W.A. No. Zc 4

PROGRESS REPORT

February 20, 1942

to

WATERTOWN ARSENAL,
UNITED STATES ARMY

Research Investigation
of Armor Plate Steels

C-547

BATTELLE
MEMORIAL INSTITUTE
505 King Avenue
COLUMBUS, OHIO

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RESEARCH INVESTIGATION OF ARMOR PLATE STEELS

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by

M. L. Samuels and C. H. Lorig

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FOREWORD

This report describes experimental results obtained from several loosely connected divisions of the program of investigation of armor plate materials. It may be helpful, therefore, to consider first, how the present work is related to that which has previously been completed and to that which is yet to be done, before attempting to summarize particular results.

A group of 32 armor plate specimens was shipped to Watertown November 21, 1941, and ballistic tests were made on December 8. A conference between representatives of Battelle and the sponsor was held on December 9. It was decided at this conference to obtain ballistic properties from each steel at three different hardness levels and to lower the carbon content of all heats made subsequently to the .30-.35% range. Hardenability tests were also added to the program at this time.

Duplicate plates had been made on 21 heats of the group tested on

December 8, but five of these plates had been used in comparative tests of the effect of surface decarburization. Plans were made to heat treat the remaining 16 plates to 400-420 Brinell and to redraw those which had been tested at the 350-370 Brinell level to 310-330 Brinell, thus making it possible to obtain ballistic properties at three hardness levels. Other heats, required to make up the original 41 compositions and two additional "base alloy" heats, were to be remade and cast into ingots large enough to obtain three plates from each heat.

The work of remaking and of heat treating the 27 new steels was started immediately after the conference, and the 81 plates from this group were shipped to Watertown January 30, 1942. A progress report containing data relating to the making and to the heat treating of the 27 new heats was compiled February 6, 1942.

In the meantime, redrawing of the plates which had been tested at the 350-370 Brinell level and the heat treatment of the 16 duplicate plates from the original had been completed. Ballistic tests were made and the plates returned for cross-section hardness surveys. The present report includes data under the following heads:

1. Ballistic test results from the original group of 32 specimens tested at the 350-370 Brinell range.
2. Investigation of the effect of surface decarburization.
3. Ballistic test results from 22 plates redrawn to the 310-330 Brinell range.
4. Heat treatment of 16 duplicate plates to the 400-420 Brinell level.
5. Ballistic tests results from the 16 duplicate plates.
6. Jominy hardenability test results from all heats, with the exception of the 27 compositions included in the February 6 report.

Data comprising this report will be followed soon by those relating to ballistic properties and to cross-section hardness surveys of the 27 heats (81 plates) now at Watertown. That division of the work will complete the study of all of the 43 compositions outlined for the preliminary part of the armor plate investigation.

SUMMARY

A list showing the compositions for the group of 32 armor plate specimens is included for reference in Table 4.

Ballistic limits and hardness values are given in Table 5. The extent of spalling, or degree of ductility, as shown by fractures on the exit surfaces of the plates, is shown by photographs in Figures 32 to 63, inclusive. The unusually high carbon plates shown in Figures 59 to 63, inclusive, can be thrown out immediately because of low ductility. No correlation between ballistic limit and composition can be pointed out among the other steels. Heat No. 7276, for example, shows the highest ballistic limit (2316 f/s) of all, and it is a plain carbon steel except for a manganese content of 1.07%. Table 5 also shows the heats arranged according to decreasing hardness, the hardness in this case varying from 375 to 341 Brinell. With the possible exception of No. 7279, no distinction on the basis of hardness (within this group) seems to be justified.

A comparison of ballistic limits from plates machined to remove surface decarburization with duplicate ones having rolled surfaces is given in Table 6. No significant differences are shown. However, in view of the fact that surface Brinell readings on the rolled plates were no lower than the true core hardness, this test only shows that practically no decarburization occurred with these particular compositions.

Twenty-two plates, which had been tested for ballistic properties at the 350-370 Brinell range, were redrawn to 310-330 Brinell. The hardness values obtained and the final drawing temperatures employed are shown in Table 7.

After ballistic tests had been made, the redrawn plates were surveyed for cross-section hardness at points near where the ballistic limits had been determined. The ballistic limit and the average cross-section hardness values are given in Table 8. This table also shows the heats arranged in order of descending hardness, and the corresponding ballistic limits are given. There is no noticeable trend of ballistic values with respect to compositions, nor is there, within the range covered for this lot of steels, a correlation between hardness and ballistic limit.

Sixteen duplicate rolled plates were heat treated to the 400-420 Brinell range. Data relating to the quenching and drawing treatments are given in Table 9. The plates were tested for ballistic properties and then surveyed for hardness over a cross-section near the location at which the ballistic limits were determined.

Ballistic limits and average hardness values from the 16 duplicate plates are given in Table 10. No correlation between composition and ballistic limit is especially noticeable. In this table, the heats have been arranged in a descending order according to hardness. With the possible exception of the two heats which are below the specified range, no distinction can be made on the basis of hardness.

It has not been possible to observe a relationship between hardness and ballistic limits in the various groups of plates so far considered when the variation in hardness is no more than would be expected at a given level. This is probably true because the experimental error in ballistic limit determination is great enough to mask out the effect of small hardness variations.

Ballistic limit and hardness values were obtained on sixteen heats at three different hardness levels. The results were plotted as curves which are given in Figures 84 to 99 inclusive.

Jominy hardenability tests were made on armor plate steels produced at Battelle previous to those cited in the February 6 report, with the exception of the high carbon ones which shattered under test. Curves showing hardness values plotted against distance from the quenched end of the hardenability test specimen are given as Figures 100 to 145, inclusive.

The 16 heats from which ballistic properties were obtained at three different hardness levels (see Figures 84 to 99, inclusive) were selected, along with the 27 heats listed in the February 6 report, to indicate the hardenability characteristics of the original group of 43 compositions. Bar graphs were made showing a comparison between the hardness of all compositions at six different distances from the quenched end (Figure 146). Each single bar graph is a hardness chart for all the steels at a given distance from the quenched end of the specimen; together, the bar graphs represent a hardenability chart from which comparisons can easily be made.

