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PROGRESS REPORT

November 28, 1941

to

WATERTOWN ARSENAL,  
UNITED STATES ARMY

Research Investigation  
of Armor Plate Steels.

S-547

BATTELLE  
MEMORIAL INSTITUTE

505 King Avenue

COLUMBUS, OHIO

FORM 43

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PROGRESS REPORT

on

RESEARCH INVESTIGATION OF ARMOR PLATE STEELS

to

WATERTOWN ARSENAL, UNITED STATES ARMY

by

M. L. Samuels and C. H. Lorig

*contract W-952-ORD-4072*

BATTELLE MEMORIAL INSTITUTE

November 28, 1941.

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PROGRESS REPORT  
ON  
RESEARCH: INVESTIGATION OF ARMOR PLATE STEELS  
to  
WATERTOWN ARSENAL, UNITED STATES ARMY  
from  
BATTELLE MEMORIAL INSTITUTE  
by  
M. L. Samuels and C. H. Lorig  
November 28, 1941

SUMMARY

A logical division of all the work so far completed on the armor plate investigation may be made as follows:

1. Representatives of Watertown Arsenal and Battelle made up a list of 40 steels with which to test the effect of composition on armor plate material.
2. The first 19 heats on the list were made and processed for testing. Ballistic properties were determined at Watertown.
3. A rather thorough postmortem examination of the 19 returned plates was made in an effort to determine whether or not there was any correlation between ballistic properties, chemical composition, and mechanical properties.
4. The fourth step consisted of making and processing the remainder of the experimental heats on the original list. It was thought

necessary to remake six heats from the first group of steels because of dirtiness. Subsequently one composition was added to the list by Watertown and three were added at Battelle, making a total of 49 steels. Also, two heats of a manganese-silicon cast iron were included.

The present report has to do with division 4, or the making and treating of the second group of 30 steels and 2 manganese-silicon cast irons.

The melting practice followed was similar to that described for the first 19 heats with the exception that 50 lb. heats were made. One plate from each heat was rolled to  $3/4$  inch and then machined to  $1/2$  inch in thickness so that the decarburized surfaces would be removed. A second plate from each heat was rolled to the final  $1/2$  inch thickness.

Critical points were determined for all the steels. Dilatometric curves, together with photomicrographs showing the as rolled structures, are given in Figures 8b to 115, inclusive. Critical points, as related to composition, are shown in Table X.

The machined plates were heated for quenching in a neutral salt bath. Hardness values after quenching and drawing are shown in Table XII.

Rolled plates from five heats were heated in air for quenching, for the purpose of producing still more decarburization. The machined and rolled plates from these five heats were shipped to Watertown on November 15. The purpose of testing this set of plates was to determine the effect of a decarburized surface on the ballistic properties. Heat treating data and the results of hardness tests from the rolled plates are shown in Table XIII.

Cleanliness ratings were made according to both the S.A.E. and Chevrolet methods. The results are shown in Table XIV.

Coupons were quenched from the temperatures designated for the corresponding plates and examined for undissolved carbides. The results are included in Table XI. An excessive amount of carbides was found in the three very high carbon steels. Further tests showed that a somewhat higher temperature causes complete solution, and the three high carbon plates were quenched from 1700°F.

The two manganese-silicon cast iron plates were not given any heat treatment.

Twenty-five steel plates and the cast iron material were shipped to Watertown by express, on November 21.

#### EXPERIMENTAL WORK

##### Preparation of Plates.

Experimental difficulties encountered in the use of a 15-pound ingot for the 1/2-inch plates studied in the first group made it advisable to use a larger ingot for the remainder of the armor plate steels. Accordingly, a 50-pound ingot was used in the manufacture of the plates included in the second group of steels.

In order to avoid decarburized surfaces on the finished plates the ingots were forged, cross rolled to width, and then rolled to 3/4-inch plate, the surfaces subsequently being machined to final thickness of 1/2 inch. Duplicate plates in the as rolled condition were prepared from excess material and have been held in reserve for any future tests that might be advisable.

The chemical compositions of the steels made in this group of plates are shown in Table X.



Dilatometric Critical Point Determinations.

Critical points for all steels were determined by the dilatometric method. The apparatus used in making these tests was the same as that described in the August 27 progress report.

Dilatometric curves for each steel are shown in Figures 86 to 115 inclusive, along with microstructures of the as rolled plates. The effect of the various alloys on the location of the critical points is shown by data summarized in Table X.

Preliminary Heat Treatment.

After critical point determinations had been made, preliminary heat treating data were collected on coupons cut from the rolled plates. Proper hardening temperatures and quenching media were determined by tests on small sections of coupon material, but approximate drawing temperatures were not determined as previous experience had shown that this data was of little value in treating the full size plates.

Tabulated data on the results of these tests are given in Table XI.

Heat Treatment of Plates.

Quenching of the plates in this group was carried out in the same manner as that described in the August 27 progress report. The plates were heated for quenching in a salt bath for 1 hour and were then quenched in oil or water, as the case may be, by means of the quenching fixture previously described. After quenching, the plates were removed from the fixture and immediately placed in a tempering furnace for 1/2 hour at 500° F. All plates were quenched after tempering to eliminate

TABLE XI. RESPONSE OF SPECIMENS TO QUENCHING TREATMENTS

Heat No.	A <sub>c3</sub> (°F.)	Quenching Temperature (1/2 hr.)	Quenching Medium	R <sub>c</sub> (Avg.)	Carbide Examination
7276	1421	1515°F.	Oil	60	No carbides
7277	1486	1590°F.	Water	55	" "
7278	1438	1540°F.	Oil	52	Few fine carbides in an undissolved grain boundary structure.
7279	1434	1540°F.	Oil	54	No carbides
7280	1441	1540°F.	Oil	54	" "
7281	1442	1540°F.	Oil	55	" "
7111	1495	1615°F.	Oil	57	Few small carbides in feathery-like grain boundary structure.
7326	1497	1590°F.	Water	50	No carbides
7327	1495	1590°F.	Oil	51	Few small carbides uniformly distributed.
7328	1486	1590°F.	Oil	53	No carbides
7329	1498	1615°F.	Oil	51	" "
7330	1455	1560°F.	Oil	55	" "
7340	1446	1540°F.	Oil	55	Few small carbides in an undissolved grain boundary structure.
7341	1533	1615°F.	Oil	52	Few small carbides randomly distributed.
7342	1465	1560°F.	Oil	58	No carbides
7343	1480	1590°F.	Oil	58	Few small carbides randomly distributed.
7344	1465	1560°F.	Water	56	Very few small spherical carbides in background.
7345	1419	1515°F.	Oil	53	No carbides
7347	1461	1560°F.	Oil	50	" "
7348	1433	1540°F.	Oil	60	Few fine carbides in background randomly distributed.
7349	1413	1515°F.	Oil	57	No carbides
7350	1453	1540°F.	Oil	57	" "
7351	1405	1515°F.	Oil	59	" "
7352	1451	1540°F.	Oil	57	" "
7353	1460	1560°F.	Oil	56	Few very fine carbides randomly distributed.

-Continued, page 81a

TABLE XI. -Continued

## RESPONSE OF SPECIMENS TO QUENCHING TREATMENTS

Heat No.	A <sub>c3</sub> (°F.)	Quenching Temperature (1/2 hr.)	Quenching Medium	R <sub>c</sub> (Avg.)	Carbide Examination
7354	1525	1615°F.	Oil	56	No carbides
7355	1498	1590°F.	Oil	58	" "
*7356	1416	1515°F.	Oil	65	Some carbides and elongated graphite stringers.
*7357	1368	1470°F.	Oil	57	Continuous grain boundary net work of carbides and also needles and globules within the grain. Very bad.
*7360	1427	1515°F.	Oil	59	Excessive amount of spherical carbides but net work not as continuous as 7357

## \* Carbide Solution Treatment

Specimens held 1 hr. at each temperature and oil quenched.

Heat No.	1700°F.	1800°F.	1900°F.
7356	No carbides	No carbides	No carbides
7357	Few spherical carbides	" "	" "
7360	No carbides	" "	" "

possible temper brittleness.

Subsequent tempering treatments necessary to produce the desired hardness were carried out in the Lindberg Cyclone tempering furnace and hardness values were determined after each treatment.

Tabulated data showing the hardness after quenching and tempering treatments for each plate are given in Table XII.

#### Heat Treatment of Decarburized Plates.

A group of five plates from heat numbers 7328, 7343, 7345, 7349, and 7352, were rolled to 1/2 inch in thickness and no effort was made to eliminate decarburization. These plates were heated for quenching in air and then quenched and tempered in the usual manner. A surface hardness of 350 to 370 Brinell was obtained on each plate. Duplicate plates from the same heats were treated in the machined condition, using a neutral salt bath for heating and the standard quenching procedure, so that a comparison of ballistic properties might be made between plates in the decarburized condition and identical material in the homogeneous condition.

Data on the heat treatment of the decarburized plates are given in Table XIII, and heat treating data for the corresponding machined plates may be found in Table XII.

#### Additional Compositions Added to the Original Group.

Two heats of a high manganese-silicon cast iron, which had shown exceptionally good impact resistance in the as cast condition, were cast into 1/2 inch plates and included in this second group for ballistic testing. It was thought that a possible use for a material of this type

TABLE XII. HEAT TREATMENT OF MACHINED PLATES

quenched from a Salt Bath

Heat No.	Critical Points		Quenching Temperature	Quenching Medium	Preliminary Draw 500°F. 1/2 hour	Brinell hardness after			
	Ar <sup>1</sup>	Ac <sup>3</sup>				Draw No.1	Draw No.2	Draw No.3	Draw No.4
7276	1187°F.	1421°F.	1500°F.	Oil	514(BHN)	725° 1 hr.	900° 1 hr.	441	352-356
7277	1274°F.	1466°F.	1600°F.	Water	444	725° 1/2 hr.			333-388
7278	1235°F.	1438°F.	1550°F.	Water	502	850° 1/2hr.	850° 1/2hr.	900° 1/2hr.	950° 1 hr.
7279	1193°F.	1434°F.	1550°F.	Oil	485	477	444	444	363-375
7280	607°F.	1441°F.	1550°F.	Oil	477	850° 1 hr.	900° 1 hr.	950° 1 hr.	1000° 1/2hr.
7281	567°F.	1442°F.	1510°F.	Oil	477	401	415	401	341-341
7111	1163°F.	1485°F.	1600°F.	Oil	477	850° 1 hr.	900° 1 hr.	950° 1 hr.	1000° 3/4hr.
7326	1286°F.	1497°F.	1600°F.	Water	464	398	383	383	368-368
7327	1318°F.	1499°F.	1585°F.	Oil	477	900° 1 hr.	950° 1/2hr.	1000° 1 hr.	1000° 3/4hr.
7328	672°F.	1466°F.	1590°F.	Oil	514	700° 1/2hr.	700° 3/4hr.	800° 1/2hr.	800° 1/2hr.
7329	1309°F.	1498°F.	1585°F.	Oil	495	429	444	406	338
7330	1216°F.	1485°F.	1560°F.	Oil	555	600° 1 hr.	800° 1 hr.	850° 1 hr.	850° 1 hr.
7340	1191°F.	1446°F.	1550°F.	Oil	514	398	388	370-370	
7341	1219°F.	1533°F.	1585°F.	Oil	477	900° 1 hr.	1000° 1 hr.	1050° 1 hr.	1100° 1/2hr.
7342	1263°F.	1465°F.	1550°F.	Oil	534	401	401	388	388
7343	1175°F.	1480°F.	1590°F.	Oil	555	950° 1 hr.	1000° 1 hr.	1050° 1 hr.	1100° 1/2hr.
						415	388	388	363-363
						444	415	393	375-363
						415	388	388	363-363
						415	401	401	388
						600° 1/2hr.	600° 3/4hr.	700° 1/2hr.	700° 1 hr.
						530	510	510	504

\* Air hardening characteristics made this plate unmachinable. Rolled to 1/2 inch

