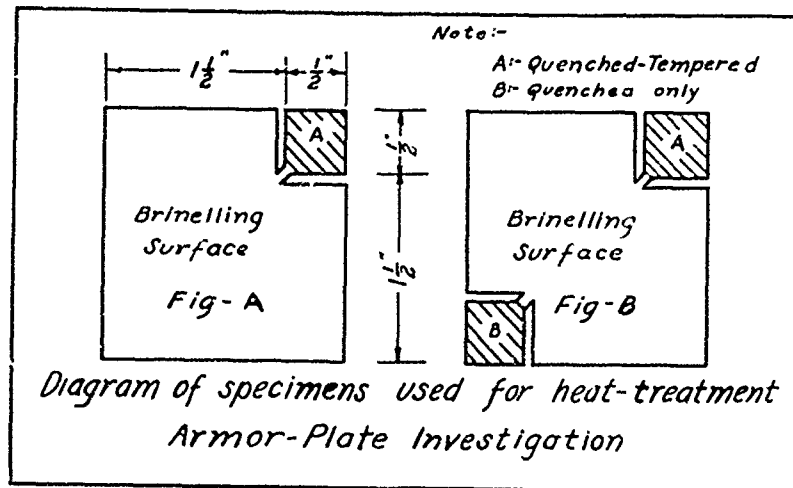


Fig. A.

Fig. B.

The corner of each specimen was slotted as shown in Fig. A.. The object of this was to provide an internal surface which could be microscopically examined to determine the results of the quenching and drawing treatments. An additional specimen for micro-examination representing each quenching temperature was prepared in the same way; by slotting a second corner, as illustrated in figure B of one of every three of the 54 specimens. The 2" specimens were then surface ground on the sides which had not been carburized. It was necessary to produce a smooth surface for brinelling and scleroscoping as well as to remove what little case may have been produced by gases penetrating the clay coating.

The quenching temperatures used ranged from just above the A_{c1} critical range ($775^{\circ} C$) to the temperature at which carburiz-

ation was carried out (925° C), while drawing was done at 150° C, 225° C, and 300° C. Tables II, III and IV, list the quenching and tempering temperatures applied.

Only carburized specimens were subjected to the double-quenching treatment (see table IV). The purpose of this was to refine the structure existing in both the case (carburized zone) and the core of the material. The quenching media used were oil and water. Their application is listed in Tables II, III, & IV.

The specimens before heating to the quenching temperatures were packed in charcoal to prevent oxidation. They were then placed in an electric muffle furnace and allowed to heat with the furnace, to the required temperature and held there for 45 minutes, after reaching the desired heat, to insure thorough soaking of the specimens.

The quenching baths were kept at practically constant temperature. The oil bath was water cooled, while a continuous flow was maintained in the water bath. These conditions insured more uniform results.

The tempering operations were conducted similarly, except that charcoal was not necessary due to the comparatively low temperatures. Water was used as the cooling medium.

After tempering the 3" blocks, the slotted specimens, as shown in figures A & B, were severed for micro examination. Those blocks having 3 specimens were stripped of one specimen after quenching but before tempering in order to determine the hardness and to observe the structure of the material in the untempered condition.

2. Brinell and Scleroscope Hardness: -

The 3" x 3" specimens after heat-treatment were surface ground. The carburized specimens were ground on both sides if warpage had been produced by quenching, otherwise the carburized side only was ground. In either case the absolute minimum of surface was removed from the case hardened side as the carbon content is a maximum near the surface. Due to the percentage gradient of carbon in the case, being a maximum at the surface and decreasing toward the junction of the case and core, the specimens for microscopic examination were removed before surface grinding in order to have the edge (as carburized) available. The surface grinding was followed by polishing all specimens (3" x 3") on No. 1 G emery paper (both sides of carburized specimens and one side of the non-carburized specimens). This final treatment produced a surface suitable for brinelling and scleroscoping.

Five brinell readings were taken on each (polished) surface, and a minimum of 16 scleroscope readings were taken (8 or more around the edge and a like number in the central portion of the 3" block).

The slotted specimens, (Fig. B), representing the condition of the carburized metal after quenching, were also ground, polished and subjected to the hardness tests as described above. Due to the size of these specimens (approximately 1/2" x 1/2") only one brinell reading and 8 scleroscope readings were taken on each side.

The results of the brinell and scleroscope hardness tests are compiled in Tables II, III and IV.

3. Microstructure: -

The specimens representative of the quenched and quenched-tempered material were prepared for microscopic examination in the usual manner. All specimens were etched in 2 % nitric acid in alcohol.

In order to portray any differences in micro-structure which might occur in the quenched specimens after tempering all structures representative of the steel in the quenched state were micrographically recorded. These appear in plates I to X. The letter "Q" following the specimen number indicates the quenched state. Upon examining the quenched-tempered specimens, those specimens showing a difference due to tempering were micrographed. These appear in plates I to XI. (see tables II, III, and IV for description of structures).

Figures 1 and 3 (Plate I) represent the structures prevailing in the specimens (3 Q and 5 Q - table II), quenched from 775° C in water and oil respectively. Comparing these with figures 2 and 4 (Plate I), which represent the structures in the specimens quenched from the same temperature in water and oil respectively followed by tempering, specimen 3 being drawn at 150° C and specimen 5 at 300° C, there is but a negligible difference. Figures 2 and 4 are representative of the structure of specimens quenched in the same manner and drawn at the temperatures as noted in Table II (see specimens 1 to 6).

Figure 5 (plate II) exhibits a martensitic structure representative of that prevailing in the specimen quenched in water from 850° C, but upon tempering begins to emulsify, al-

though still retaining the needle imprint when drawn at 300° C. (specimen 11, table II, also Fig. 8, Plate II).

Fig. 7 (plate II) is representative of the structure of the specimen quenched from 850° C, in oil. The structure does not differ appreciably from that shown in Fig. 8 (plate II) which is representative of the structure in the specimen tempered at 150° C. Of those drawn at 225° C and 300° C respectively, the imprint of the martensite as shown in Fig. 9 (plate II) is lacking.

The transition of the structure of the specimens quenched from 925° C in water and oil respectively are very marked when compared with the structure in these specimens after tempering at 300° C. This marked difference may be observed by comparing figure 9 (plate III) with figure 10 (plate III) and figure 11 (plate III) with figure 12 (plate III). Although figure 12 is representative of the structure prevailing in the specimen quenched from 925° C in oil and drawn at 225° C, it is similar to the structure in the specimen which was given the same quenching treatment but drawn at 300° C.

All of the specimens thus far referred to were of the plates which were heat-treated in the condition as received (not case-hardened). The discussion from this point on will deal with the carburized plate.

The specimens quenched from 775° C in water showed a marked change in hardness upon tempering at 225° C and 300° C respectively, when compared with the specimen tempered at 150° C.

The change is well accounted for, when comparing the structure depicted in figures 13, 14, and 15 (plate IV) which represent the structure in the specimens tempered at 150° C, 235° C, and the originally quenched specimen respectively. Figures 13 and 15 portray only a fine martensite while in figure 14 troostite, sorbite and pearlite are represented.

Figures 16 and 17 (plate V) represent the prevailing structure in the outer and inner portion of the carburized zone respectively of the specimens oil quenched from 775° C. The tempered specimens show a structure very closely allied to the non-tempered one. Figure 18 (plate V) is representative of the structure in the tempered condition. The hardness number of the specimens of this quench are low as may be expected after observing the structure which is composed of pearlite and sorbite in the main and some troostite.