EXPERIMENTAL WORK

The November 28, 1941, progress report included data in connection with the making and the heat treating of a group of 32 experimental armor plate specimens. Dilatometer curves, showing the locations of the critical points, and photomicrographs giving the structures of the as rolled plates were included.

At the time the November 28th report was written, the plates had just been shipped to Watertown and no final results had been obtained. Since that time, some additional investigations have been made and complete results are on hand.

It will be necessary later to refer frequently to various heat numbers, so a list showing the compositions of the armor plate specimens is included in Table 4.

A. Ballistic Test Results

The specimens tested in this group had been heat treated to the 350-370 Brinell range with the exception of the two austenitic cast irons - Heats 7358 and 7476. With one exception, Heat No. 7281, the plates were rolled to 3/4 inch and then machined to final thickness. The average Brinell hardness and the ballistic limit values are given in Table 5.

In addition to ballistic limit determinations, one high velocity .50 cal. bullet was fired as an impact test. Photographs of the plates listed in Table 5 are shown as Figures 32 to 63 inclusive.

B. Investigation of the Effect of Surface Decarburization Upon Ballistic Properties.

A group of plates, representing five heats, were rolled to 1/2 inch in thickness, and no effort was made to eliminate decarburization. These plates were heated in air and then quenched and tempered in the usual manner. Each plate was drawn to a surface hardness of 350-370 Brinell.

After the five plates had been tested for ballistic properties, the back surfaces were photographed. These views are shown in Figures 64 to 68, inclusive, (see Figures 41, 47, 49, 52, and 55 for views of the comparable machined plates from these heats). Subsequently, these plates, and also the five duplicate machined specimens, were cut for cross-section hardness surveys. Results from ballistic limit determinations and the hardness surveys are given in Table 6.

TABLE 4. CHEMICAL COMPOSITION OF ARMOR PLATE STEELS

Plate Number	%C	%Mn	%Si	%Ni	%Cr	%Mo	%V	%Cu
7111	.46	1.58	.20				.10/.20	
7276	.50	1.07	.30					
7277	.39	.35	.23					
7278	.47	.91	.26					
7279	.40	.91	.95	1.3/1.6	.70/.90			
7280	.35	.92	.28	1.3/1.6	.70/.90	.20/.30		
7281	.36	1.63	.30	1.3/1.6	.70/.90	.25/.35		
7326	.30	.73	.20		.90/1.1			
7327	.35	.88	.26		2.3/2.7			
7328	.34	.89	.20		1.3/1.7	.35/.45		
7329	.34	.88	.25		1.3/1.7		.10/.20	
7330	.46	.86	.24			.25/.35	.10/.20	
7340	.46	.84	.29			.25/.35		
7341	.34	.94	1.06		.90/1.1	.35/.45		
7342	.46	.77	.25		.90/1.1	.25/.35	.10/.20	
7343	.45	.79	.19		1.1/1.3	.60/.80	.20/.30	
7344	.46	.75	.20				.20/.30	
7345	.44	1.54	.28					1.4/1.6
7347	.34	.83	.26		.90/1.1			1.4/1.6
7348	.47	1.48	.32			.40/.50		.30/.50
7349	.46	.71	.24			.40/.50		.30/.50
7350	.46	.80	.23			.40/.50		1.0/1.5
7351	.46	1.49	.29			.40/.50		1.0/1.5
7352	.44	1.11	1.03					1.3/1.6
7353	.45	.84	.73					
7354	.45	.88	1.71					
7355	.46	.78	1.07			.40/.50		
7356	1.02	.52	1.10					
7357	1.26	1.57	.22			.40/.60		3.0/3.25
7360	1.17	.61	1.31					
7358	3.23	10.4	2.85					
7476	2.55	8.0	7.29					

TABLE 5. HARDNESS AND BALLISTIC LIMIT VALUES FROM THIRTY-TWO ARMOR PLATE SPECIMENS

Heat No.	Nature of Plate Surface	Average* Brinell Hardness	Ballistic Limit f./s.	Heats Arranged in Order of Decreasing Hardness: Heat No.	Brinell Hardness	Ballistic Limit, f./s.
7111	Machined	363	2259	7350	375	2246
7276	"	357	2316	7328	375	2237
7277	"	366	2142	7345	371	2268
7278	"	369	2250	7349	371	2260
7279	"	341	2149	7352	370	2242
7280	"	365	2291	7327	370	2209
7281	Rolled	369	2275	7351	369	2135
7326	Machined	368	2264	7345	369	2170
7327	"	370	2209	7330	369	2203
7328	"	375	2237	7281	369	2275
7329	"	366	2193	7278	369	2250
7330	"	369	2203	7326	368	2264
7340	"	363	2220	7329	366	2193
7341	"	355	2181	7277	366	2142
7342	"	365	2289	7342	365	2289
7343	"	363	2293	7280	365	2291
7344	"	351	2235	7347	363	2150
7345	"	371	2268	7343	363	2293
7347	"	363	2150	7340	363	2220
7348	"	369	2170	7111	363	2259
7349	"	371	2260	7355	362	2215
7350	"	375	2246	7354	358	2300
7351	"	369	2135	7276	357	2316
7352	"	370	2242	7341	355	2181
7353	"	347	2220	7344	351	2235
7354	"	358	2300	7353	347	2220
7355	"	362	2215	7279	341	2149
7356	"	365	2300 (Shattered)			
7357	"	363	Shattered			
7358	Cast	359	Shattered			
7360	Machined	363	Shattered			
7476	Cast	275	Shattered			

* These are surface hardness readings.