REPRODUCED AT GOVERNMENT EXPENSE

TREATMENT OF MACHINED PLATES

rolled from a Salt Bath

Wire	Brinell Hardness after Drawing Treatment							Final Tempering Treatment		
	Draw No. 1	Draw No. 2	Draw No. 3	Draw No. 4	Draw No. 5	Draw No. 6	Draw No. 7	Time (hrs)	Temperature (°F)	Hardness (BHN) avg.
10	900°							1	900	357
10	367-356									
10								1/2	725	366
10	368									
10	850°	900°	950°					1	950	369
10	444	444	363-375							
10										
10	900°	950°	1000°					1	1000	341
10	415	401	341-341							
10										
10	900°	950°	1000°	1050°				1/2	1050	365
10	401	363	388	366-363						
10										
10	950°	1000°	1000°					1 3/4	1000	369
10	283	363-373	373-361							
10										
10	700°	800°	800°	850°	850°	900°	950°	1/2	950	363
10	444	406	388	360	388	380	363-363			
10										
10	850°	850°						1/4	850	368
10	388	368-363								
10										
10	935°	1000°						1	1000	370
10	383	370-370								
10										
10	600°	700°	700°	1050°	1100°	1100°		1 1/4	1100	375
10	474	467	464	388	388	375-375				
10										
10	900°	950°	1000°	1050°				1/2	1050	366
10	415	388	398	370-363						
10										
10	900°	950°	1000°					1	1000	369
10	415	393	375-363							
10										
10	900°	950°	1000°					1	1000	363
10	388	388	363-363							
10										
10	1000°	1050°	1100°	1125°	1150°			1/2	1150	355
10	401	388	388	388	359-352					
10										
10	1000°	1050°	1100°	1125°	1150°	1200°		1/4	1200	365
10	401	401	388	388	388	368-363				
10										
10	600°	700°	700°	1050°	1100°	1150°	1225°	1	1225	363
10	510	510	504	429	415	401	363-363			

Plate. Rolled to 1/2 inch thickness.

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TABLE XII. - Continued.

HEAT TREATMENT OF MACHINED PLATES

Quenched from a Salt Bath

Heat No.	Critical Points		Quenching Temperature	Quenching Medium	Preliminary Draw 500°F. 1/2 hr.	Brinell hardness after				
	Ar <sup>1</sup>	Ac <sup>2</sup>				Draw No.1	Draw No.2	Draw No.3	Draw No.4	Draw No.5
7344	1247°F.	1465°F.	1550°F.	Water	578 (S.H.)	850° 1 hr.	900° 1 hr.	950° 1/2hr.	1000° 1 hr.	356-347
7345	1144°F.	1419°F.	1515°F.	Oil	522	600° 1/2hr.	600° 3/4hr.	700° 1/2hr.	700° 1 hr.	9. 370 481 477 467 370
7347	1253°F.	1461°F.	1550°F.	Oil	471	950° 1 hr.	363-383			
7348	801°F.	1433°F.	1550°F.	Oil	547	900° 1 hr.	950° 1 hr.	1000° 1 hr.	1050° 1 hr.	1. 415 406 390 388 360
7349	879°F.	1413°F.	1515°F.	Oil	555	600° 1/2hr.	600° 3/4hr.	700° 1/2hr.	700° 1 hr.	10. 514 510 477 467 380
7350	928°F.	1453°F.	1560°F.	Oil	534	850° 1 hr.	900° 1 hr.	950° 1 hr.	1000° 1 hr.	429 415 401 375-375
7351	734°F.	1405°F.	1500°F.	Oil	514	900° 1 hr.	950° 1 hr.	1000° 1 hr.	1050° 1 hr.	1. 401 415 401 388 370
7352	1203°F.	1451°F.	1560°F.	Oil	532	600° 1/2hr.	600° 3/4hr.	700° 1/2hr.	700° 1 hr.	10. 554 534 522 514 370
7353	1251°F.	1460°F.	1560°F.	Oil	477	725° 1 hr.	900° 1 hr.	343-356		
7354	1292°F.	1525°F.	1600°F.	Water	555	900° 3/4hr.	950° 1 hr.	383-354		
7355	1214°F.	1498°F.	1600°F.	Oil	477	800° 1 hr.	900° 1 hr.	950° 1/2hr.	1000° 1 hr.	10. 444 388 409 393 360
#7356	1303°F.	1416°F.	1700°F.	Oil	578	725° 1 hr.	900° 1 hr.	950° 1 hr.	1000° 1 hr.	10. 592 461 415 385 370
7357	811°F.	1368°F.	1700°F.	Oil	269	800° 1 hr.	363-363			
#7358	1314°F.	1427°F.	1700°F.	Oil	564	725° 1 hr.	900° 1 hr.	950° 1 hr.	1000° 1 hr.	10. 601 477 429 393 370

#These plates were not quenched from a salt bath but were graphite packed in

REPRODUCED AT GOVERNMENT EXPENSE

ATTACHMENT OF MACHINED PLATES

ched from a Salt Bath

Finell hardness after drawing Treatment							Final Tempering Treatment		
Draw No.2	Draw No.3	Draw No.4	Draw No.5	Draw No.6	Draw No.7	Draw No.8	Time (hrs.)	Temperature (°F.)	hardness (BHN)avg.
900°	950°	1000°					1	1000	351
1 hr.	1/2hr.	1 hr.							
388	388	356-347							
600°	700°	700°	950°				1	950	371
3/4hr.	1/2hr.	1 hr.	1 hr.						
481	477	467	375-366						
							1	950	363
950°	1000°	1050°	1100°				1	1100	369
1 hr.	1 hr.	1 hr.	1 hr.						
406	390	388	363-375						
600°	700°	700°	1050°	1075°	1075°		2	1075	371
3/4hr.	1/2hr.	1 hr.	1 1/2hr.	1 hr.	1 hr.				
510	477	467	380	380	375-368				
900°	950°	1000°					1	1000	375
1 hr.	1 hr.	1 hr.							
415	401	375-375							
950°	1000°	1050°	1100°				1	1100	369
1 hr.	1 hr.	1 hr.	1 hr.						
415	401	388	375-363						
600°	700°	700°	1000°				1	1000	370
3/4hr.	1/2hr.	1 hr.	1 hr.						
534	522	514	370-370						
900°							1	900	347
1 hr.									
43-356									
950°							1	950	358
1 hr.									
363-354									
900°	950°	1000°	1050°	1100°			1	1100	362
1 hr.	1/2hr.	1 hr.	1 hr.	1 hr.					
388	409	393	385	368-356					
900°	950°	1000°	1050°	1100°	1100°	1125°	1/4	1125	365
1 hr.	1 hr.	1 hr.	1/2hr.	1/4hr.	1/2hr.	1/4hr.			
461	415	385	375	375	---	363-368			
							1	800	363
900°	950°	1000°	1050°	1100°	1100°	1125°	1/4	1125	363
1 hr.	1 hr.	1 hr.	1 hr.	1/4hr.	1/2hr.	1/4hr.			
477	429	393	375	375	--	363-363			

were graphite packed in the furnace to prevent decarburization.

TABLE XIII. HEAT TREATMENT OF PLATES IN ASROLLED CONDITION

Quenched from an Oxidizing Atmosphere

Heat No.	Critical Points		Quench- ing Tempera- ture	Quench- ing Medium	Preliminary Draw 500°F. 1/2 hr.	Draw No.1	Draw No.2	Draw No.3	Draw No.4	Brinell
	A <sub>r</sub> 1	A <sub>c</sub> 3								Draw No.5
7328	672°F.	1486°F.	1590°F.	Oil	488(BHN)	600° 1/2hr. 499	600° 3/4hr. 457	700° 1/2hr. 448	700° 1 hr. 444	800° 1/2hr. 444
7343	1175°F.	1480°F.	1590°F.	Oil	514	600° 1/2hr. 495	600° 3/4hr. 488	700° 1/2hr. 477	700° 1 hr. 474	800° 1/2hr. 471
7345	1144°F.	1419°F.	1515°F.	Oil	495	600° 1/2hr. 499	600° 3/4hr. 477	700° 1/2hr. 477	700° 1 hr. 471	800° 1/2hr. 438
7349	879°F.	1413°F.	1515°F.	Oil	526	600° 1/2hr. 488	600° 3/4hr. 474	700° 1/2hr. 477	700° 1 hr. 454	800° 1/2hr. 438
7352	1203°F.	1451°F.	1560°F.	Oil	495	600° 1/2hr. 503	600° 3/4hr. 495	700° 1/2hr. 510	700° 1 hr. 503	800° 1/2hr. 471

Hardness after Drawing Treatment									Final Tempering Treatment		
Draw No.6	Draw No.7	Draw No.8	Draw No.9	Draw No.10	Draw No.11	Draw No.12	Draw No.13	Draw No.14	Time (hrs.)	Temperature (°F.)	Hardness (BHN) avg.
950° 1 hr 412	975° 1-1/2hr. 409	1025° 1 hr. 401	1050° 1 hr. 393	1050° 1-1/2hr. 388	1100° 3/4hr. 375	1100° 1/2hr. 368-368			1-1/4	1100	368
950° 1 hr. 441	975° 2 hr. 438	1025° 2 hr. 429	1050° 2 hr. 444	1100° 2 hr. 429	1150° 2 hr. 423	1225° 1 hr. 388	1225° 3/4hr. 385	1250° 1/2hr. 356-368	1/2	1250	362
950° 1hr. 361-363									1	950	362
950° 1 hr 401	975° 3/4hr 388	1000° 1/2hr 388	1050° 3/4hr 375-380	1050° 1/2hr. 380-375	1050° 1 hr 375-375				2-1/4	1050	375
950° 1hr. 388	975° 1/2hr. 388	1000° 1 hr. 350-356							1	1000	355

might exist in the cast armor plate field provided that satisfactory ballistic properties could be attained. The cast iron plates are to be tested in the as cast condition.

In addition to the cast plates, two graphitic steels and a manganese-copper-molybdenum austenitic steel were added to the original list of compositions. These steels were forged, rolled, and heat treated in the usual manner, and were all tempered to the specified hardness range of 350 to 370 Brinell. The graphitic steels were included in this group because of the wide range of properties obtainable by simple heat treatment, and the austenitic steel was thought to be practical from a standpoint of its inherent work hardening characteristics.

Heat treating data on the austenitic steel and the graphitic steels are included in Table XII.

#### Microscopic Examination of the Plates.

a. Inspection for Cleanliness. Small longitudinal specimens representing the full cross-section of each rolled plate were examined for inclusions. The specimens were rated according to both the S.A.E. and Chevrolet methods, and the results are shown in Table XIV.

b. Examination of the As-rolled Microstructures. After the inspection for cleanliness, the specimens were etched in order to reveal the grain size and the nature of the structural constituents of the plates in the as rolled condition. Typical locations were photographed and are shown in Figures 86 to 115, inclusive. The photomicrographs are included alongside the dilatometer curves because there is ordinarily a close relationship between grain size, structural constituents, and the location of the critical points.