The water quenched specimens (850° C) showed a constant increase in hardness with increased drawing temperature (see specimens 34 to 36, Table III), which is due to the retention of austenite due to the quench from the above temperature and the gradual transition to martensite when drawn. Figure 19 is representative of the structure existing in the quenched specimen. It shows the presence of much austenite (large white irregular patches) while figure 20 portrays the structure

of the same specimen tempered at 150° C and shows a more clearly defined martensitic structure. This transition continues on to 200° C, (see specimens 31 to 33 Table III).

The hardness of the specimens oil quenched from 850° C showed little difference after tempering. Figures 21 and 22 (plate VI) representing the structure prevailing in the specimen which was quenched and one which was quenched followed by tempering at 200° C respectively, very closely resemble each other, altho the structure is finer in specimen 31 (see figure 23 Plate VI). This likeness seems to account for the closely corresponding hardness. Specimen 32 (table III) tempered 225° C showed the maximum hardness of this series, and may be accounted for by the fact that it possesses much free cementite and more readily passes to the emulsified form of martensite of which structure it is possessed.

The following conditions of structure would account for the hardness; (a) the presence of austenite in the specimen tempered at 150° C, (b), maximum martensite when drawn at 225° C; (c), a mixture of decomposition products of martensite when drawn at 700° C (see specimens 31 to 33 Table III).

The specimens quenched from 925° C in water retained some austenite and clearly defined martensite (see figure 23 Plate VII). This structure upon tempering passed from clearly defined

martensite into an emulsified form, altho the imprint of the needle structure was still in evidence. Small patches of austenite remained in the tempered specimens. The structure in the tempered condition is illustrated in figure 24 (Plate VII), the arrows indicating the austenitic patches. It is probable that this structure represents a metastable condition as tempering at 150° C produced a structure containing maximum martensite (of this quench). This was indicated by the maximum hardness (see specimens 25 to 27 Table III). Further tempering (225° C) produced a structure which showed the martensite beginning to break up but still retaining the patches of austenite thus accounting for the decreased hardness (see figure 24 Plate VII). When tempered at 700° C, the austenite passed over to martensite and the hardness increased, but did not reach the value recorded for the specimen tempered at 150° C.

The oil quenched specimens (from 925° C) (see figure 25 Plate VII) showed a receding hardness with increased drawing temperatures. The quenched specimen (without further treatment), produced a structure most nearly approaching 100 % martensite. This showed the maximum hardness while the specimen tempered at 200° C, showed a minimum hardness. The latter possessed a structure of fine or emulsified martensite and probably some troostite and sorbite (see figure 26 Plate

VII). The specimens tempered at 150° C and 325° C respectively showed a gradation from the maximum to the minimum hardness respectively.

The specimens double quenched at 775° C in water (see figure 2 Plate VIII) produced a maximum hardness in the non-tempered condition, and softened with increasing tempering temperatures. The specimens drawn at 225° C and 300° C (specimens 46 and 47 respectively, Table IV) showed a structure which would indicate that the latter tempering did not produce a change over the former. The hardness numbers bear this out. Figure 28 (Plate VIII) showed the characteristic structure of the tempered specimens.

Figure 29 (Plate VIII) which represents the structure existing in the specimen quenched and requenched from 775° C in oil, is composed of fine martensite while the tempered specimen of this quench showed a structure composed of martensite (emulsified), troostite and sorbite (see figure 20 Plate VIII). This accounts for the decreasing hardness with increasing drawing temperature.

Figure 21 (Plate IX) depicts the structure prevailing in specimen 41 (Table IV) which was quenched from 850° C followed by a quench from 775° C; water being the quenching medium used in both cases. The specimen thus treated was found to be harder than those treated in a like manner and then drawn. This

is explained by comparing figures 31 and 32 (Plate IX). The former shows a purely martensitic structure while the latter, (representative of the structure in the tempered condition), shows decomposition products of martensite which account for the decreased hardness.

Figure 33 represents the structure existing in the specimens quenched in oil from 850° C followed by a similar quench from 775° C. Here as in the previous case where water was used for quenching (same quenching temperatures) the quenched specimen (no tempering) was harder than the specimens which were drawn. The same explanation as given for the water quenched specimens may be used to explain the decreased hardness with increased tempering temperatures (compare figures 33 and 34 Plate IX).

Figures 35 and 36 (Plate X) represent the structure of the specimens quenched from 925° C and requenched from 775° C (using water as the quenching medium). The quenched specimen possessed the maximum hardness as compared with the specimens quenched and drawn. The reason for this is that the structure of specimen 33Q (figure 35) is practically pure martensite while the structure of specimen 32 (figure 33) appears to be passing into the decomposition products of martensite (probably troostite and sorbite).

The structure shown in figure 37 (Plate X) is representa-

tive of the specimen quenched from 925° C in oil followed by an oil quench from 775° C, while figure 38 (Plate X) portrays the structure of a specimen treated similarly but followed by tempering at a temperature of 225° C. The explanation of the quenched specimen being the hardest and the hardness decreasing with increased drawing temperature (see specimens 20Q, 19, 20, and 21, Table IV) is accounted for as described for figures 35 and 36 (Plate X); namely martensite passing into its decomposition products.

Figures 39, 40, and 41 (Plate XI), are representative of the various types of structure existing in the cores of the various specimens after heat-treatment. The first is referred to as an emulsified or fine martensite, the second as a needle type martensite, and the third as pearlite-sorbite complex, (see explanation of cores Tables III and IV). The white patches in figure 41 are free ferrite which is present due to the slow cooling following carburization. It is but slightly affected by the subsequent heat-treatment due to being heated very slightly above the critical range thus causing the partial solution of the constituents before quenching.

Conclusions: - On a thoroughly comparative basis as regards structure, hardness and general macrographic conditions (quench cracks etc.), of the specimens after heat-treatment as well as minimum quenching temperature, the series comprising

41Q, 40, 41 and 42 (Table IV) which were quenched from 850° C in water and requenched from 775° C in water, were chosen as the most desirable in making a final selection for the treatment to be given the ballistic test plates.

It was especially desired to double quench in order to insure a thorough treatment of both the case and core. By observing figures 13 and 14 (Plate IV); 15 and 17 (Plate V); 19, 20, 31, and 22 (Plate VI), and 23, 24, and 26 (Plate VII), the structure can in no instance be said to approach the degree of fineness shown in specimens 41Q, 40, 41, and 42 (Table IV) (see also figures 31 and 32 (Plate IX)).

In choosing between specimens 40, 41, and 42 it was decided that number 40 would be the most practical as the tempering temperature applied in its treatment is sufficient to permit the application of pressure to the plates for flattening without the inherent danger of cracking.

Section C: - Preparation for Ballistic Test.

1. Carburization: -

The plates as described in the first part of this paper were divided into three lots, each lot constituting a certain thickness (see Table I).

In keeping with the system used in labeling plates of previous shipments, the plates of this group will be known as lots C - D - and E, as explained on page 3 and outlined in Table I (page 2).

Inasmuch as these plates contained no chromium, it was necessary to approximate the time of carburization for the various depths of penetration desired on the basis of such data compiled from the experiments carried out at the Bureau of Standards on lots A and B of Armor plate (chrom-nickel steel) for rate of penetration and other published data*.