TABLE 6. THE EFFECT OF REMOVING SURFACE DECARBURIZATION BY MACHINING UPON BALLISTIC PROPERTIES

Heat No.	Surface Finish	Cross-Section Survey, Rockwell C*	Equiv-alent Brinell	Actual Brinell		Ballistic Limit Velocity F./S.
				Surface	Center	
7328	Machined	38	363	366	369	2237
7328	Rolled	38	363	368	369	2229
7343	Machined	37	352	353	346	2293
7343	Rolled	38	363	352	354	2312
7345	Machined	37	352	361	358	2268
7345	Rolled	37	352	361	358	2287
7349	Machined	37	352	361	351	2260
7349	Rolled	39	369	356	374	2309
7352	Machined	38	363	363	363	2242
7352	Rolled	36	341	337	350	2285

* Average of 14 readings taken at staggered 1/16" intervals over the cross-section.

C. Ballistic Tests Results from Twenty-two Plates Redrawn to the 310-330 Brinell Range.

It was suggested, at the Watertown meeting, that plates which had been tested at the 350-370 Brinell range be redrawn to a lower hardness. The original list of 32 plates was reduced by five (three high carbon steels and the two austenitic cast irons) because these specimens shattered. Another five heats had been used in the decarburization study; this left 22 plates for redrawing.

Drawing time, temperature, and final hardness values obtained are listed in Table 7.

The twenty-two redrawn plates were tested for ballistic properties at Watertown and then shipped back for cross-section hardness surveys. The hardness specimens were cut from the plates near the location from which the ballistic limit was determined. Average cross-section hardness values and the ballistic limits from the redrawn plates are listed in Table 8.

D. Heat Treatment of Sixteen Duplicate Rolled Plates.

The plates in this group were heated in a salt bath, quenched, and immediately placed in the drawing furnace at 500° F. Two opposite corners were ground down to at least 1/16", in all cases, and tested for hardness. Subsequent drawing treatments were given until the average hardness was within the specified range of 400-420 Brinell. Data covering quenching temperature, quenching medium, and successive and final drawing temperatures are given in Table 9.

TABLE 7. REDRAWING OF PLATES TO 310-330 BRINELL

Plate Number	Brinell Hardness After Drawing Treatments-°F. Draw No. 1	Draw No. 2	Draw No. 3	Draw No. 4	Draw No. 5	Draw No. 6	Final Treatment °F. Temp.	BHN (Ave.)
7276	950° 1 hr. 338	1000° 1 hr. 317					1000°	317
7277	750° $\frac{1}{2}$ hr. 366	800° 1 hr. 334	800° 1 hr. 334	850° $\frac{1}{4}$ hr. 319			850°	319
7278*	1000° 1 hr. 301	800° 1 hr. 390	900° $1\frac{1}{4}$ hrs. 321				900°	321
7279	1000° 1 hr. 321						1000°	321
7280	1100° $\frac{1}{2}$ hr. 338	1125° $\frac{1}{2}$ hr. 323					1125°	323
7281	1050° 1 hr. 341	1050° 1 hr. 338	1075° $\frac{1}{2}$ hr. 336	1100° $\frac{1}{2}$ hr. 323			1100°	323
7111	1000° 1 hr. 337	1000° $\frac{1}{2}$ hr. 325					1000°	325
7326*	900° 1 hr. 344	1000° $\frac{1}{2}$ hr. 305	800° 1 hr. 385	900° $1\frac{1}{4}$ hrs. 337	925° $\frac{1}{2}$ hr. 324		925°	324
7327	1050° 1 hr. 312						1050°	312
7329	1050° 1 hr. 352	1050° 1 hr. 342	1075° $\frac{1}{2}$ hr. 339	1100° $\frac{1}{2}$ hr. 338	1100° 1 hr. 330	1150° $\frac{1}{4}$ hr. 321	1150°	321
7330	1050° 1 hr. 363	1100° $\frac{1}{2}$ hr. 352	1125° 1 hr. 346	1150° 1 hr. 336	1175° 1 hr. 325	1200° $\frac{1}{2}$ hr. 323	1200°	323
7340	1050° 1 hr. 341	1050° 1 hr. 345	1075° $\frac{1}{2}$ hr. 335	1100° $\frac{1}{2}$ hr. 326			1100°	326

TABLE 7. (CONT.)

Plate Number	Brinell Hardness After Drawing Treatments-°F.						Final Treatment	
	Draw No. 1	Draw No. 2	Draw No. 3	Draw No. 4	Draw No. 5	Draw No. 6	°F. Temp.	BHN (Ave.)
7341	1150° 1 hr. 343	1150° 1 hr. 341	1175° 1 hr. 324				1175°	324
7342	1200° 1 hr. 352	1225° 2 hrs. 326					1225°	326
7344	1050° 1 hr. 320						1050°	320
7347	1000° 1 hr. 335	1000° ½ hr. 329					1000°	329
7348	1150° 1 hr. 339	1150° 1 hr. 339	1175° 1 hr. 333	1200° ¼ hr. 321			1200°	321
7350	1050° 1 hr. 361	1100° ½ hr. 351	1125° 1 hr. 341	1150° 1 hr. 326			1150°	326
7351	1150° 1 hr. 345	1150° 1 hr. 346	1175° 1 hr. 333	1200° ½ hr. 317			1200°	317
7353*	950° 1 hr. 334	1000° 1 hr. 307	800° 1 hr. 412	900° 1¼ hrs. 344	950° ½ hr. 326		950°	326
7354	1000° 1 hr. 343	1000° 1 hr. 341	1050° 1 hr. 326				1050°	326
7355	1150° 1 hr. 333	1150° 1 hr. 330	1175° ½ hr. 323				1175°	323

* Plate numbers designated by an asterisk (*) were requenched after unintentionally drawing below the specified hardness level.