TABLE XIV. CLEANLINESS RATING

Heat No.	(1) S.A.E. Rating			General (2)	Chevrolet Rating (3)	Remarks
	Length of Longest.	Average Length of Long Inclusions	Back-ground			
7276	12vdg	2 1/2	C-	f-	S <sub>8</sub> O <sub>3</sub>	Three heavy silicates * (7092)
7277	7vdg	3	B+	g-	S <sub>2</sub> O <sub>4</sub>	(7091)
7278	29vdgh	5	C+	p+	S <sub>3</sub> O <sub>4</sub>	Nine long, heavy inclusions (7092)
7279	3vd	1 1/2	B+	g+	S <sub>2</sub> O <sub>3</sub>	(7099)
7280	22vd	6	B+	g-	S <sub>2</sub> O <sub>4</sub>	One long inclusion (7101)
7281	15vdg	2 1/2	C	f+	S <sub>2</sub> O <sub>3</sub>	(7103)
7311	7vdg	2	B+	g+	S <sub>2</sub> O <sub>3</sub>	
7326	16vdg	5	B	f+	S <sub>2</sub> O <sub>4</sub>	
7327	6vd	3	B-	g	S <sub>2</sub> O <sub>4</sub>	
7328	8vdg	3	B	f-	S <sub>2</sub> O <sub>4</sub>	Inclusion colonies
7329	9vd	3	B+	g+	S <sub>2</sub> O <sub>3</sub>	
7330	5vdg	2	B+	g	S <sub>3</sub> O <sub>4</sub>	
7340	7vdg	2	C+	f+	S <sub>2</sub> O <sub>4</sub>	
7341	3vdg	1	H+	e-	S <sub>2</sub> O <sub>2</sub>	Very clean
7342	4vdg	2	B	g	S <sub>2</sub> O <sub>3</sub>	
7343	15vdg	2	B-	g-	S <sub>2</sub> O <sub>3</sub>	
7344	9vdg	3	B	g	S <sub>2</sub> O <sub>4</sub>	
7345	9vdg	4	B+	g-	S <sub>2</sub> O <sub>3</sub>	
7347	8vdg	2	B	f+	S <sub>2</sub> O <sub>3</sub>	Inclusion colonies
7348	13vdg	3	B	f	S <sub>2</sub> O <sub>3</sub>	One clustered section
7349	7vdg	3	B-	g	S <sub>2</sub> O <sub>6</sub>	
7350	7vdg	3	B-	f-	S <sub>5</sub> O <sub>4</sub>	One large, isolated silicate
7351	5vdg	2	B+	g+	S <sub>2</sub> O <sub>4</sub>	
7352	3vd	1	A	e	S <sub>2</sub> O <sub>2</sub>	Very clean
7353	4vdg	2	B	g+	S <sub>2</sub> O <sub>5</sub>	
7354	1vd	1	C-	f-	S <sub>2</sub> O <sub>4</sub>	Densely scattered inclusions
7355	2vd	1	A-	e-	S <sub>2</sub> O <sub>3</sub>	
7356	3vd	2	B	g+	S <sub>2</sub> O <sub>3</sub>	
7357	2vd	1	A	e	S <sub>2</sub> O <sub>2</sub>	Very clean
7360	4vdg	1	B	g-	S <sub>3</sub> O <sub>2</sub>	Dirty layer near rolled surface edges

(1) vd - very divided  
g - group  
h - very wide and heavy

A, B, C, D rates back-ground from good to bad.

(2) e - excellent  
g - good  
f - fair  
p - poor

\* Replaced heats

(3) S - sulphides and inclusions elongated on rolling.  
O - oxides and inclusions not elongated on rolling.

c. Inspection for Undissolved Carbides. Coupons from all of the rolled plates were heated for 1/2 hour at the temperatures selected for quenching the large plates (approximately 100°F. above the  $A_{c3}$  point) and quenched in oil. Examination for undissolved carbides was then made and the results are given in Table XI.

It was necessary to go to higher temperatures to effect complete solution of the carbides in the three very high carbon steels. Specimens from each steel were heated for 1 hour at 1700, 1800, and 1900° F., respectively, and then oil quenched. It was found that 1700°F. was high enough to completely dissolve the carbides, and this temperature was subsequently employed for quenching the large plates.

#### DISCUSSION OF RESULTS

The treatment of the plates listed in this report was similar to that applied to the first group with the exception of machining the surfaces. The machined surfaces were free of decarburization, of course, when the plates were put into the neutral salt bath for heating preparatory to quenching. There is good reason for believing that surface and core hardness will be almost the same for the machined plates.

The extent of decarburization on the five rolled plates, shipped to Watertown on November 15, will not be known until cross section hardness surveys are made on the returned plates. Different steels decarburize at widely different rates in a given atmosphere and it is possible that none of the five steels will show a response equal to Heat No. 7093 from the first group. If none of these compositions are very susceptible to decarburization they will probably show approximately the same core hard-

ness in both the machined and rolled conditions. Similar ballistic properties would be expected in that case.

Chemical analyses for carbon, manganese, and silicon were made on all heats. The following tabulation shows those heats which were out of the specification range, how much they were off, and what elements were out of line.

Heat Number		Chemical Analysis	
		% C	% Mn
7276	Intended	.42/.48	.60/.90
	Actual	.50	1.07
7277	Intended	.42/.48	
	Actual	.39	
7278	Intended		.60/.90
	Actual		.91
7279	Intended	.32/.38	.60/.90
	Actual	.40	.93
7280	Intended		.60/.90
	Actual		.92
7281	Intended		1.4/1.6
	Actual		1.63
7356	Intended	1.10/1.25	
	Actual	1.02	

The ballistic properties of the high carbon, manganese-molybdenum-copper steel, Heat No. 7357, will be of special interest. Table XII shows that after quenching and drawing at 500° F. this plate showed a Brinell hardness of only 269. Magnetic tests showed that the steel was at least partly austenitic so it was drawn at a still higher temperature, 800° F., in order to produce further transformation. The hardness after this draw happened to fall into the middle of the specification range. The structure should consist of austenite plus transformation products. It

is possible that the work hardening characteristics of this steel may be different from those of conventional armor plate steels.

Some thought should be given to the possible use of 19 duplicate plates in the rolled condition, which are still on hand. The only additional cost which would be involved is that of heat treating. These duplicate plates could be drawn to a hardness level differing from that at which the corresponding plates are to be tested for the purpose of obtaining comparative results on the effect of hardness upon ballistic properties.

#### FUTURE WORK

The subject of future work will be discussed during the next visit to Watertown.

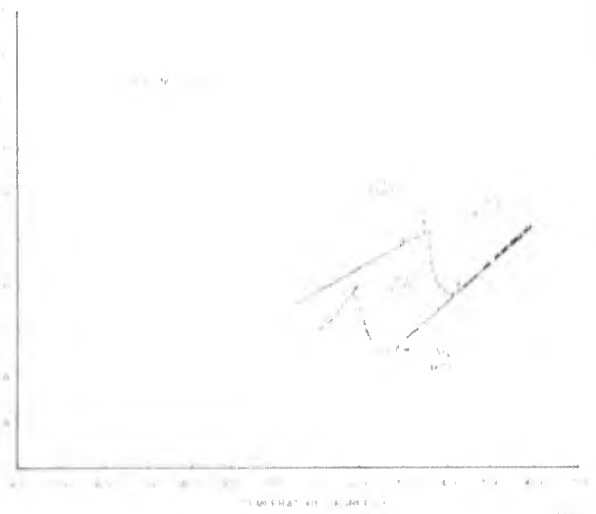
Data from which this report was written are recorded in Notebooks 799 and 849, pages 62 to 100, and pages 4 to 38, respectively.

MLS-CHL:DW  
12-2-41



Figure 86. Heat No. 7276 - Repeat on Heat 7092.  
Microstructure of the as-rolled 3/4-in. plate.  
13310  
X100

Actual analysis:  
Carbon ----- 0.50%  
Manganese ----- 1.07  
Silicon ----- 0.30



Dilatometer Curves

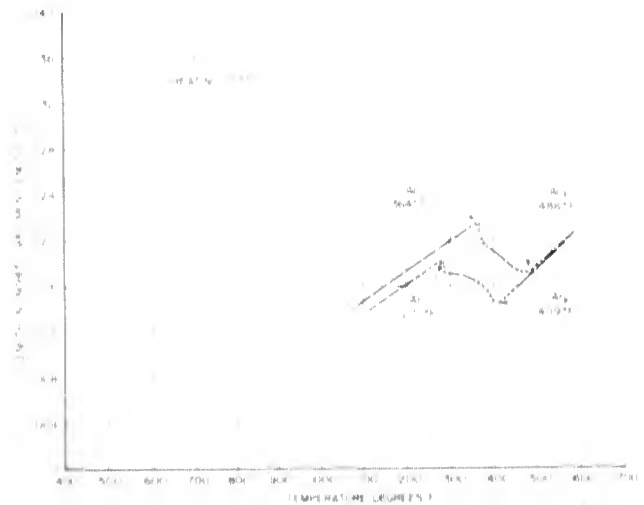
Intended composition:  
Carbon ----- .42/.48%  
Manganese ----- .60/.90  
Silicon ----- .20/.30

Grainal Treated



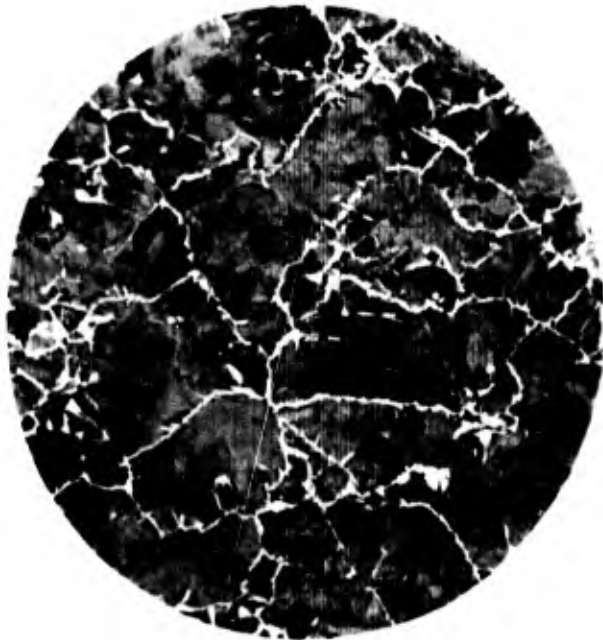
Figure 87. Heat No. 7277 - Repeat on Heat 7091  
(Aluminum treated). Microstructure of the  
as-rolled 3/4-in. plate.  
13311  
X100

Actual analysis:  
Carbon ----- 0.39%  
Manganese ----- 0.35  
Silicon ----- 0.23



Dilatometer Curves

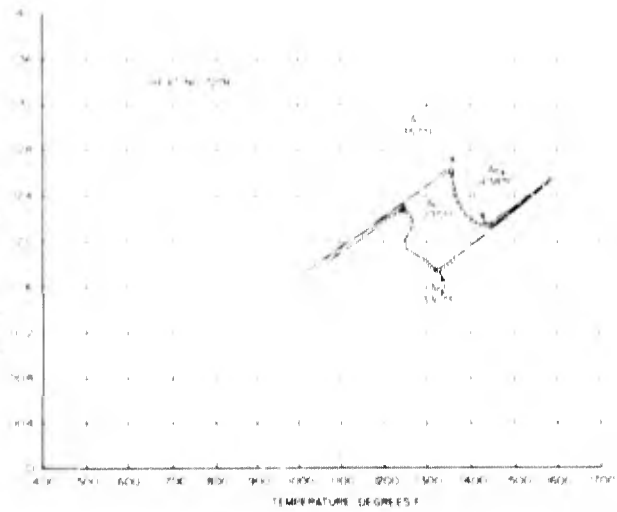
Intended composition:  
Carbon ----- .42/.48%  
Manganese ----- .30/.40  
Silicon ----- .20/.30