* G. F. Mansfield. Surface Carburizing - pp. 431 - J. Am. Steel Treating Society - 1919-20 - No. 2.

The carburizer used was a mixture of 4 parts of charcoal, 2 parts of bone and 4 parts of barium carbonate. This is known as a 4 - 2 - 4 mixture and adopted as a standard for these armor plate tests.

The plates were packed in pairs. The two surfaces intended for carburization were exposed while the opposite surfaces were placed together with a refractory material between them which resisted the penetration of the carburizing gases. A special refractory material* was applied to each plate in three to four

* Described in Report No. 4 on coating for selective carburization.

coats. The coated sides of two plates were put face to face as described above.

The plates were packed so that at least one inch of carburizer compound bordered the face to be carburized.

Table V is an outline of the time of carburisation and depth of case of the ballistic plates.

Table V.

Plate	Computed depth of case in inches	Actual depth of case in inches	Time in hours
C-1	0.125	0.185	29
C-2	0.125	0.173	29
C-3	0.188	0.285	52
C-4	0.188	0.254	52
C-5	0.250	0.332	75
C-6	0.250	0.326	75
D-1	0.125	0.153	29
D-2	0.125	0.139	29
D-3	0.188	0.246	52
D-4	0.188	0.219	52
D-5	0.250	0.295	75
D-6	0.250	0.224	75
E-1	0.188	0.255	29
E-2	0.188	0.266	29
E-3	0.063	0.126	9
E-4	0.063	0.104	9
E-5	0.125	0.109	29
E-6	0.125	0.125	29

* Note: - Penetration took place from both sides.

The box having been packed, the top was coated with fire clay (65 % plastic clay and 35 % calcined clay, the latter for the prevention of shrinkage and consequent exposure of the inner part of box to the flame of furnace).

The time of carburization was measured from the time the box reached the required temperature, namely 925° C. This temperature was maintained for the time outlined in Table V. The box after carburization was allowed to furnace-cool to room temperature which required from 30 to 36 hours.

A specimen was severed from each plate for the purpose of measuring the depth of penetration (see Table V), and the microstructure, (see Plate XII for rate of penetration curves).

Figure 42 (Plate XIII) is characteristic of the structure existing in the plates after carburization, previous to any further treatment. Figure 43 (Plate XIII) is an exception to the structure existing in the plates. This exception applies to plates D-1 and D-2 which were carburized to a depth of 3/16" but due to the poor insulation used on the non-carburized surfaces, the gases did penetrate to quite an extent. The penetration from the two sides met at some distance in the plate (as D-1 and D-2 were only about 0.27 inches thick). This permitted a piling up of the carbide as shown in figure 43 which portrays a substantial excess of cementite. This condition might lead to the danger of cracking either during

ballistic test or during the quenching or straightening processes.

2. Rolling: -

Following the program of having one rolled plate for each unrolled plate, lots (C-D-E) were accordingly divided.

The following plates were selected for rolling - C-2, C-3, C-5, D-1, D-2, D-5, E-1, E-2, and E-5 (see Table V for rate of penetration). These plates were rolled according to the specifications outlined by the War Department which are listed in Table VI.

Table VI.

Lot	Number	Thickness in Inches		Final Thickness after reduction in inches
		greater than	less than	
C	2	.710	.735	.438
	3	"	"	"
	5	"	"	"
D	1	.670	.690	.375
	3	"	"	"
	5	"	"	"
E	1	.270	.280	.250
	3	"	"	"
	5	"	"	"

The plates were packed in lump charcoal to prevent oxidation, and then heated to 1100° C, held one hour for thorough soaking of the plates at this temperature. The pass reduction in all cases was 3 %. Table VII contains the results of this operation. The plates after rolling were reheated to a red heat and straightened under a 150 ton hydraulic press.

Table VII.

Plate No.	Critical Temperature	Finishing Temperature	Number of Passes	Heating required	Final Thickness	Gage After Rolling.
G-2	1100° C	847° C	20	3	0.452	0.091
3	"	no record	19	2	0.454	0.143
5	"	889° C	19	3	0.445	0.122
D-1	"	749° C	21	2	0.393	0.091
3	"	691° C	20	2	0.435	0.175
5	"	no record	22	2	0.406	0.171
F-1	"	792° C	5	1	0.255	0.255
3	"	847° C	5	1	0.260	0.131
5	"	889° C	5	1	0.270	0.143

3. Heat treatment: -

As described in section B (under heat-treatment) the treatment selected for the ballistic plates was a double quench in water, first from 850° C and then from 775° C. This treatment was followed by tempering at 300° C and quenching to room temperature in water.

All plates were packed in charcoal to prevent oxidation during heating.

In order to have condition as constant as possible during quenching, a continuous flow tank was used thus keeping the water at a fairly constant temperature.

Due to the high initial quenching temperature, the plates were not quenched to water temperature, but to approximately 150° C to 200° C, thus reducing internal stresses, to a minimum. The same procedure was followed in ^{the} re-quench

Table VIII.

Plate	Hardness				Remarks,
	Brinell		Scleroscope		
	Side A	Side B	Side A	Side B	
C-1	76	76	535	541	
C-2	78	76	559	518	Rolled plate.
C-3	78	67	555	460	Cracked on quenching. Rolled plate.
C-4	72	65	541	459	
C-5	68	64	501	454	Cracked on quenching.* Rolled plate.
C-6	84	74	600	525	
D-1	78	72	535	501	Rolled plate.
D-2	73	65	555	512	
D-3	63	62	427	402	Cracked on quenching.* Rolled plate.
D-4	72	73	640	555	
D-5	76	73	512	493	Cracked on quenching.* Rolled plate.
D-6	80	74	600	521	
E-1	76	69	532	477	Cracked on quenching.*
E-2	71	70	594	517	
E-3	78	77	591	529	Cracked on quenching.*
E-4	77	76	544	512	
E-5	64	54	427	328	Cracked on quenching.*
E-6	77	72	520	474	

* Note: - These cracks were eliminated by cutting plates to final size (see Table IX).

All rolled plates with the exception of C-2 and D-1 cracked, not during quenching but during cooling to room temperature.

Table VIII contains the data of the heat-treatment, including the brinell and scleroscope hardness of the various plates.

1 b. Micro-structure.

Specimens were cut from the rolled plates (in heat-treated condition. The rolled plates, distorted during rolling would be expected to vary in structure to some extent.

In figures 44 and 45 (Plate XIV) are portrayed structures characteristic of the carburized zone and the core respectively of the rolled plates after heat-treatment.

The structure of the unrolled plates after heat-treatment was very similar to that depicted in figure 33 Plate IX with the exception of C-5, D-5, E-3, and E-6, which showed the presence of cementite network after quenching. The former two were no doubt due to the extremely heavy and concentrated carburized zone. A much higher temperature than was used would have been required but the possibility of cracking prevented its application.

The failure of the cementite to diffuse in plates E-3 and E-6 in spite of their short period of carburization, may have been caused by the greater degree of fiberization in these more severely worked plates. These 2 plates were given a normalizing treatment, consisting of heating to 925° C and air cooling. Following the normalizing, the regular heat-treatment; namely a double quench and draw, (850°, 775°, and 500° C) was applied.