TABLE 8. RESULTS OF BALLISTIC LIMIT DETERMINATIONS AND CROSS-SECTION HARDNESS SURVEYS FROM THE TWENTY-TWO REDRAWN PLATES

			Heats Arranged in Order of Decreasing Hardness		
Heat No.	Average Cross-section Hardness (Equiv. Brinell)	Ballistic Limit f./s.	Heat No.	Brinell Hardness	Ballistic Limit, f./s.
7111	312	2157	7326	339	2124
7276	297	2182	7281	338	2190
7277	277	2187	7353	336	2183
7278	330	2187	7350	333	2123
7279	319	2162	7278	330	2187
7280	322	2202	7354	328	2247
7281	338	2190	7280	322	2202
7326	339	2124	7340	321	2123
7327	305	2104	7342	319	2176
7329	307	2131	7279	319	2162
7330	303	2157	7341	319	2108
7340	321	2123	7347	316	2171
7341	319	2108	7111	312	2157
7342	319	2176	7355	307	2150
7344	302	2122	7329	307	2131
7347	316	2171	7327	305	2104
7348	304	2132	7348	304	2132
7350	333	2123	7330	303	2157
7351	291	2094	7344	302	2122
7353	336	2183	7276	297	2182
7354	328	2247	7351	291	2094
7355	307	2150	7277	277	2187

TABLE 9. HEAT TREATMENT OF DUPLICATE ROLLED PLATES

Heat No.	°F. Quenching Temperature	Quenching Medium	Brinell Hard. After Preliminary Draw 500°F. 1/2 hour	Brinell Hardness After Drawing Treatments - °F. Draw No. 1	Draw No. 2	Draw No. 3	Draw No. 4	Draw No. 5	Draw No. 6	Final Tempering Treatment Temperature °F.	Hardness (BHN) Ave.
7111	1600°	Oil	508	700° 1 hr. 457	800° 1 hr. 444	850° 1 hr. 409				850°	409
7326	1600°	Water	577	700° 1 hr. 422	700° 1/4 hr. 421	700° 1 hr. 416				700°	416
7327	1600°	Oil	482	850° 1 hr. 439	875° 1 hr. 429	900° 1 hr. 415				900°	415
7329	1600°	Oil	500	850° 1 hr. 420	850° 1/4 hr. 417					850°	417
7330	1550°	Oil	510	800° 1 hr. 432	800° 1/4 hr. 430	800° 1/2 hr. 432	850° 1 hr. 414			850°	414
7340	1550°	Oil	526	800° 1 hr. 421	800° 1/6 hr. 420	800° 1/2 hr. 415				800°	415
7341	1600°	Water	508	900° 1 hr. 444	950° 1 hr. 426	950° 2 hrs. 413				950°	413
7342	1550°	Oil	520	900° 1 hr. 436	950° 1 hr. 420	950° 2 hrs. 415				95[illegible]°	415

TABLE 9. (CONT.)

Heat No.	°F. Quenching Temperature	Quenching Medium	Brinell Hard. After Preliminary Draw 500°F. 1/2 hour	Brinell Hardness After Drawing Treatments - °F.						Final Tempering Treatment	
				Draw No. 1	Draw No. 2	Draw No. 3	Draw No. 4	Draw No. 5	Draw No. 6	Temperature °F.	Hardness (BHN) Ave.
7344	1650°	Water	534	850° 1 hr. 404						850°	404
7347	1650°	Water	486	800° 1 hr. 416						800°	416
7348	1550°	Oil	516	850° 1 hr. 442	850° 1/2 hr. 444	875° 1/2 hr. 420	900° 1/4 hr. 416			900°	416
7350	1550	Oil	512	800° 1 hr. 430	800° 1/2 hr. 420					800°	420
7351	1550°	Oil	528	850° 1 hr. 445	850° 1/2 hr. 445	875° 1 hr. 437	900° 1 hr. 430	950° 1 hr. 422	950° 2 hrs. 413	950°	413
7353	1650°	Water	545	700° 1 hr. 510	800° 1 hr. 436	850° 1 hr. 401				850°	401
7354	1600°	Water	555	850° 1 hr. 444	850° 1/2 hr. 444	875° 1 hr. 426	900° 1/2 hr. 415			900°	415
7355	1600°	Oil	522	850° 1 hr. 451	850° 1/2 hr. 447	875° 1 hr. 441	900° 1 hr. 426	950° 1/2 hr. 416		950°	416

E. Ballistic Test Results From the Sixteen Duplicate Rolled Plates.

The plates were tested for ballistic properties at Watertown and returned to Battelle. The back surfaces were photographed and these views are shown as Figures 69 to 83, inclusive. Results of the cross-section hardness surveys and of the ballistic limit determinations are given in Table 10.

TABLE 10. RESULTS OF BALLISTIC LIMIT DETERMINATIONS AND CROSS-SECTION HARDNESS SURVEY FROM SIXTEEN DUPLICATE ROLLED PLATES

			Heats Arranged According to Descending Hardness Values		
Heat No.	Average Cross-Section Hardness (Equiv. Brinell)	Ballistic Limit, f./s.	Heat No.	Average Brinell Hardness	Ballistic Limit, f./s.
7111	404	2445	7329	421	2455
7326	420	2245	7326	420	2245
7327	414	2362	7340	418	2318
7329	421	2455	7350	418	2356
7330	404	2412	7355	417	2427
7340	418	2388	7327	414	2362
7341	413	2230	7341	413	2230
7342	409	2410	7347	410	2274
7344	390	2267	7351	410	2426
7347	410	2274	7342	409	2410
7348	402	2345	7111	404	2445
7350	418	2356	7330	404	2412
7351	410	2426	7354	404	2417
7353	379	2328	7348	402	2345
7354	404	2417	7344	390	2267
7355	417	2427	7353	379	2328

F. Correlation of Hardness and Ballistic Limits.

Cross-section hardness surveys were not made, of course, on the plates which were tested for ballistic properties at 350-370 Brinell and subsequently drawn back to 310-330 Brinell. All of the other plates, including those tested at both the 400-420 and the 310-330 levels, were surveyed after ballistic tests had been run. The results are shown in Table 11.

Ballistic test results are available at three hardness levels for 16 steels and at two hardness levels for a few others. Ballistic limit values have been plotted against hardness for the 16 heats from which complete data are available. The resulting curves are shown as Figures 84 to 99, inclusive.

G. Jominy Hardenability Study.

End quench hardenability tests were made on the remaining heats studied to date, using the equipment and the procedure described on pages 12 and 13 of the February 6, 1942, report. Individual curves showing the hardenability of the various steels are given as Figures 100 to 145, inclusive.