13312  
Figure 88. Heat No. 7278 - Repeat on Heat 7092.  
Microstructure of the as-rolled 3/4-in. plate.  
X100

## Actual analysis:

Carbon ----- 0.47%  
Manganese ----- 0.91  
Silicon ----- 0.26



Dilatometer Curves

## Intended composition:

Carbon ----- .42/.48%  
Manganese ----- .60/.90  
Silicon ----- .20/.30

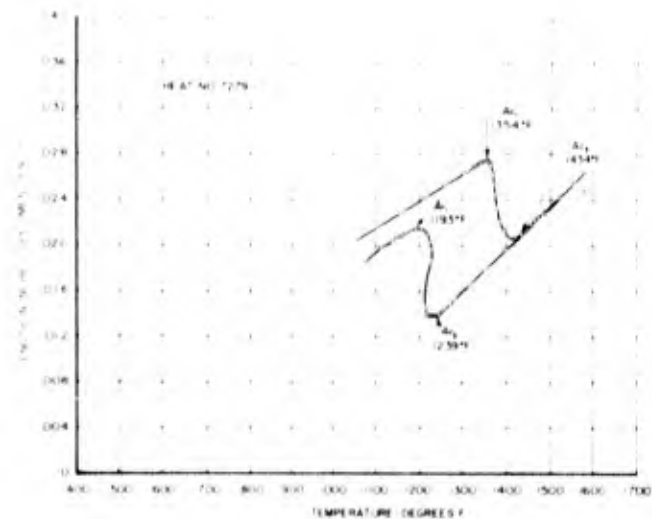
## Aluminum Treated



13313  
Figure 89. Heat No. 7279 - Repeat on Heat 7099.  
Microstructure of the as-rolled 3/4-in. plate.  
X100

## Actual analysis:

Carbon ----- 0.40%  
Manganese ----- 0.93  
Silicon ----- 0.25



Dilatometer Curves

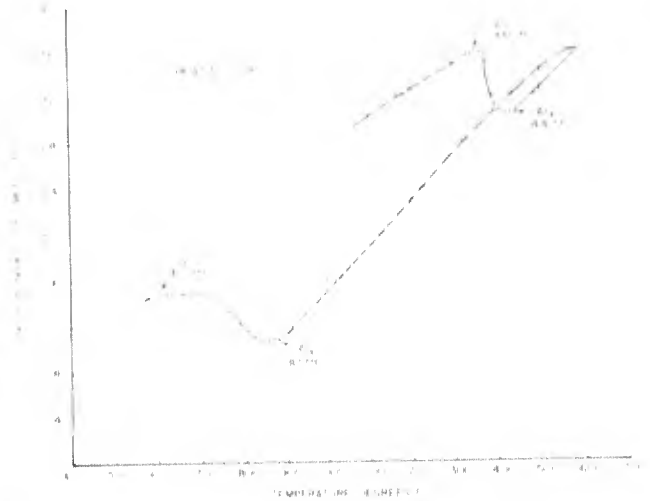
## Intended composition:

Carbon ----- .32/.38%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Nickel ----- 1.3/1.6  
Chromium ----- .70/.90



Figure 90. Heat No. 7280 - Repeat on Heat 7101.  
Microstructure from the as-rolled 3/4-in. plate.  
13314  
X100

Actual analysis:  
Carbon ----- 0.35%  
Manganese ----- 0.92  
Silicon ----- 0.28



Dilatometer Curves

Intended composition:

Carbon ----- .32/.38%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Nickel ----- 1.3/1.6  
Chromium ----- .70/.90  
Molybdenum ----- .20/.30

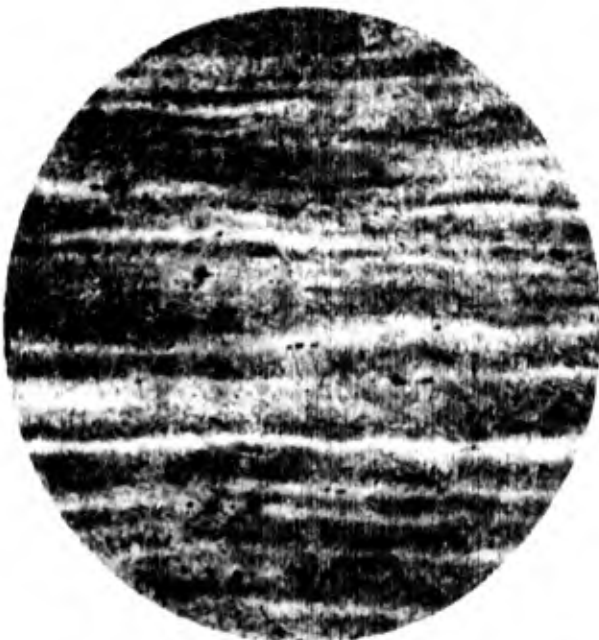
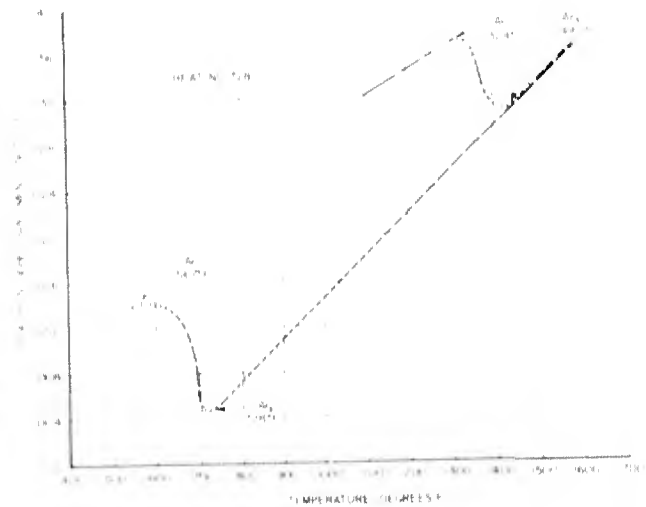


Figure 91. Heat No. 7281 - Repeat on Heat 7103.  
Microstructure from the as-rolled 3/4-in. plate.  
13315  
X100

Actual analysis:  
Carbon ----- 0.36%  
Manganese ----- 1.63  
Silicon ----- 0.30



Dilatometer Curves

Intended composition:

Carbon ----- .32/.38%  
Manganese ----- 1.4/1.6  
Silicon ----- .20/.30  
Nickel ----- 1.3/1.6  
Chromium ----- .75/.90  
Molybdenum ----- .25/.35

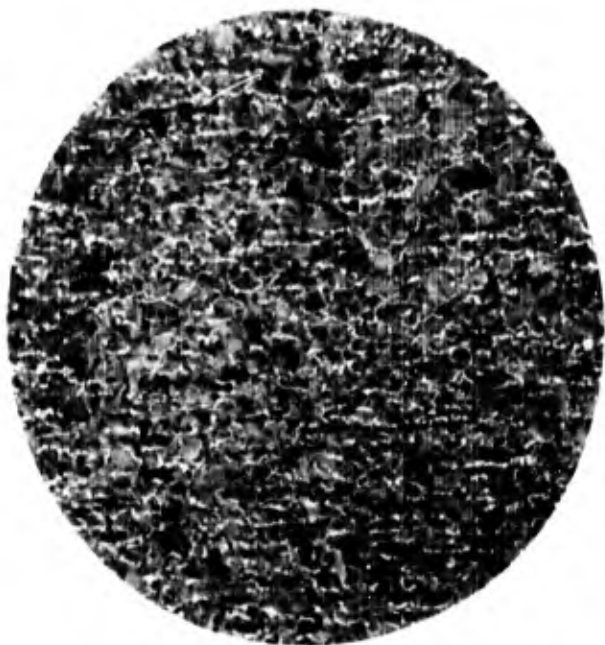
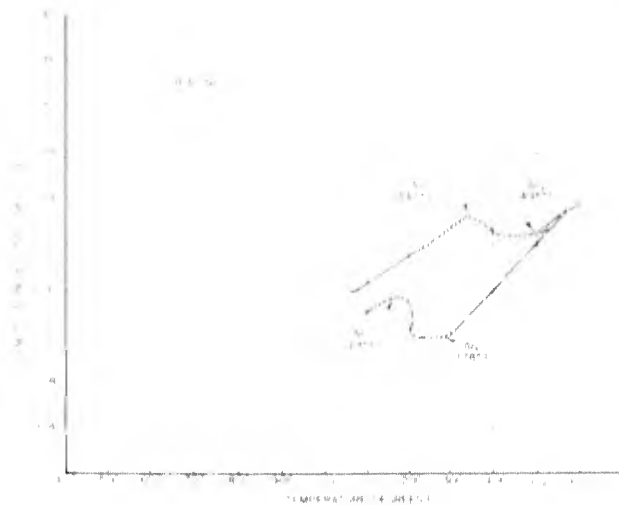


Figure 92. Heat No. 7111. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:

Carbon ----- 0.46%  
Manganese ----- 1.58  
Silicon ----- 0.20

13316



Dilatometer Curves

Intended composition:

Carbon ----- .42/.48%  
Manganese ----- 1.4/1.6  
Silicon ----- .20/.30  
Vanadium ----- .10/.20

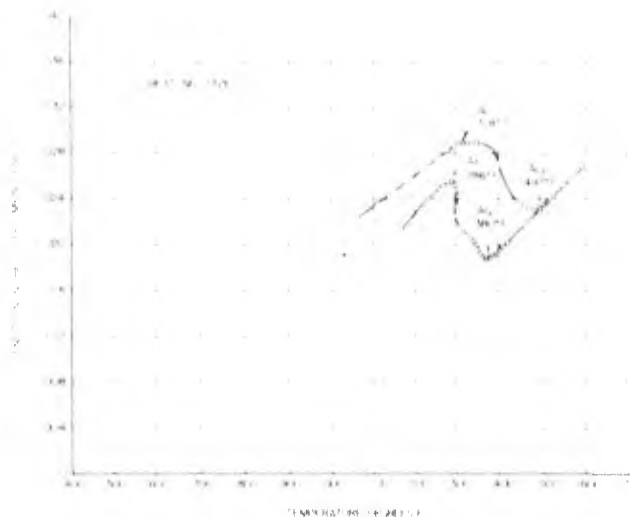


Figure 93. Heat No. 7326. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:

Carbon ----- 0.30%  
Manganese ----- 0.73  
Silicon ----- 0.20

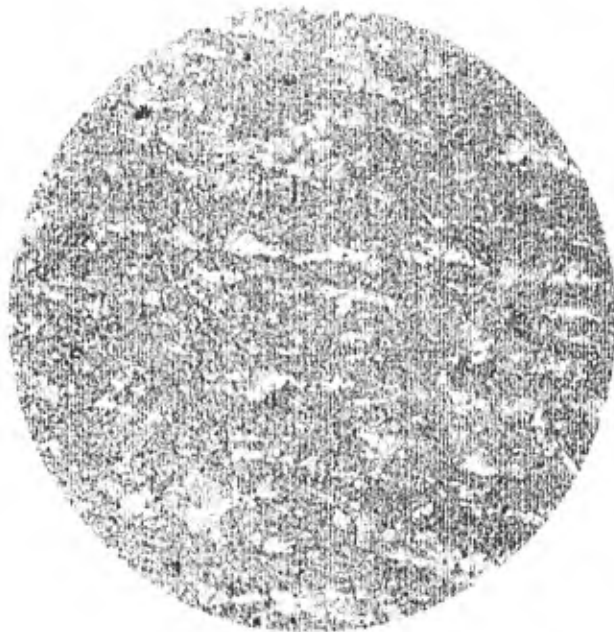
13317



Dilatometer Curves

Intended composition:

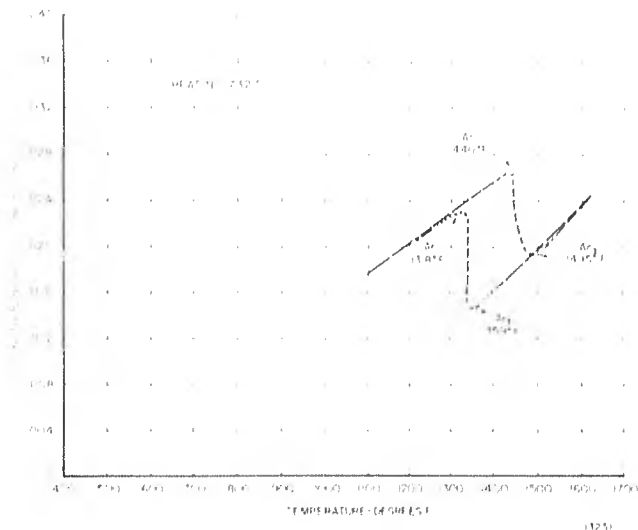
Carbon ----- .30/.35%  
Manganese ----- .60/.80  
Silicon ----- .20/.30  
Chromium ----- .90/1.10



13318  
 Figure 94. Heat No. 7327. Microstructure  
 of the as-rolled 3/4-in. plate. X100

Actual analysis:

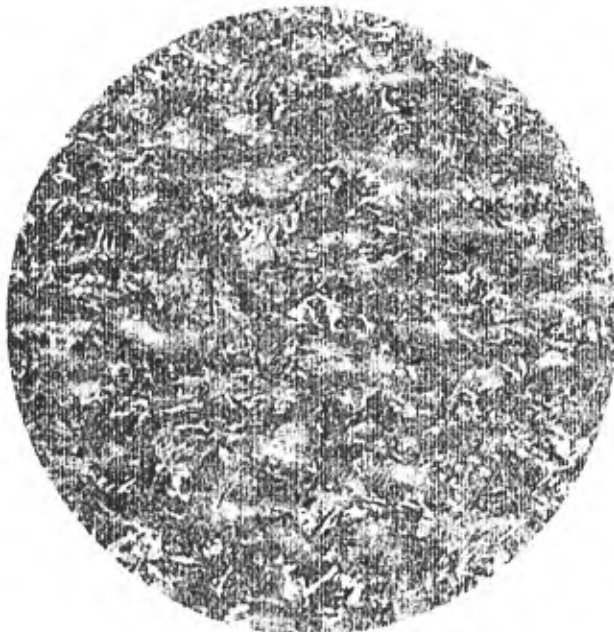
Carbon ----- 0.35%  
 Manganese ----- 0.88  
 Silicon ----- 0.26



Dilatometer Curves

Intended composition:

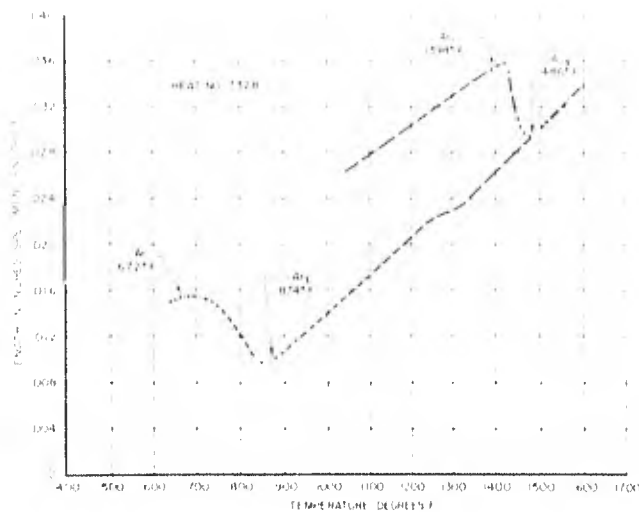
Carbon ----- .30/.35%  
 Manganese ----- .60/.90  
 Silicon ----- .20/.30  
 Chromium ----- 2.3/2.7



13319  
 Figure 95. Heat No. 7328. Microstructure  
 of the as-rolled 3/4-in. plate. X100

Actual analysis:

Carbon ----- 0.34%  
 Manganese ----- 0.89  
 Silicon ----- 0.20



Dilatometer Curves

Intended composition:

Carbon ----- .30/.35%  
 Manganese ----- .60/.90  
 Silicon ----- .20/.30  
 Chromium ----- 1.3/1.7  
 Molybdenum ----- .35/.45

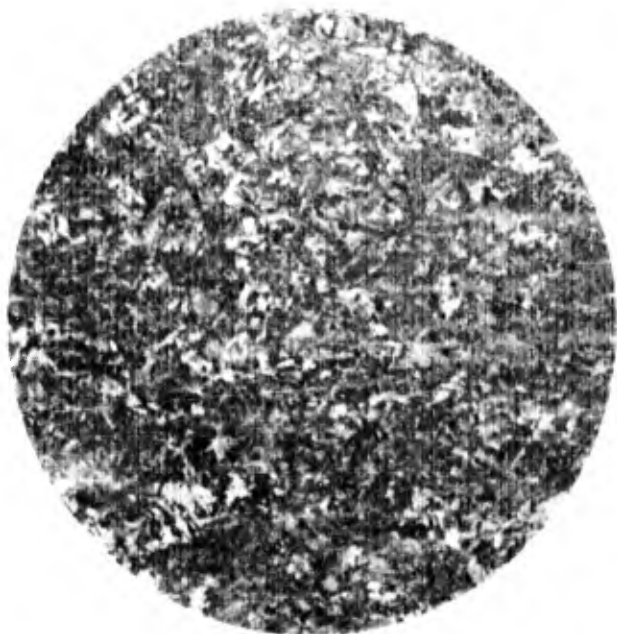


Figure 96. Heat 7329. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.34%  
Manganese ----- 0.88  
Silicon ----- 0.25



Dilatometer Curves

Intended composition:  
Carbon ----- .30/.35%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Chromium ----- 1.3/1.7  
Vanadium ----- .10/.20

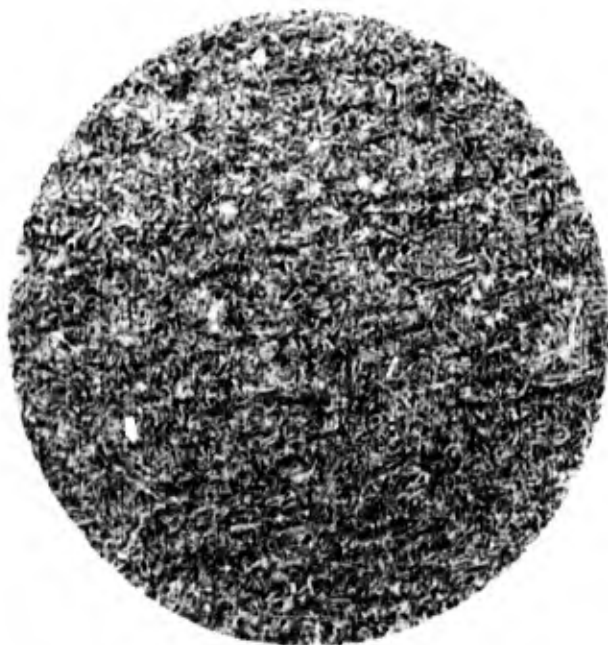
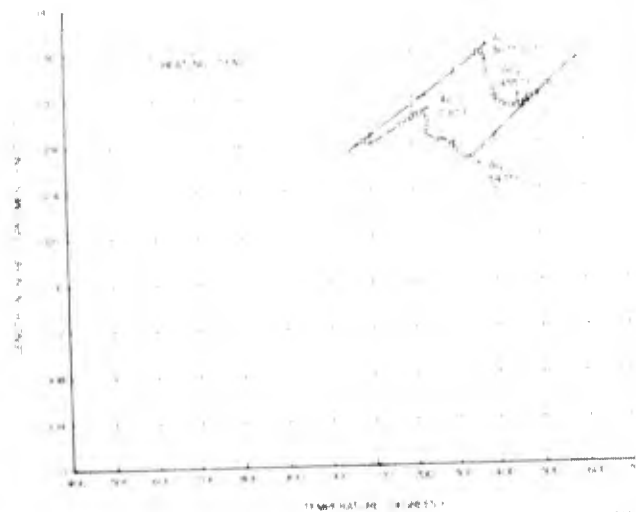


Figure 97. Heat No. 7330. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.46%  
Manganese ----- 0.86  
Silicon ----- 0.24



Dilatometer Curves

Intended composition:  
Carbon ----- .45/.50%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Molybdenum ----- .25/.36  
Vanadium ----- .10/.20

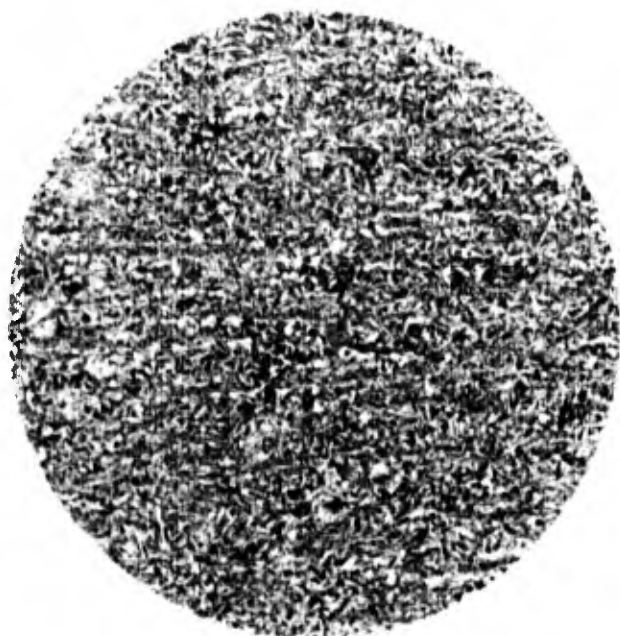
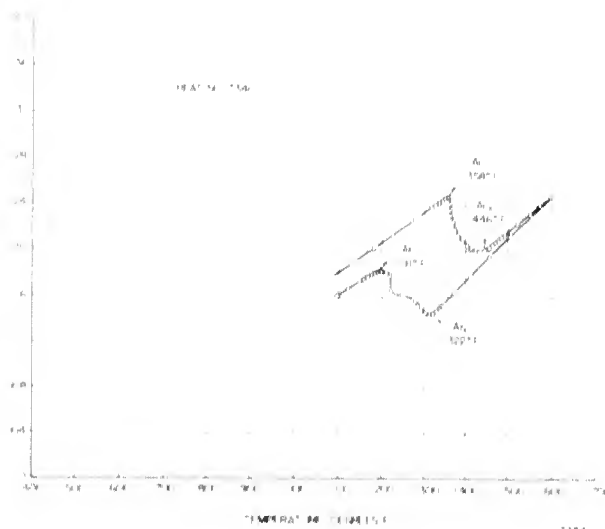


Figure 98. Heat No. 7340 - Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:

Carbon ----- 0.16%  
Manganese ----- 0.84  
Silicon ----- 0.29

13322



Dilatometer Curves

Intended composition:

Carbon ----- .45/.50%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Molybdenum ----- .25/.35

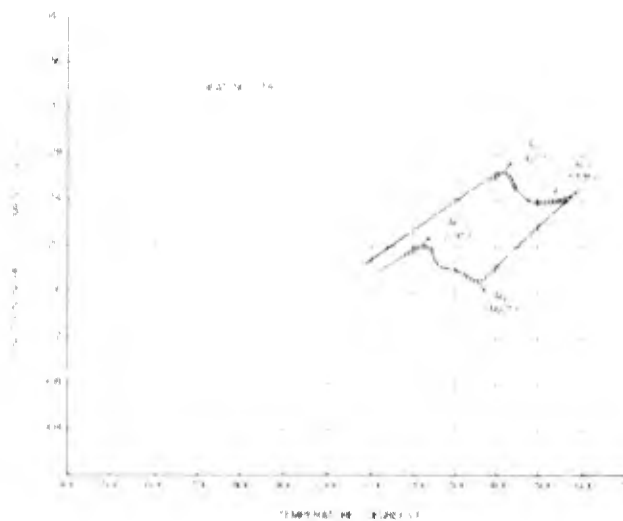


Figure 99. Heat No. 7341. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:

Carbon ----- 0.34%  
Manganese ----- 0.94  
Silicon ----- 1.06

13323



Dilatometer Curves

Intended composition:

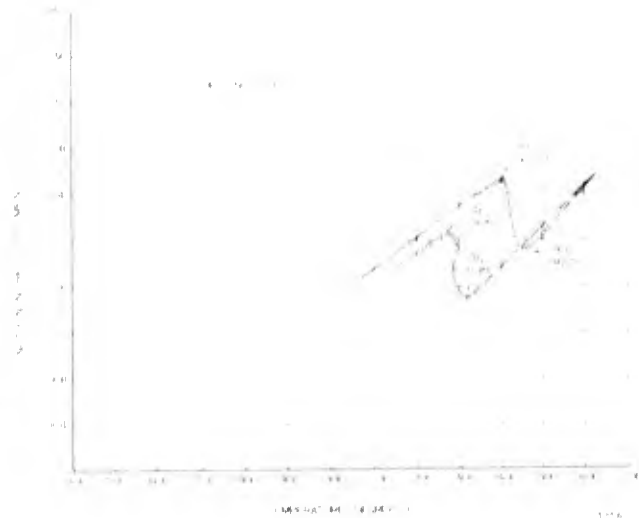
Carbon ----- .30/.35  
Manganese ----- .60/.90  
Silicon ----- .90/1.10  
Molybdenum ----- .35/.45  
Chromium ----- .90/1.10