The rolled plates showed a complete absence of cementite. This was no doubt due to the high temperature to which these plates were subjected for rolling and the air cooling which followed (during and after rolling). The heating and cooling no doubt materially assisted in breaking up and absorbing the network of cementite.

Final preparation.

In order to eliminate defective portions, plates were cut into sections 12" x 12" or as near this size as possible, by the use of an acetylene torch. All rough edges were then ground.

The brittle condition of the edges due to the high temperature of the acetylene torch and the subsequent air cooling, required a tempering for a second time at a temperature of 275° C, for the purpose of removing strains which might be present due to the above conditions.

Conclusions: -

Cracks appeared in the rolled plates only, no fractures being visible on the unrolled plates. This was probably due to strain lines being set up in rolling near the finishing temperature.

Table IX.

Serial No.	B. S. No.	Size (in inches)	Thickness (in inches)	Case before rolling	Case after rolling	Depth of heat	Remarks.
4	C-1	17-1/8 x 18	0.728	0.165			
5	C-2	12-1/2 x 12-1/2	0.452	0.172	0.091	0.092	Rolled from 0:57+
6	D-5	11-7/8 x 12-3/4	0.405	0.247	0.171	0.184	Rolled from 0:57+
7	D-5	10 x 13	0.407	0.247	0.171	0.184	Rolled from 0:57+
8	C-4	17-1/2 x 18-1/8	0.711	0.254			
9	C-5	8-3/4 x 12-1/4	0.445	0.322	0.122	0.200	Rolled from 0:57+
10	C-6	18 x 18-1/4	0.735	0.326			
11	D-1	12-1/4 x 12-1/4	0.293	0.153	0.091	0.178	Rolled from 0:57+
12	D-1	11-3/4 x 13	0.393	0.153	0.091		Rolled from 0:57+
13	D-3	17-1/4 x 18-1/8	0.575	0.133			
14	D-3	12-1/4 x 12-1/2	0.435	0.245	0.175	0.234	Rolled from 0:57+
15	D-4	17-3/8 x 18-1/8	0.690	0.219			
16	C-3	8-3/4 x 10-1/2	0.454	0.285	0.143	0.025	Rolled from 0:57+
17	D-6	16-1/4 x 17-1/2	0.632	0.324			
18	E-1	8-3/8 x 12-1/8	0.355	0.255	0.255	---	Rolled from 0:28+
19	E-2	12-1/8 x 6-3/4	0.375	0.266			
20	E-3	7-3/4 x 13	0.380	0.138	0.131	0.100	Rolled from 0:28+
21	E-4	12-1/2 x 12-1/2	0.375	0.104			
22	E-5	8-3/4 x 12-1/4	0.370	0.109	0.143	0.333	Rolled from 0:28+
23	E-6	12 x 5-1/2	0.375	0.135			

* Note: - Depth to which heat of acetylene torch (used for cutting plates) affected the structure of plates.

The plates were marked on the back only. The case hardened side was kept free of all marking. Marks other than "white-paint" marks are to be disregarded. The plates bore the following marking in the manner shown.

Back	B-1
	S-1

Table IX contains the final dimensions of the plates as shipped.

Acting Director.

915

Plate I.

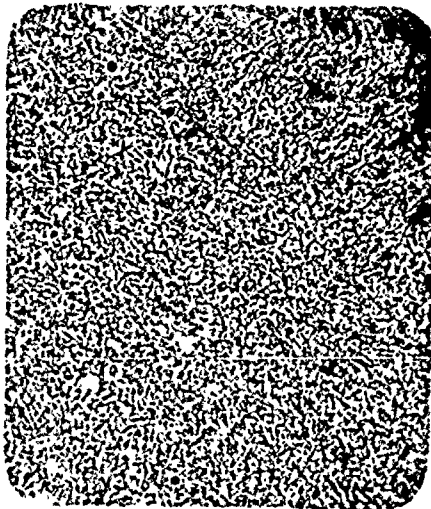


Fig. 1. x 500
Specimen No. 3 Q. Quenched
from 775° C in water

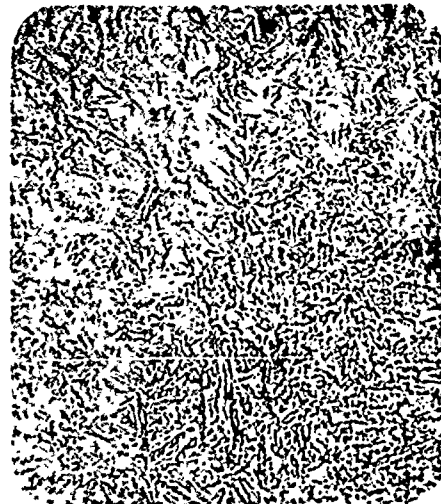


Fig. 2. x 500.
Specimen No. 3. Quenched
from 775° C in water. Tem-
pered at 150° C.

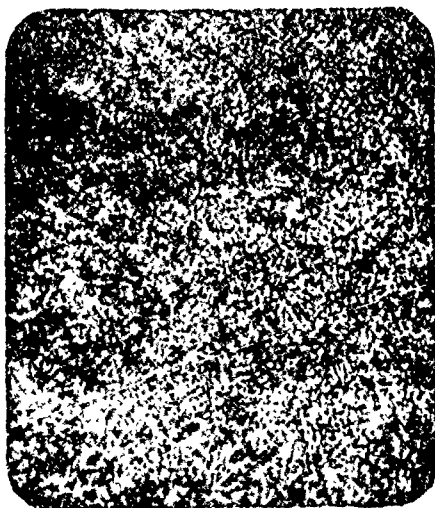


Fig. 3. x 500
Specimen No. 5 Q. Quenched from
775° C in oil.

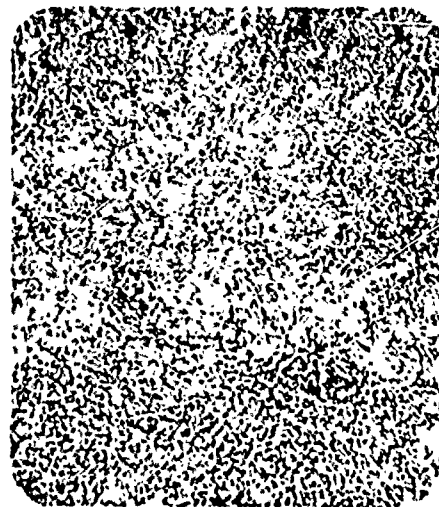


Fig. 4. x 500.
Specimen No. 5. Quenched from
775° C in oil. Tempered 300° C.

All specimens etched in 2 % nitric acid in alcohol.

Plate II.