To facilitate comparison of the hardenability characteristics, bar graphs were made showing the hardness values at points 1/16", 1/2", 3/4", 1", 1-1/2", and 2" from the quenched ends of the Jominy test specimens. The heats included in these bar graphs are the ones from which ballistic properties are being determined at three hardness levels. The graphs are shown in Figure 146.

TABLE 11. CROSS-SECTION HARDNESS SURVEY ON ARMOR PLATE SPECIMENS AFTER BALLISTIC TESTING

Heat No.	Description of Plate Surface	Rockwell "C" Hardness Locations							Average Equiv. Brinell	Ballistic Limit f./s.
		1/16"	1/8"	3/16"	C	3/16"	1/8"	1/16"		
7111-320	Machined	34	35	34	33	34	34	33	312	2157
7111-410	As rolled	43	43	43	43	43	43	43	404	2445
7276-320	Machined	32	31	32	31	32	33	33	297	2182
7277-320	Machined	36	28	23	23	24	29	35	277	2187
7278-320	Machined	35	36	36	36	36	36	36	330	2187
7279-320	Machined	34	34	35	35	35	35	35	319	2162
7280-320	Machined	35	35	35	35	35	35	35	322	2202
7281-320	As rolled	36	36	37	37	37	37	36	338	2190
7326-320	Machined	34	37	37	38	38	37	36	339	2124
7326-410	As rolled	43	44	45	45	45	45	44	420	2245
7327-320	Machined	33	33	33	33	33	33	33	305	2104
7327-410	As rolled	43	43	44	44	44	44	44	412	2362
7328-360	Machined	38	38	38	38	38	38	38	352	2237
7328-360	As rolled	38	38	38	38	38	38	38	352	2229
7329-320	Machined	32	33	34	34	34	33	33	307	2131
7329-410	As rolled	44	45	45	45	45	44	44	421	2455
7330-320	Machined	32	31	32	33	33	34	34	303	2157
7330-410	As rolled	43	43	42	43	43	43	44	404	2412
7340-320	Machined	35	34	35	35	35	35	35	321	2123
7340-410	As rolled	45	44	44	45	44	44	44	418	2328
7341-320	Machined	34	35	35	35	34	35	35	319	2108
7341-410	As rolled	43	44	44	44	44	44	44	413	2230
7342-320	Machined	34	34	35	35	35	35	35	319	2176
7342-410	As rolled	43	44	44	43	43	44	43	409	2410
7343-360	Machined	36	36	36	36	37	36	36	332	2293
7343-360	As rolled	39	38	38	38	39	39	39	362	2312
7344-320	Machined	34	33	31	30	31	34	35	302	2122
7344-410	As rolled	42	43	44	42	43	41	41	390	2267
7345-360	Machined	37	37	37	37	38	36	38	342	2268
7345-360	As rolled	36	37	37	37	37	37	36	342	2287
7347-320	Machined	34	38	33	33	34	34	34	316	2171
7347-410	As rolled	44	44	43	43	44	44	43	410	2274
7348-320	Machined	33	33	32	33	33	33	33	304	2132
7348-410	As rolled	41	41	42	43	44	44	45	402	2345
7349-360	Machined	37	36	35	37	37	35	36	332	2260
7349-360	As rolled	39	39	39	39	39	39	39	362	2309
7350-320	Machined	36	37	36	36	36	37	35	333	2123
7350-410	As rolled	44	44	44	45	45	44	44	418	2356
7351-320	Machined	31	31	31	31	31	32	31	291	2094
7351-410	As rolled	43	44	44	44	43	43	44	410	2426
7352-360	Machined	38	38	38	37	38	38	38	352	2242
7352-360	As rolled	36	36	37	37	37	37	36	332	2285
7353-320	Machined	36	37	36	36	37	37	36	336	2183
7353-410	As rolled	41	41	41	41	40	41	40	379	2328
7354-320	Machined	34	35	36	36	35	37	36	328	2247
7354-410	As rolled	43	43	43	43	43	43	43	404	2417
7355-320	Machined	33	34	33	33	33	34	33	307	2150
7355-410	As rolled	45	44	45	43	44	45	44	417	2427

DISCUSSION.

The major function of the alloying elements, other than carbon, seems to be to produce full hardening with slower cooling rates. The amount of alloying elements and their selection are, therefore, governed to a great extent by the thickness of the plate to be heat treated.

The bar graphs shown in Figure 146 are adequate for making comparisons between the various steels, and a steel whose composition is known to behave satisfactorily for certain plate thicknesses may be compared with the other compositions accordingly. It is difficult, however, from available data on hardness at a given distance from the quenched end, to calculate the limiting plate thickness through which the particular steel would harden under given quenching conditions.

Jominy and Boegehold have worked out a relationship between the hardness at stated distances from the quenched end of the standard bar and the diameter, of the same steel, which will just harden to the center. Cooling rates were determined and a curve constructed showing the cooling velocity at intervals along the standard bar. Cooling velocities were then determined at the center of round sections with various diameters. Working on the premise that, for a specimen of a given steel, two different locations having the same cooling rate will show the same hardness, it was found possible to determine, from the hardenability test data alone, what diameter would fully harden to the center.

Similar data could be worked up for plates instead of rounds. Cooling velocities would be determined at the centers of plates representing a number of cross-sections. Cooling velocities would then be taken at intervals along a standard hardenability test bar turned from one of the plates. Curves could be drawn by plotting cooling velocity against distance from the quenched end of the Jominy specimen in one case, and cooling velocity against plate thickness in another. Subsequently, it would be possible to note the distance from the quenched end of the hardenability specimen at which a hardness of, say, 50 Rockwell C was found, obtain the cooling velocity corresponding to this distance, and check the other curve to determine what plate thickness would have the same cooling velocity.