Figure 100. Heat No. 7342. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.46%  
Manganese ----- 0.77  
Silicon ----- 0.25

13324



Dilatometer Curves

Intended composition:  
Carbon ----- .45/.50%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Chromium ----- .30/1.10  
Molybdenum ----- .25/.35  
Vanadium ----- .10/.20

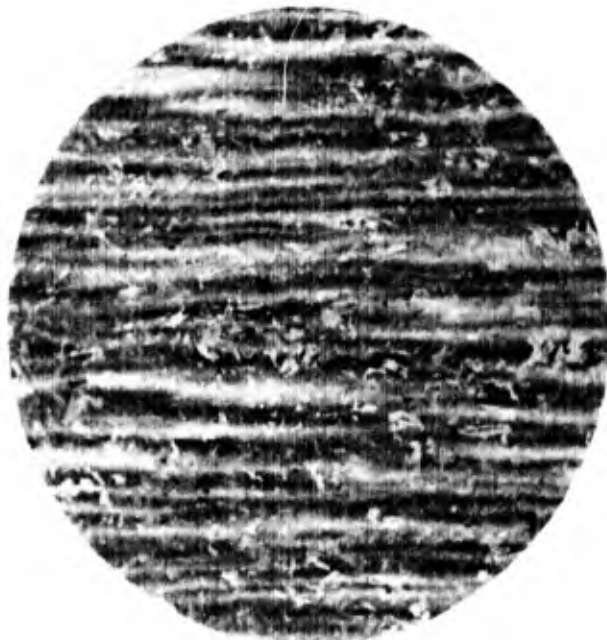
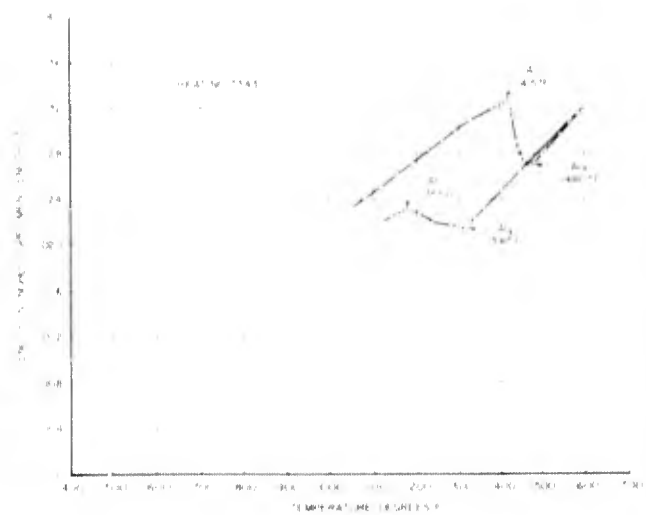


Figure 101. Heat No. 7343. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.45%  
Manganese ----- 0.79  
Silicon ----- 0.19

13325



Dilatometer Curves

Intended composition:  
Carbon ----- .45/.50%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Chromium ----- 1.10/1.30  
Molybdenum ----- .60/.80  
Vanadium ----- .20/.30

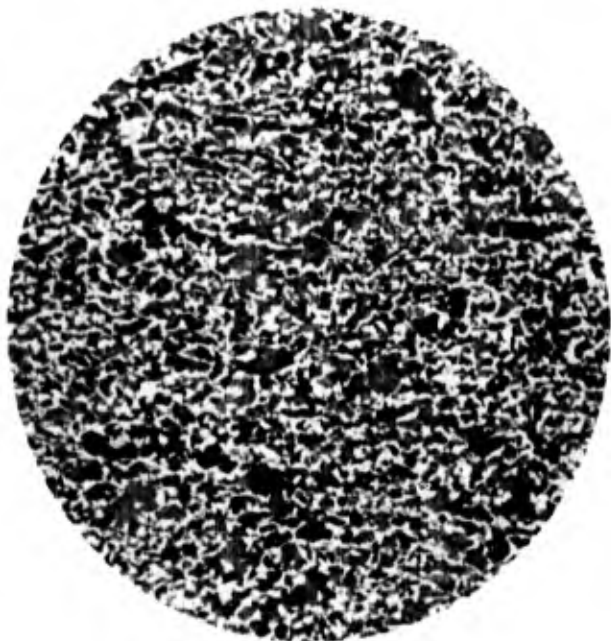
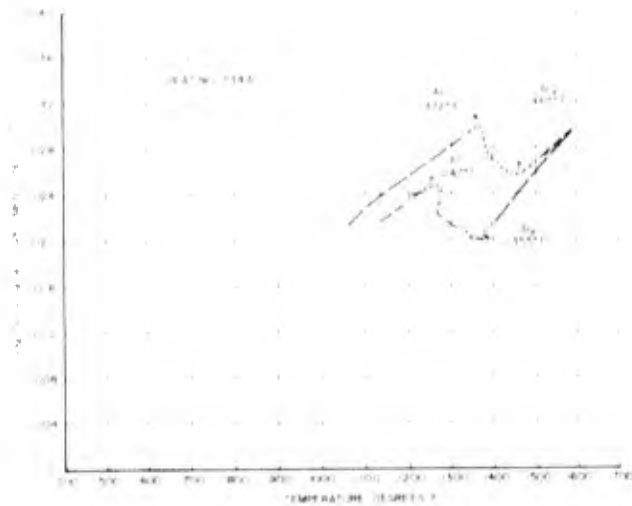


Figure 102. Heat No. 7344. Microstructure  
of the as-rolled 7/4-in. plate. X100

Actual analysis:

Carbon ----- 0.46%  
Manganese ----- 0.75  
Silicon ----- 0.20



Intended composition:

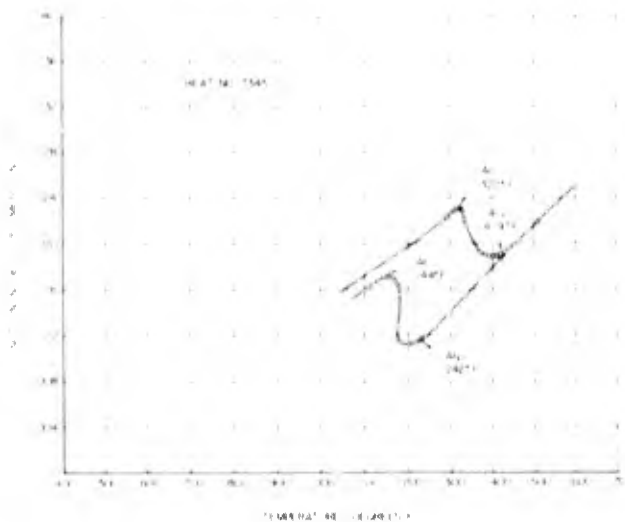
Carbon ----- .45/.50%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Vanadium ----- .20/.30



Figure 103. Heat No. 7345. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:

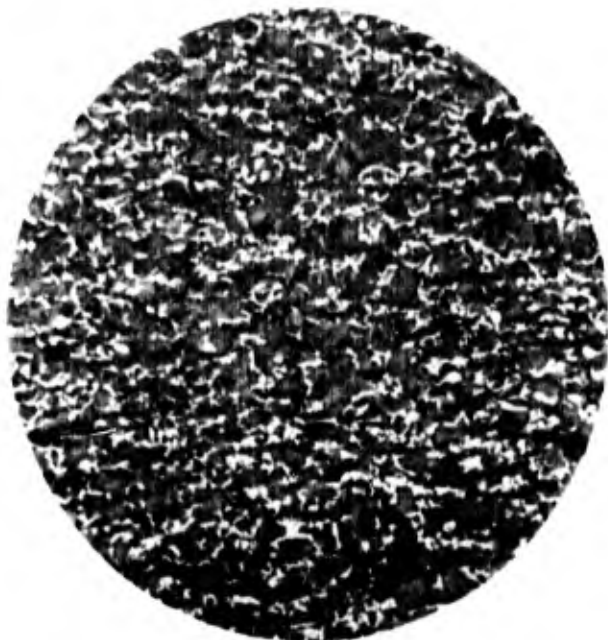
Carbon ----- 0.44%  
Manganese ----- 1.54  
Silicon ----- 0.28



Dilatometer Curves

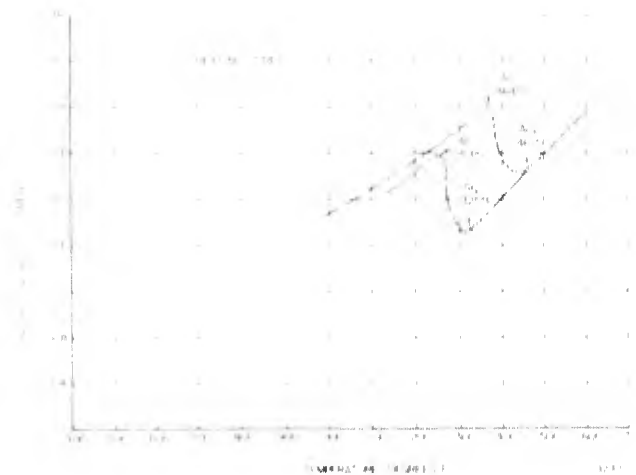
Intended composition:

Carbon ----- .42/.48%  
Manganese ----- 1.4/1.6  
Silicon ----- .20/.30  
Copper ----- 1.4/1.6



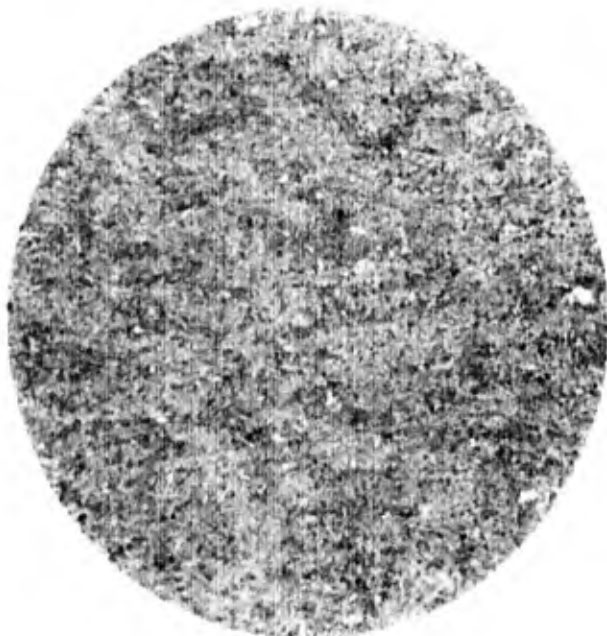
13328  
Figure 104. Heat No. 7347. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.34%  
Manganese ----- 0.83  
Silicon ----- 0.26



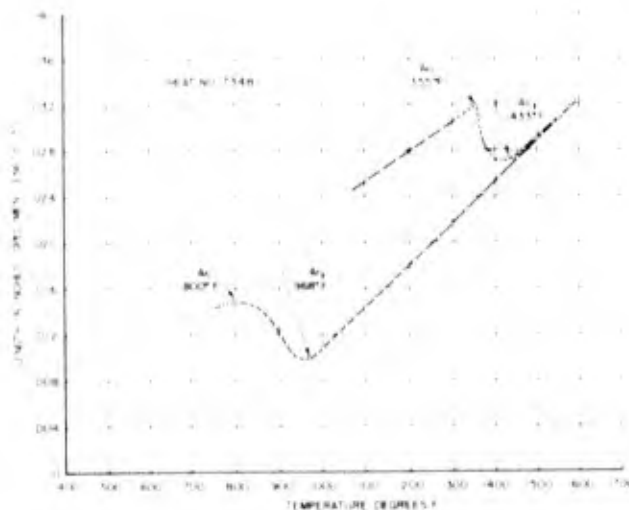
Dilatometer Curves

Intended composition:  
Carbon ----- .30/.35%  
Manganese ----- .60/.90  
Silicon ----- .20/.30  
Chromium ----- .90/1.10  
Copper ----- 1.4/1.6



13329  
Figure 105. Heat No. 7348. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.47%  
Manganese ----- 1.48  
Silicon ----- 0.32



Dilatometer Curves

Intended composition:  
Carbon ----- .45/.50%  
Manganese ----- 1.2/1.6  
Silicon ----- .20/.30  
Molybdenum ----- .40/.50  
Copper ----- .30/.50

100.