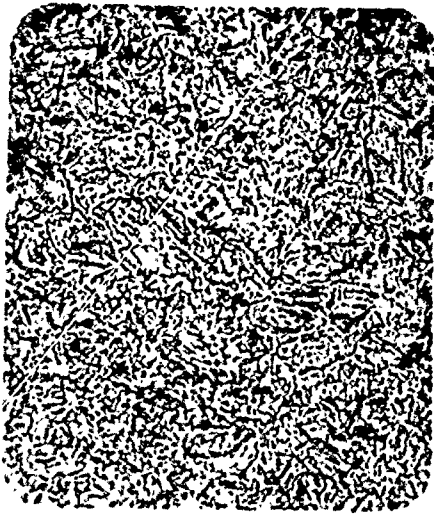


Fig. 5 x 500
Specimen # 10 Q
Quenched from 850°C in water

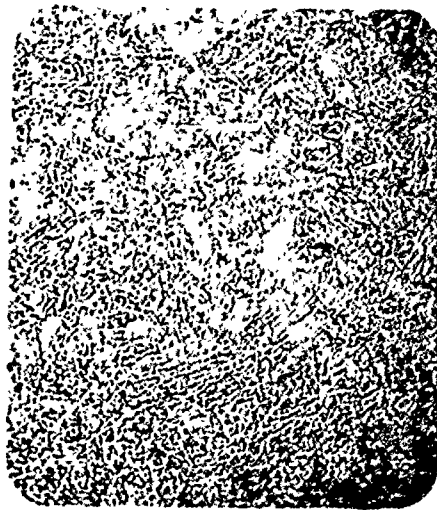


Fig. 6 x 500
Specimen # 11
Quenched from 850°C in water
Tempered at 150°C

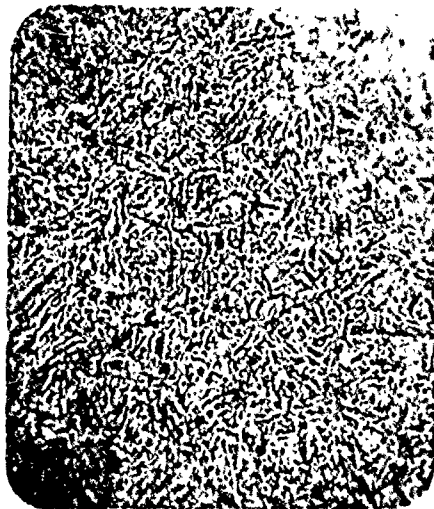


Fig. 7 x 500
Specimen #9 Q
Quenched from 850°C in oil

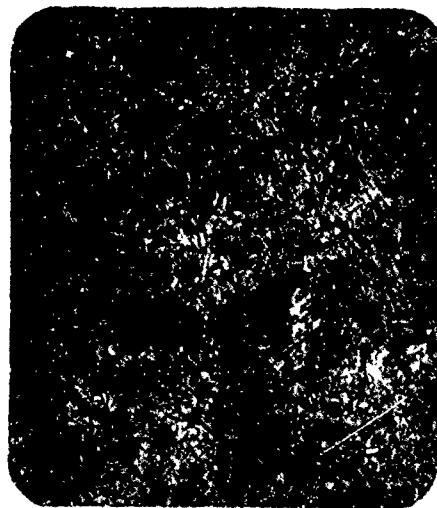


Fig. 8 x 500
Specimen # 9
Quenched from 850°C in oil
Tempered at 150°C

All specimens etched in 2% nitric acid in alcohol.

Plate III.

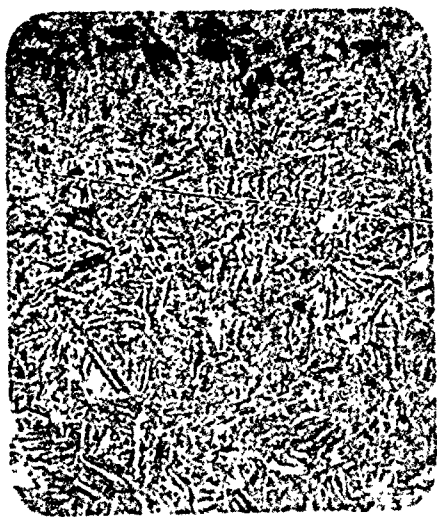


Fig. 9. x 500
Specimen No. 18 Q. Quenched
from 925° C in water

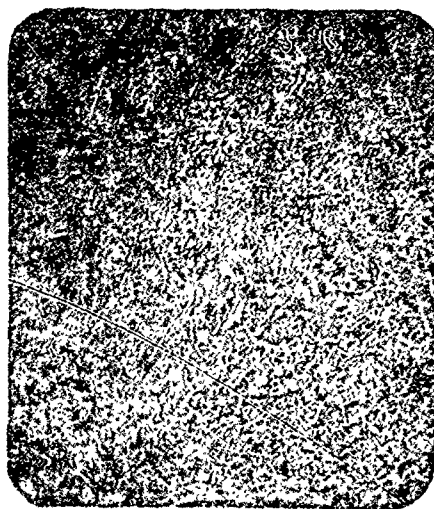


Fig. 10. x 500
Specimen No. 18. Quenched from
925° C in water. Tempered at
200° C.



Fig. 11. x 500.
Specimen No. 15 Q. Quenched
from 925° C in oil.

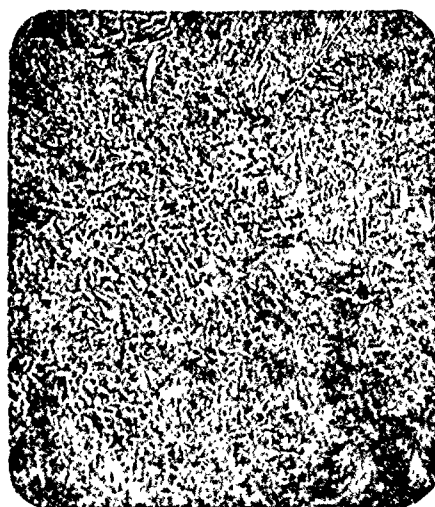


Fig. 12. x 500.
Specimen No. 15. Quenched from
925° C in oil. Tempered at
225° C.

All specimens etched in 3 % nitric acid in alcohol.

Plate IV.

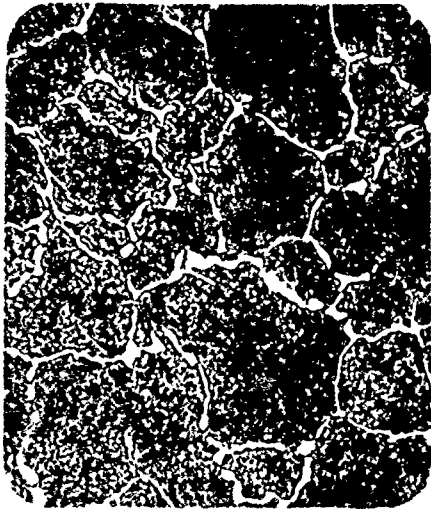


Fig. 13. x 500.
Specimen No. 51. Quenched
from 775° C in water. Tem-
pered at 150° C.

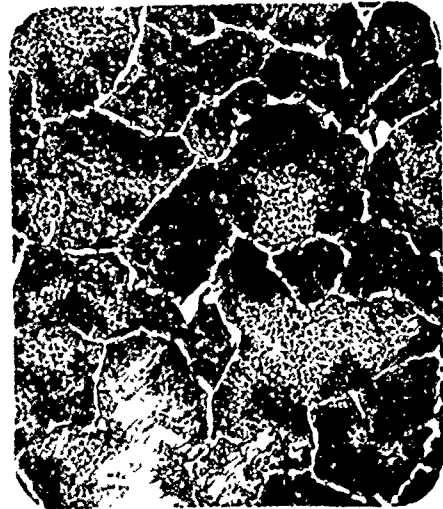


Fig. 14. x 500.
Specimen No. 45. Quenched from
775° C in water. Tempered at
225° C.