Another method for evaluating the hardenability curves to show approximately what thickness of plate could be made to harden throughout the cross-section is shown by the curves in Figure 147. For example, pick the point of maximum deflection from the hardenability curve of Heat 7353 as being 36 Rockwell C. Measure the distance of this point from the hardness axis and place this measured distance along the abscissa of Figure 147. The corresponding points read from the curves and the ordinate give values of 4/5 in. for an oil quenched plate and 1-1/5 in. for a water quenched plate. These values are the "critical thicknesses" for oil and water quench respectively, using a severity of quench of H = 0.6 for oil and H = 1.8 for water. The "critical thickness" (Hardening Characteristics of Steels - by Asimow & Grossman, Transactions of the A.S.M., Dec. 1940, p. 951) is defined as that plate thickness which is just half hardened (50% martensite) at the center cross-section of the plate. It should also be pointed out that this same process of using the curves of Figure 147 could be reversed. For instance, if it is desired to

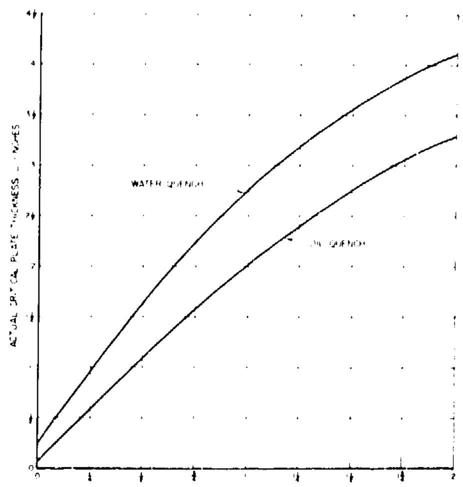

FIG 147

see what would be the center hardness of a 1/2 in. thick water quenched plate for Heat 7353, it would be found to be 57 Rockwell "C" and 56 Rockwell "C" if oil quenched. This indicates that the plate could be either water or oil quenched and have full hardness throughout the cross-section. However, consider the case of a 1 in. thick plate. Water quenching will give a center hardness of 48 Rockwell "C" but oil quenching gives an entirely unsatisfactory value of 29 Rockwell "C".

In using this curve, it must be kept in mind that it gives an approximate or comparable trend, and not an exact value. A brief derivation of the curves of Figure 147 will show why. Grossman (Hardenability Calculated From Chemical Compositions, Metals Technology, preprint T.P. No. 1437, p. 26, Figure 28) shows a chart for estimating ideal critical diameters of round bars from the Jominy distance. Since this chart was based on a standard 1 in. diameter Jominy bar, a possible error would result in reading from the chart and also from the small difference that may exist in hardenability between a 1 in. and a 1/2 in. Jominy bar. After obtaining the ideal critical diameters of round bars from a number of corresponding Jominy distances, the next step is to convert the ideal critical diameter values of rounds to ideal diameter thicknesses of plates by using the formula $L_1 = \frac{D_1}{1.377}$ where L_1 is the ideal plate thickness and D_1 is the ideal round bar diameter (Hardening Characteristics of Various Shapes -- by Asimow and Grossman, Transactions of the A.S.M., Dec. 1940, p. 964). The constant 1.377 used in the formula has been criticized but is probably as good as any other which has been proposed. Changing the ideal critical plate thickness, L_1, to the critical plate thickness, L, probably introduces the greatest error of all because it involves estimating the actual severity of quench used. Grossman (Hardenability Calculated from Chemical Composition, Metals Technology, preprint

T. P. No. 1437 p. 28) states that his original publication presenting quantitative data undoubtedly used a severity of quench which now appears to have been too high. Acknowledging but disregarding, because of the approximate data, the error which would result in using Grossman's previously published curves (Hardening Characteristics of Various Shapes -- by Asimow and Grossman, Transactions of the A.S.M., Dec. 1940, pp. 954 and 955, Figures 5 and 6) showing the relationship between ideal critical thickness, L_1, critical thickness, L, and severity of quench, H, a number of L values were obtained using an estimated severity of quench for our apparatus of H = 0.6 for oil and H = 1.8 for water. The L_{oil} and L_{water} values were then plotted against the distance, J, from the quenched end of a Jominy test piece.

Table 12 gives the calculated values for the various conversions which were used to construct Figure 147.

TABLE 12. CONVERTED VALUES FROM JOMINY BAR TO PLATE THICKNESS

J	D_1	L_1	$L_{(oil)}$	$L_{(water)}$
0	0.77	0.56	0.09	0.25
0.2	1.66	1.21	0.42	0.79
0.4	2.55	1.85	0.87	1.40
0.6	3.30	2.40	1.31	1.87
0.8	3.97	2.88	1.65	2.35
1.0	4.50	3.27	2.00	2.75
1.2	5.00	3.63	2.31	3.10
1.4	5.42	3.94	2.59	3.38
1.6	5.80	4.22	2.88	3.70
1.8	6.14	4.46	3.08	3.90
2.0	6.44	4.68	3.29	4.11

J - Distance in inches from the quenched end of a Jominy test bar.

D_1 - Ideal critical diameter of round bars - inches. Diameter of bar just fully hardened at center for the perfect quench.

L_1 - Ideal critical thickness of plates - inches. Thickness of plate for conditions mentioned for D_1.

$L_{(oil)}$ Critical thickness in inches of a plate quenched in oil with a severity of quench, H = 0.6.

$L_{(water)}$ - Critical thickness in inches of a plate quenched in water with a severity of quench, H = 1.8.

Considering now the relation between ballistic limit and hardness, four specimens from the list of 48 shown in Table 11 upon which cross-section hardness surveys were made, are more than 10 Brinell numbers out of the specified range. Two of these four heats, 7276 and 7277, showed soft centers indicating a lack of sufficient hardness penetration. Since original Brinell readings were taken near the surfaces, instead of over the cross-sections, this condition could not be foreseen, nor could it have been remedied in any case.

After the cross-section hardness survey, hardness tests were made on the coupons cut from the ends of the other two plates, 7351 and 7353. The readings checked fairly well with the original ones which indicates some irregularity in hardness of the corners as compared to the centers of these plates.

Too few tests were made, of course, to warrant drawing smooth curves between the points in plotting the ballistic limits against hardness values. The general trend, however, may be shown by averaging ballistic limits and hardness values from the 16 heats upon which ballistic limits were determined at three different hardness levels.