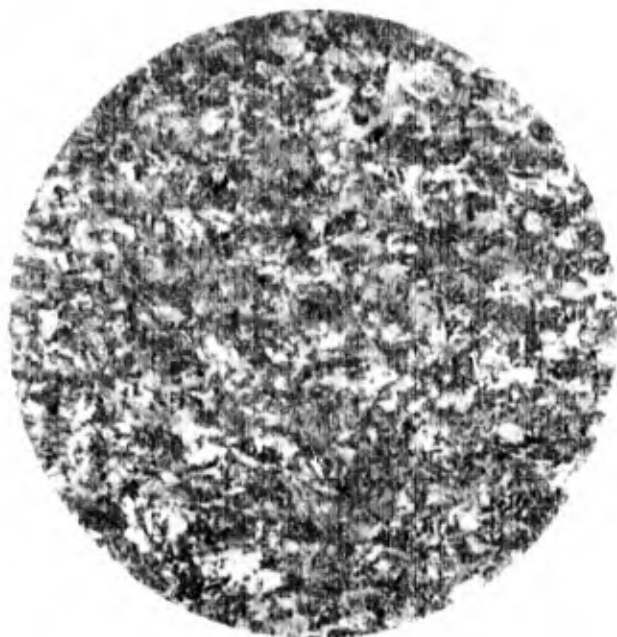
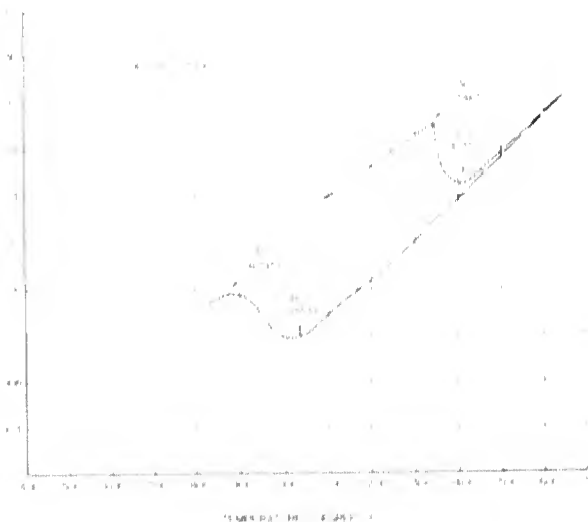


Figure 106. Heat No. 7349. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.46%  
Manganese ----- 0.71  
Silicon ----- 0.24

13330



Dilatometer Curves

Intended composition:

Carbon ----- .45/.50%  
Manganese ----- .80/.90  
Silicon ----- .20/.30  
Copper ----- .30/.50  
Molybdenum ----- .40/.50

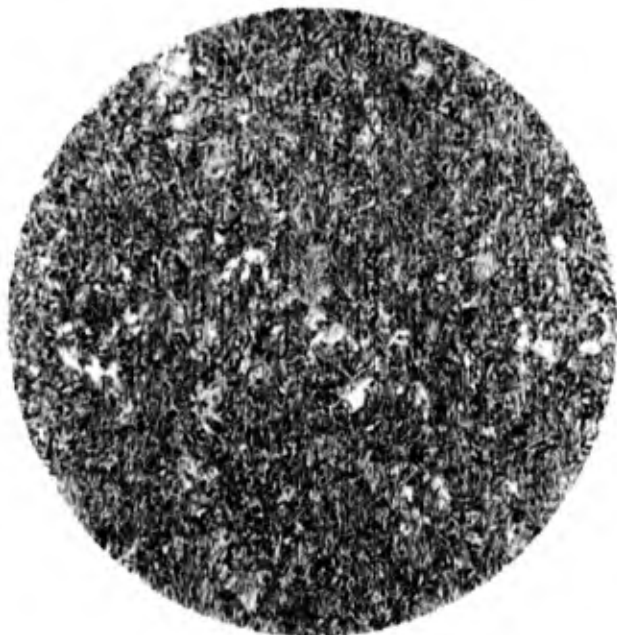
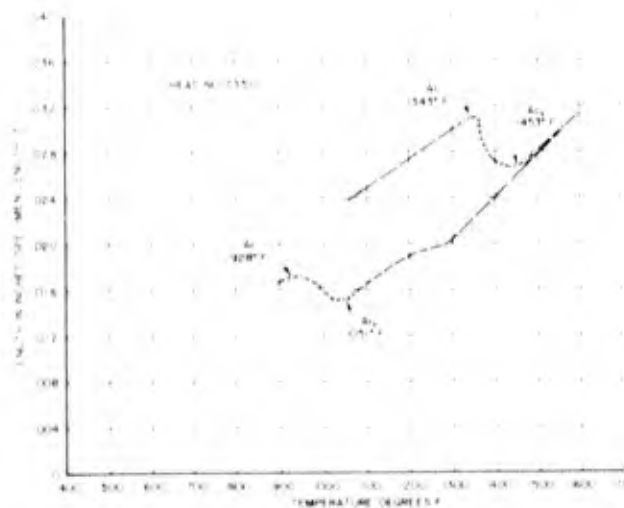


Figure 107. Heat No. 7350. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.46%  
Manganese ----- 0.80  
Silicon ----- 0.23

13331



Dilatometer Curves

Intended composition:

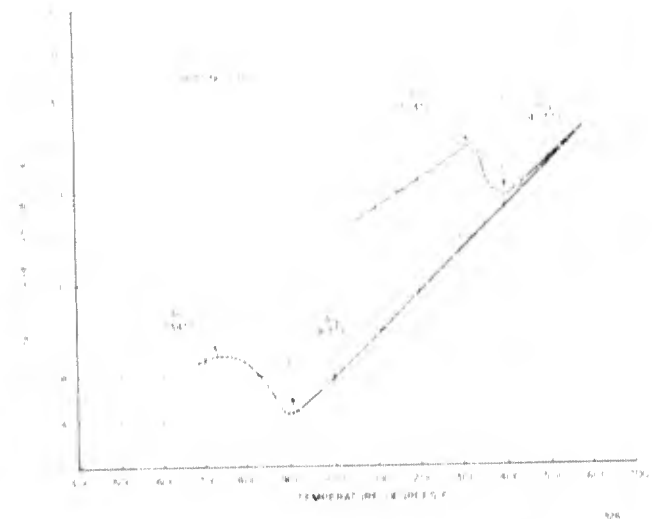
Carbon ----- .45/.50%  
Manganese -- .60/.90  
Silicon ----- .20/.30  
Molybdenum - .40/.50  
Copper ----- 1.0/1.5



Figure 108. Heat No. 7351. Microstructure  
of the as-rolled 3/4-in. plate. 13332 X100

Actual analysis:

Carbon ----- 0.46%  
Manganese ----- 1.49  
Silicon ----- 0.29



Dilatometer Curves

Intended composition:

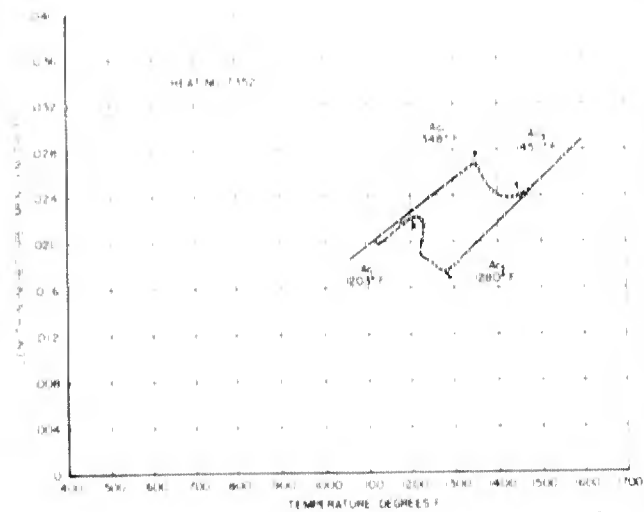
Carbon ----- .45/.50%  
Manganese ----- 1.2/1.6  
Silicon ----- .20/.30  
Molybdenum ----- .40/.50  
Copper ----- 1.0/1.5



Figure 109. Heat No. 7352. Microstructure  
of the as-rolled 3/4-in. plate. 13333 X100

Actual analysis:

Carbon ----- 0.44%  
Manganese ----- 1.11  
Silicon ----- 1.03



Dilatometer Curves

Intended composition:

Carbon ----- .45/.50%  
Manganese ----- .90/1.2  
Silicon ----- .90/1.2  
Copper ----- 1.3/1.6

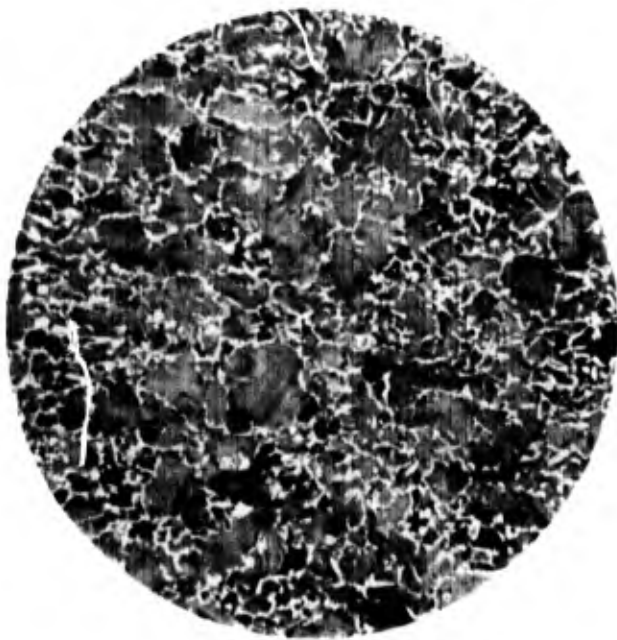
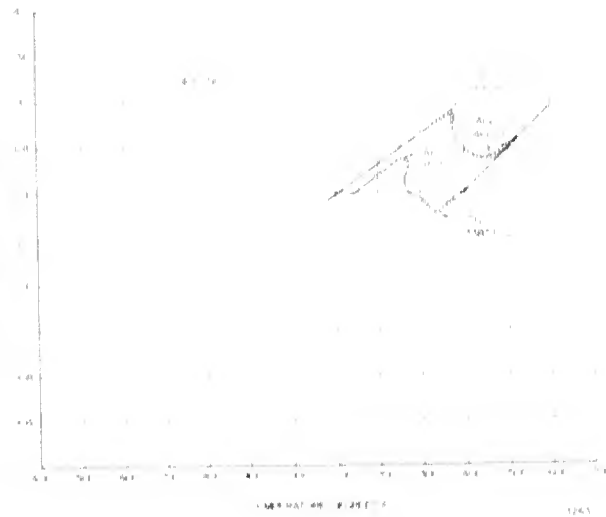


Figure 110. Heat No. 7353. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.45%  
Manganese ----- 0.84  
Silicon ----- 0.73

13334



Dilatometer Curves

Intended composition:  
Carbon ----- .45/.50%  
Manganese ----- .60/.90  
Silicon ----- .50/.30