Fig. 15. x 500.
Specimen No. 51 Q. Quenched
from 775° C in water.

All specimens etched in 2 % nitric acid in alcohol.

Plate V.



Fig. 19. $\times$ 500.
Specimen No. 52 Q.

Fig. 17. $\times$ 500.
Specimen No. 52 Q₂.

Quenched from 775° C in oil.

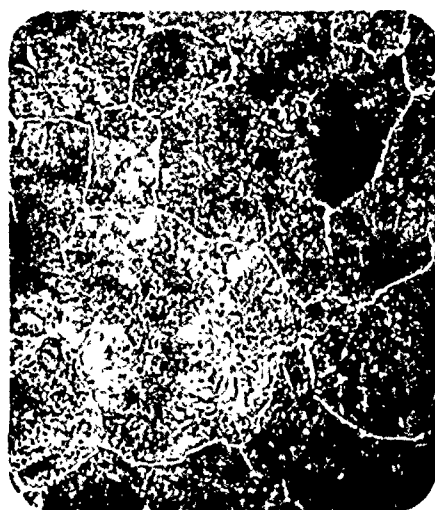


Fig. 18. $\times$ 500.
Specimen No. 54. Quenched from 775° C
in oil. Tempered at 150° C.

All specimens etched in 2 % nitric acid in alcohol.

Plate VI.



Fig. 19. x 500.
Specimen No. 36 Q. Quenched
from 850° C in water.

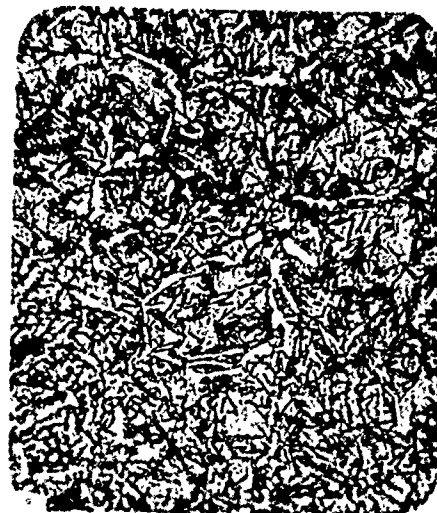


Fig. 20. x 500.
Specimen No. 36. Quenched from
850° C in water. Tempered at
150° C.



Fig. 21. x 500.
Specimen No. 32 Q. Quenched
from 850° C in oil.

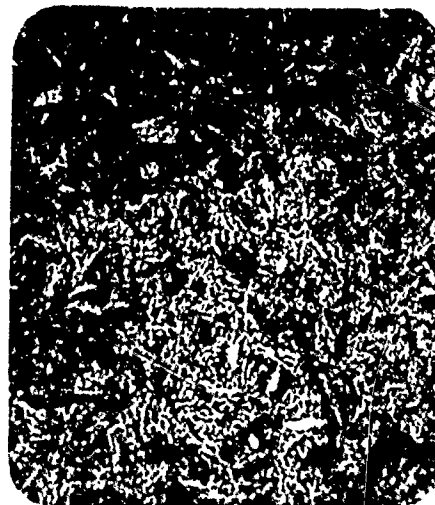


Fig. 22. x 500.
Specimen No. 31. Quenched from
850° C in oil. Tempered at
200° C.

All specimens etched in 2 % nitric acid in alcohol.

Plate VII.



Fig. 23. x 500.
Specimen No. 27 Q. Quenched
from 925° C in water.

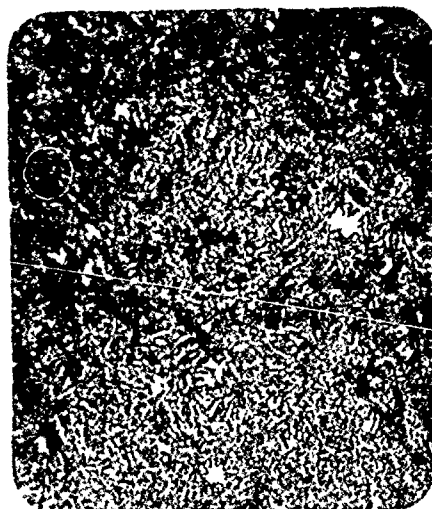


Fig. 24. x 500.
Specimen No. 26. Quenched from
925° C in water. Tempered at
225° C.

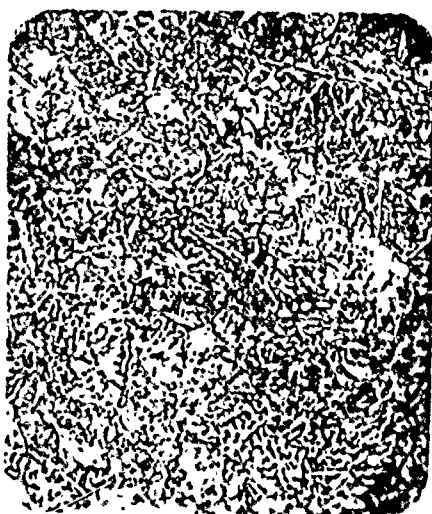


Fig. 25. x 500.
Specimen No. 925-O. Quenched
from 925° C in oil.

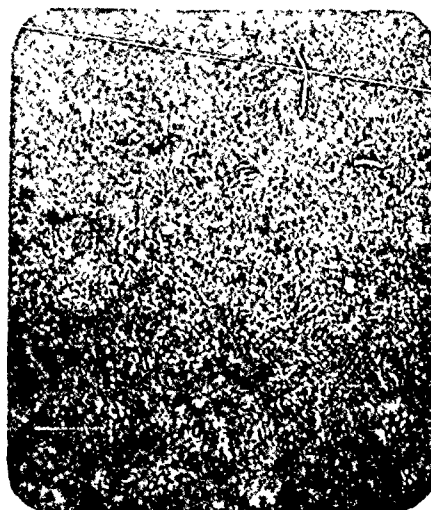


Fig. 26. x 500.
Specimen No. 28. Quenched from
925° C in oil. Tempered at
200° C.

All specimens etched in 2 % nitric acid in alcohol.

Plate VIII.



Fig. 27. x 500.
Specimen No. 47 Q. Quenched
from 775° C in water. Requenched
from 775° C in water.

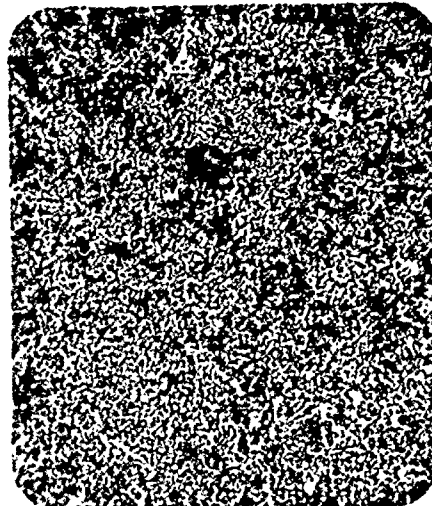


Fig. 28. x 500.
Specimen No. 49. Quenched from
775° C in water. Requenched
from 775° C in water. Tempered
at 150° C.



Fig. 29. x 500
Specimen No. 49 Q. Quenched
from 775° C in oil. Requenched
from 775° C in oil.