	310-330 Brinell Range		350-370 Brinell Range*		400-420 Brinell Range	
Heat No.	Ballistic Limit, Ft./Sec.	Equiv. Brinell Hardness	Ballistic Limit, Ft./Sec.	Equiv. Brinell Hardness	Ballistic Limit, Ft./Sec.	Equiv. Brinell Hardness
7111	2157	312	2259	---	2445	404
7326	2124	339	2264	---	2245	420
7327	2104	305	2209	---	2362	412
7329	2131	307	2207	---	2455	421
7330	2157	303	2203	---	2412	404
7340	2123	321	2220	---	2388	418
7341	2108	319	2181	---	2230	413
7342	2176	319	2289	---	2410	409
7344	2122	302	2235	---	2267	390
7347	2171	316	2150	---	2274	410
7348	2132	304	2170	---	2345	402
7350	2123	333	2246	---	2356	418
7351	2094	291	2135	---	2426	410
7353	2183	336	2220	---	2328	379
7354	2247	328	2300	---	2417	404
7355	2150	307	2215	---	2427	417
Average	2143	315	2218		2361	408

* Cross-section hardness surveys were not made.

When the results from the 27 heats which are now being tested are in, the values for ballistic limits can be plotted against hardness for the purpose of showing the trend.

FUTURE WORK

Plans for future work include a cross-section hardness survey on the 81 plates which are now at Watertown for ballistic testing. After this work is completed, it is understood that a conference will be held for the purpose of picking out a few of the more promising compositions so that a more exhaustive study of their possibilities as armor plate steels may be carried out.

Data from which this report was written are recorded in Laboratory Notebook No. 615, pages 69 to 99, inclusive, and Laboratory Notebook No. 849, pages 4 to 46, inclusive.

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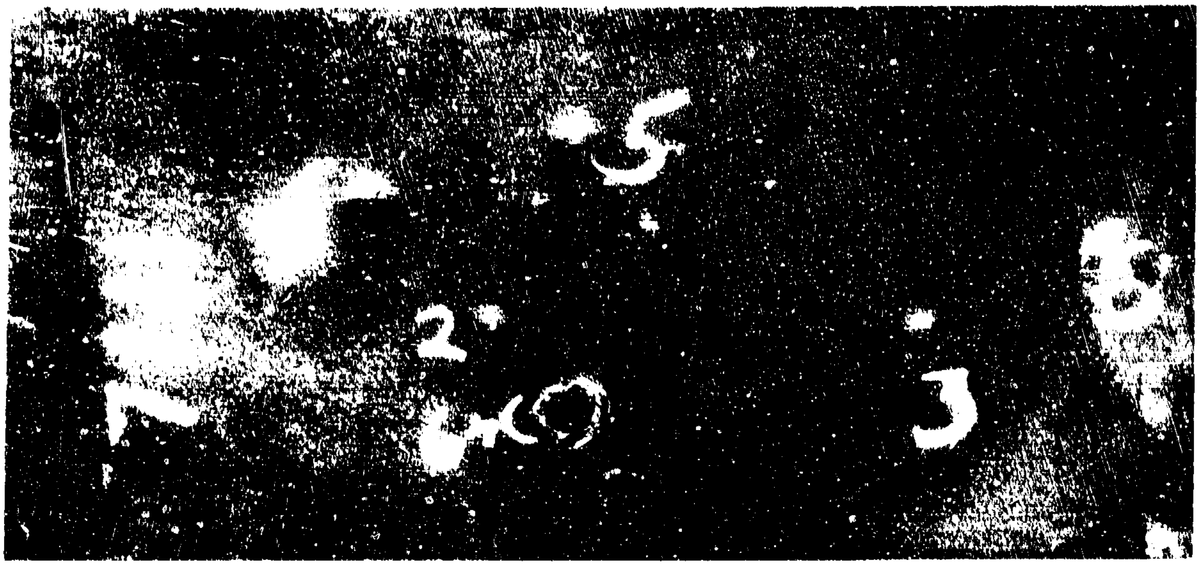
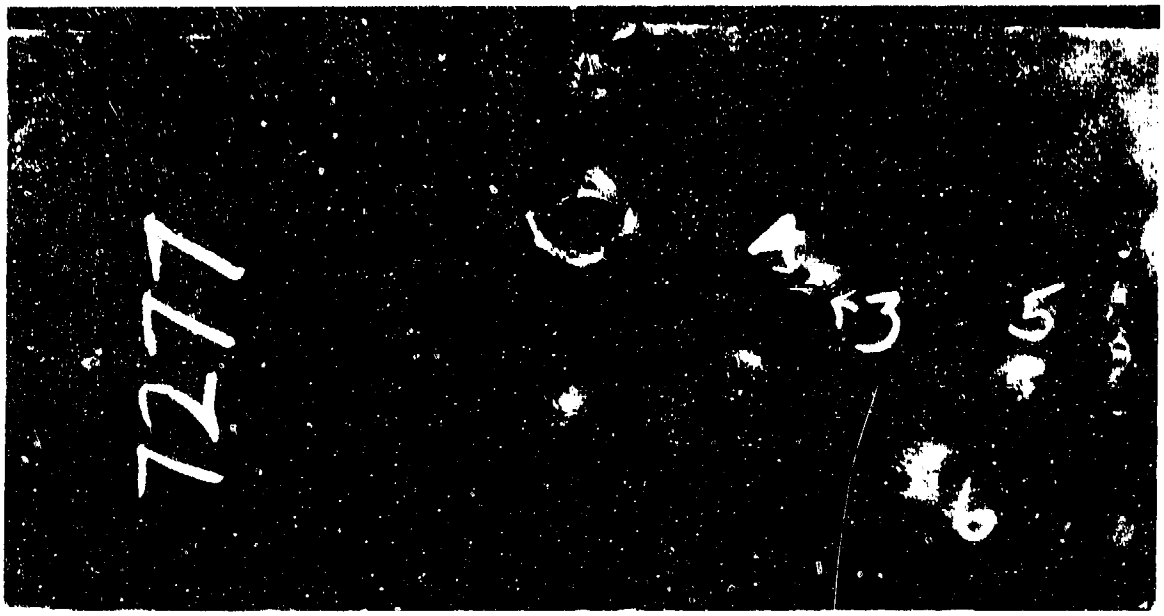


13700

Figure 32. Heat No. 7111. Back of plate after ballistic tests. Ballistic limit: 2259 feet per second, .30 cal. A. P. bullet. Average Brinell-363. Photograph 1/2 Actual Size.