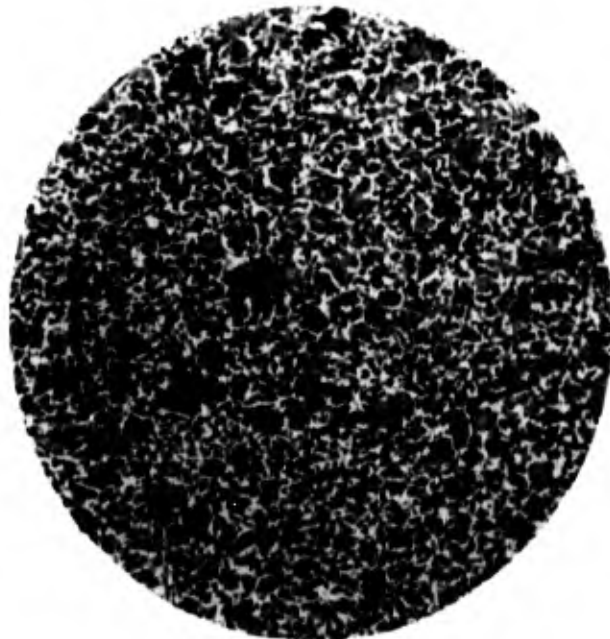
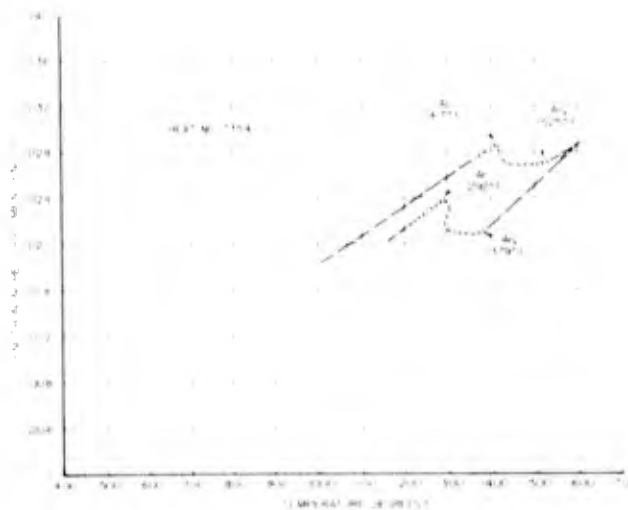


Figure 111. Heat No. 7354. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 0.45%  
Manganese ----- 0.88  
Silicon ----- 1.71

13335



Dilatometer Curves

Intended composition:  
Carbon ----- .45/.50%  
Manganese ----- .60/.90  
Silicon ----- 1.5/1.8

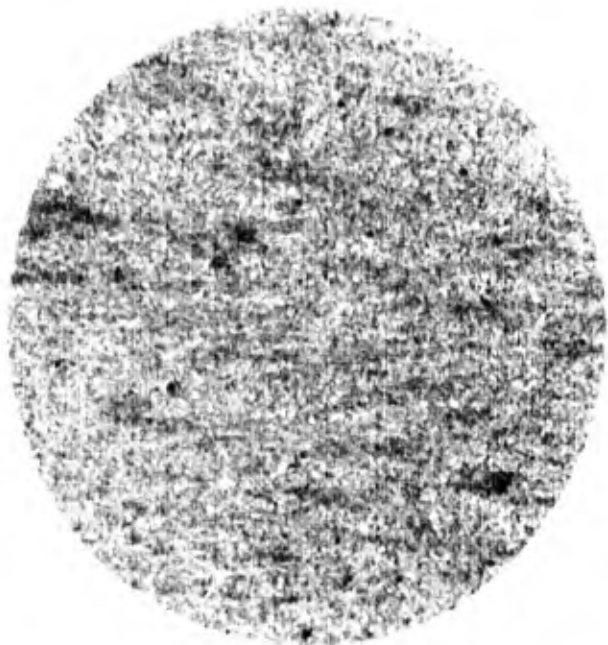
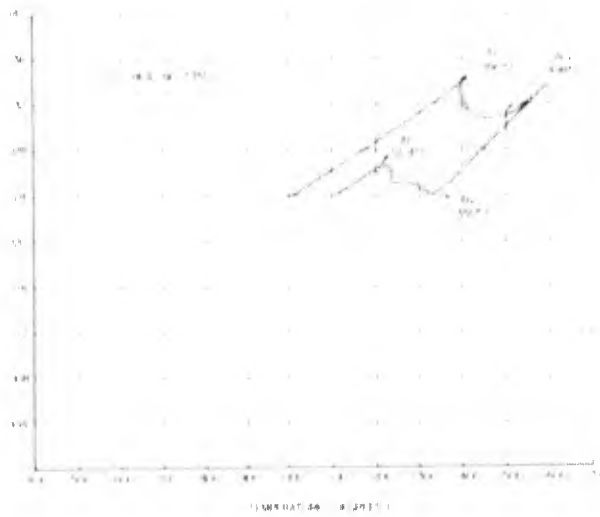


Figure 112. Heat No. 7355. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:

Carbon ----- 0.46%  
Manganese ----- 0.78  
Silicon ----- 1.07

13336



Dilatometer Curves

Intended composition:

Carbon ----- .40/.50%  
Manganese ----- .50/.80  
Silicon ----- .30/1.10  
Molybdenum ----- .40/.50

(Suggested by Watertown Arsenal)

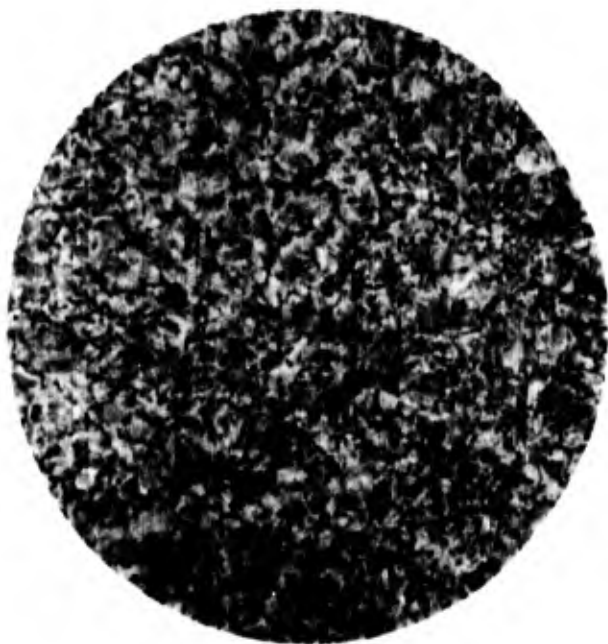
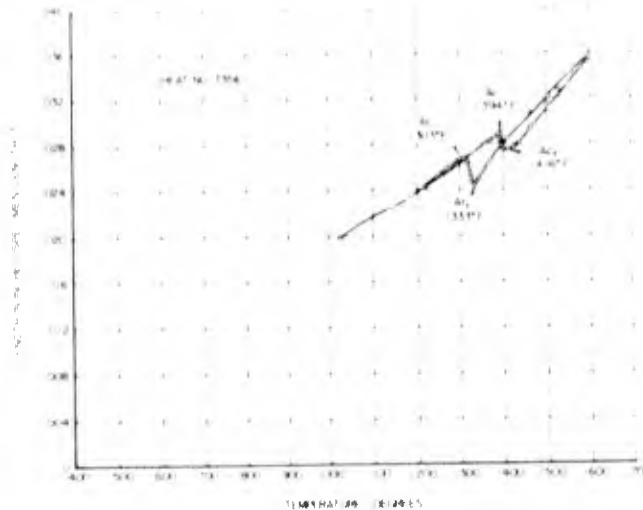


Figure 113. Heat No. 7356. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:

Carbon ----- 1.02%  
Manganese ----- 0.52  
Silicon ----- 1.10

13337



Dilatometer Curves

Intended composition:

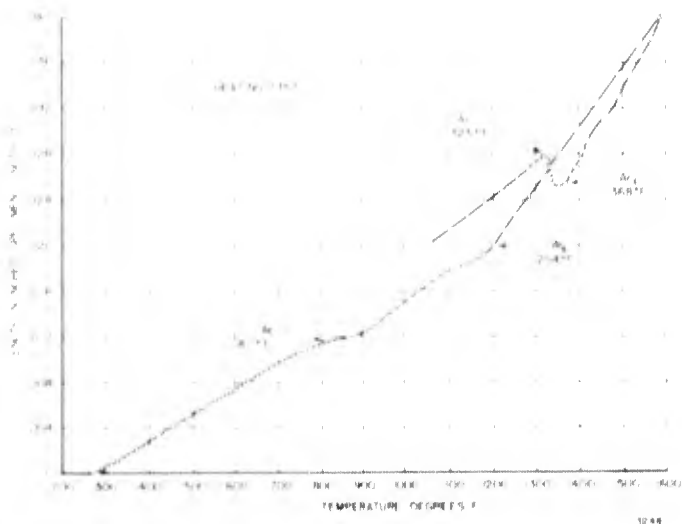
Carbon ----- 1.10/1.25%  
Manganese ----- .40/.60  
Silicon ----- 1.00/1.40  
Phosphorus & Sulphur 0.04 max.



Figure 114. Heat No. 7357. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 1.26%  
Manganese ----- 1.57  
Silicon ----- 0.22

13338



Dilatometer Curves

Intended composition:  
Carbon ----- 1.15/1.35%  
Manganese ----- 1.5/1.75  
Silicon ----- .20  
Molybdenum ----- .10/.60  
Copper ----- 3.00/3.25

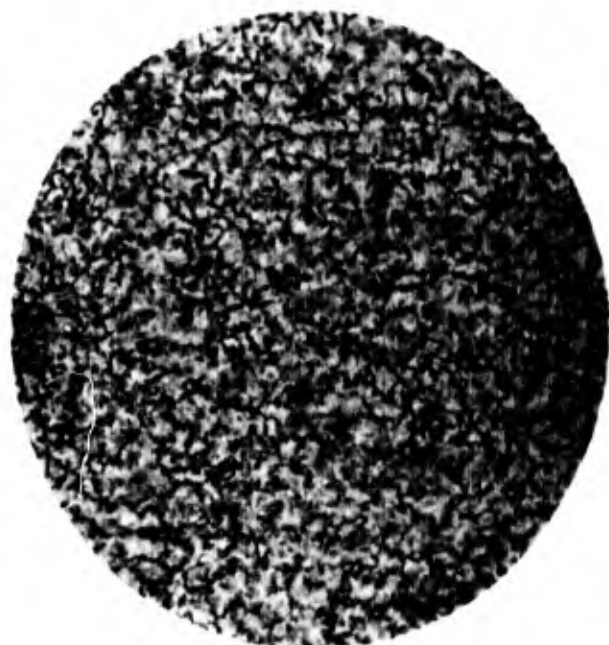
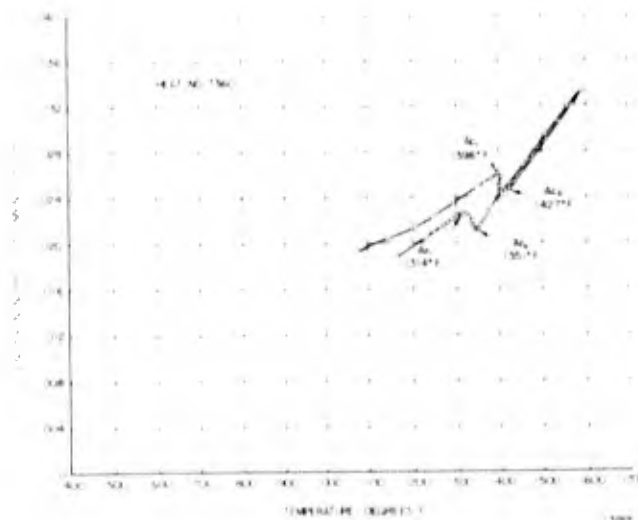


Figure 115. Heat No. 7360. Microstructure  
of the as-rolled 3/4-in. plate. X100

Actual analysis:  
Carbon ----- 1.17%  
Manganese ----- 0.61  
Silicon ----- 1.31

13339



Dilatometer Curves

Intended composition:  
Carbon ----- 1.10/1.25%  
Manganese ----- .40/.60  
Silicon ----- 1.00/1.40  
Phosphorus & Sulphur 0.04 max.