Fig. 30. x 500,
Specimen No. 50. Quenched from
775° C in oil. Requenched from
775° C in oil. Tempered at
285° C.

All specimens etched in 2 % nitric acid in alcohol.

Plate IX.

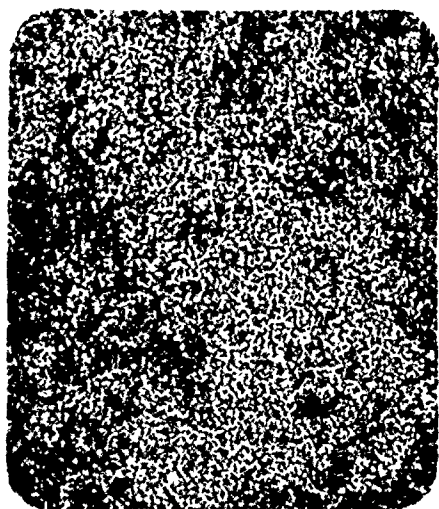


Fig. 31. x 500.
Specimen No. 41 Q. Quenched
from 850° C in water. Requenched
from 775° C in water.

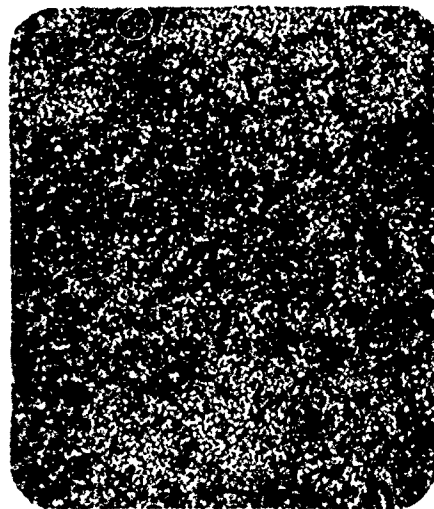


Fig. 32. x 500.
Specimen No. 40. Quenched from
850° C in water. Requenched from
775° C in water. Tempered at
200° C.

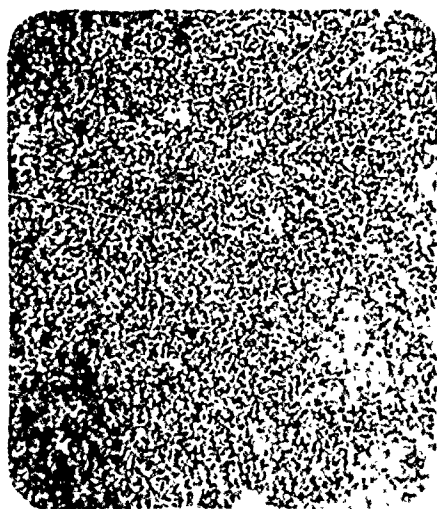


Fig. 33. x 500.
Specimen No. 38 Q. Quenched from
850° C in oil. Requenched from
775° C in oil.

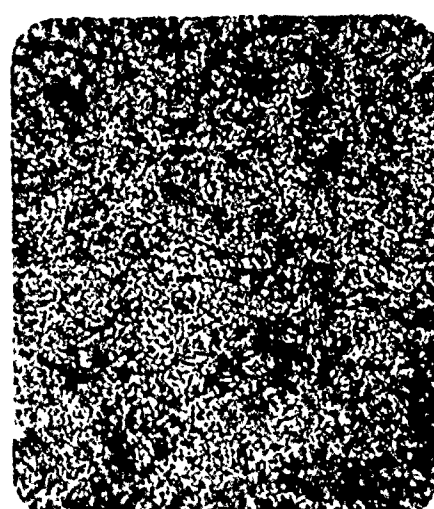


Fig. 34. x 500.
Specimen No. 39. Quenched from
850° C in oil. Requenched from
775° C in oil. Tempered at 150° C.

All specimens etched in 2 % nitric acid in alcohol.

Plate X.

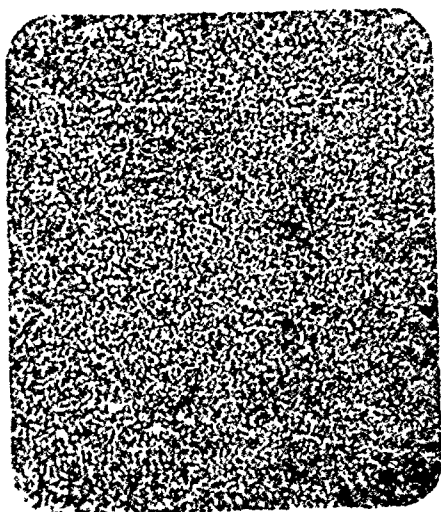


Fig. 35. x 500.
Specimen No. 22 Q. Quenched from
935° C in water. Requenched from
775° C in water.

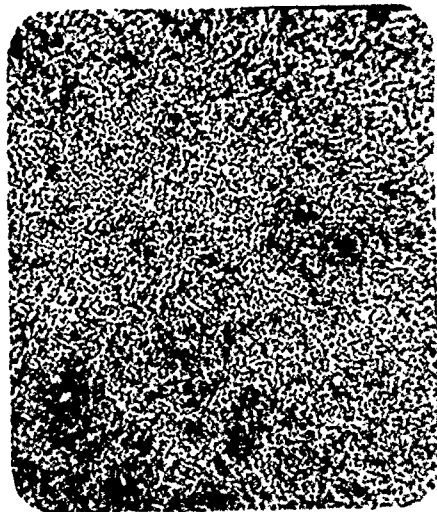


Fig. 36. x 500.
Specimen No. 23. Quenched from
935° C in water. Requenched
from 775° C in water. Tempered
at 300° C.

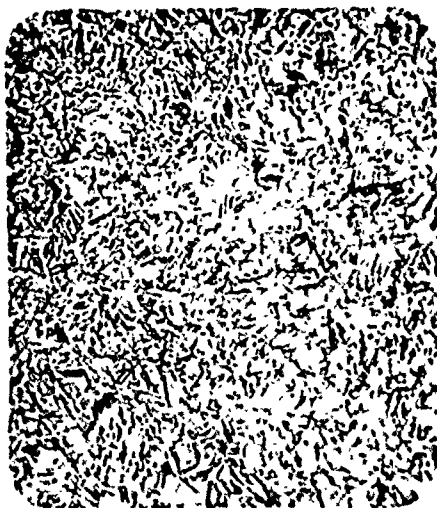


Fig. 27. x 500
Specimen No. 20 Q. Quenched from
925° C in oil. Requenched from
775° C in oil.

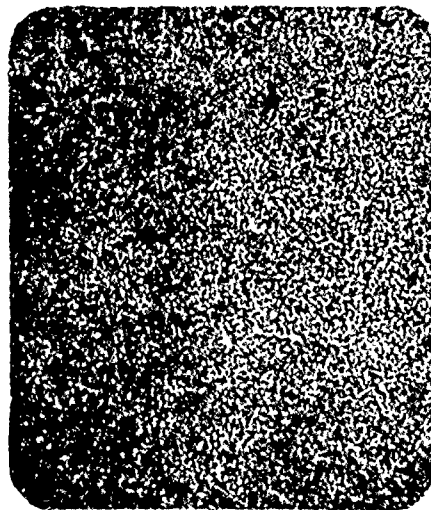


Fig. 28. x 500.
Specimen No. 19. Quenched from
935° C in oil. Requenched from
775° C in oil. Tempered 335° C.

All specimens etched in 2 % nitric acid in alcohol.

Plate XI.



Fig. 39, x 500.
Specimen No. 24 (core). Representative of emulsified martensite in the non-carburized areas.



Fig. 40, x 500.
Specimen No. 30. (core). Representative of martensite (needle structure) in the non-carburized areas.



Fig. 41, x 500.
Specimen No. 54. (core). Representative of pearlite, sorbite, troostite and ferrite in the non-carburized areas.
All specimens etched in 3 % nitric acid.

Plate XII.

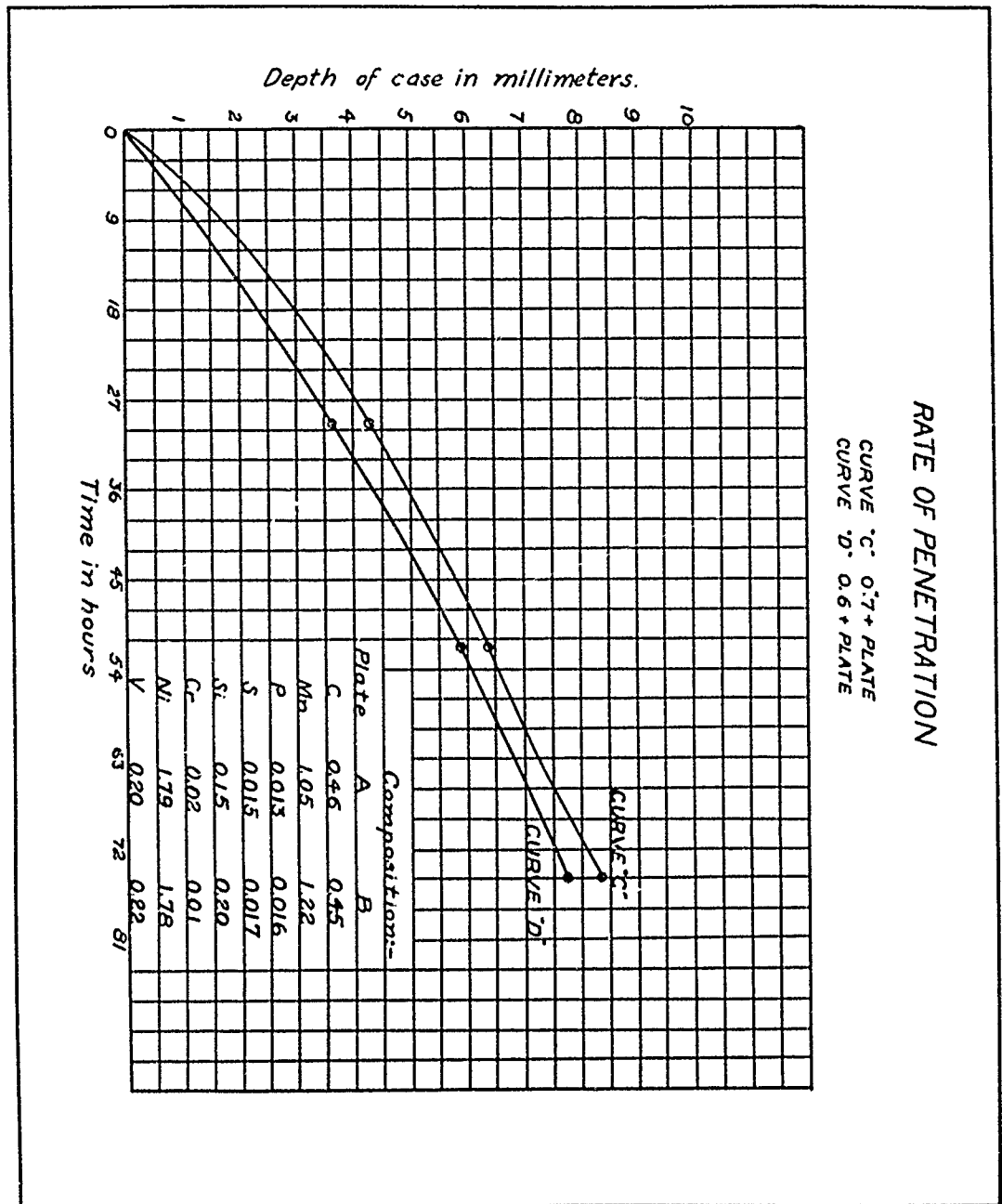


Plate XIII.

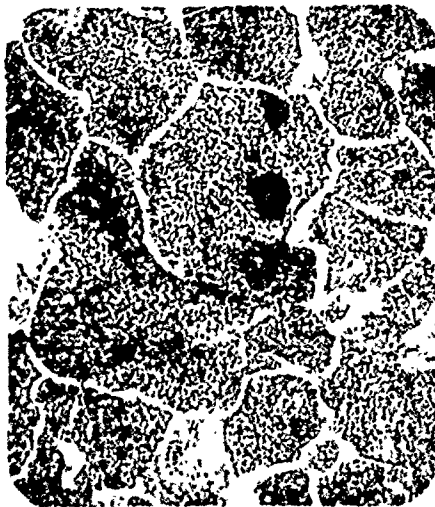


Fig. 42. x 500.
Structure in armor plates of lot C D E after
carburizing but before heat-treatment.



Fig. 43. x 100.
Exceptional structure in armor plates of lot
C D E after carburization but before heat treatment.

All specimens etched in 2 % nitric acid in alcohol.

Plate XIV.

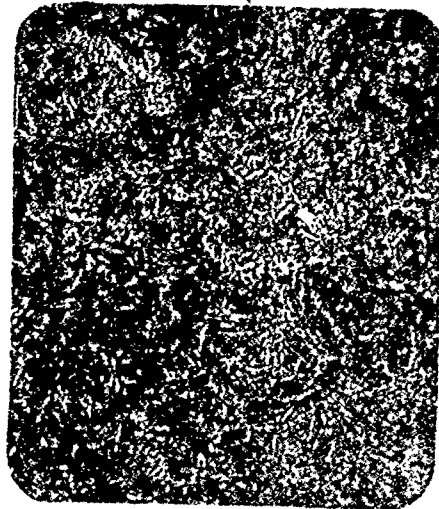


Fig. 44. x 500.
Structure in carburized zone of rolled armor plates
of lot C D E after heat treatment.

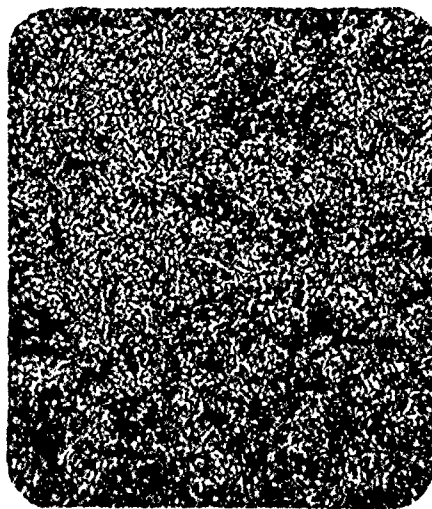


Fig. 45. x 500.
Structure in core of rolled armor plates of lot
C D E after heat treatment.

All specimens etched in 2 % nitric acid in alcohol.