13706

Figure 33. Heat No. 7276. Back of plate after ballistic tests. Ballistic limit: 2316 feet per second, .30 cal. A. P. bullet. Average Brinell-357. Photograph 1/2 Actual Size.



13696

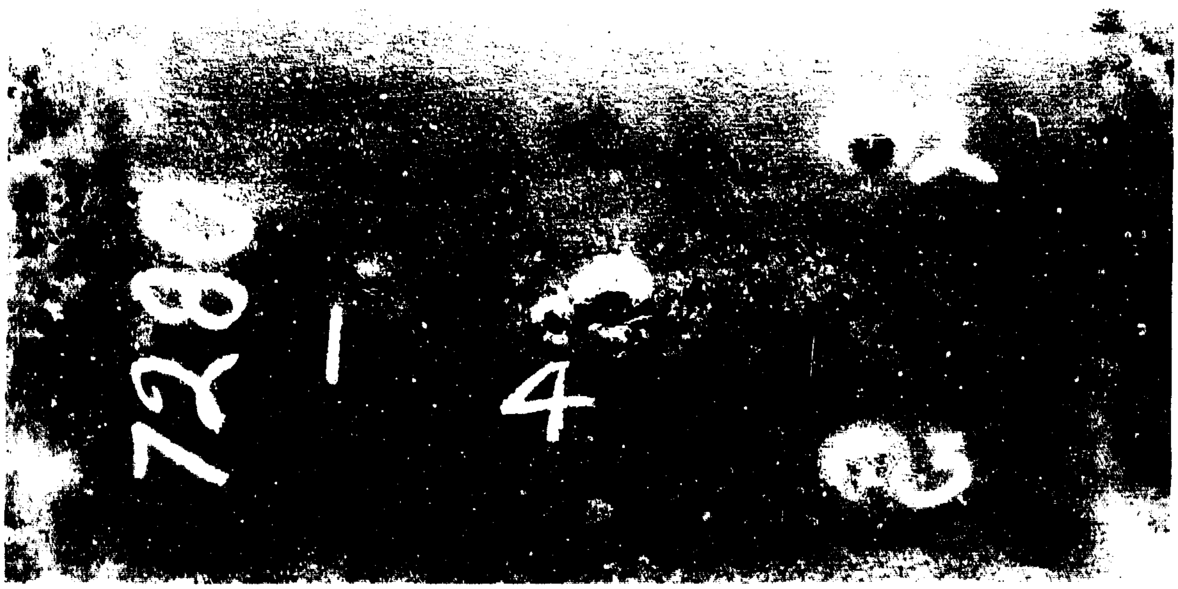
Figure 34. Heat No. 7277. Back of plate after ballistic tests. Ballistic limit: 2142 feet per second, .30 cal.A. P. bullet. Average Brinell-366. Photograph 1/2 Actual Size.

13699

Figure 35. Heat No. 7278. Back of plate after ballistic tests. Ballistic limit: 2250 feet per second, .30 cal. A. P. bullet. Average Brinell-369. Photograph 1/2 Actual Size.

13710

Figure 36. Heat No. 7279. Back of plate after ballistic tests. Ballistic limit: 2149 feet per second, .30 cal. A. P. bullet. Average Brinell-341. Photograph 1/2 Actual Size.



13698

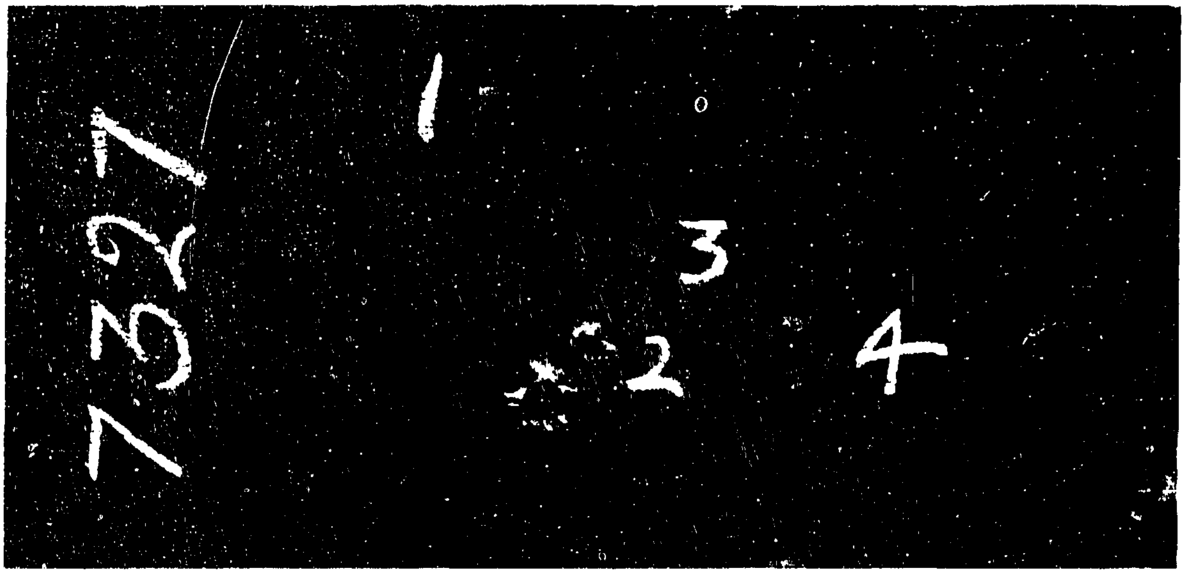
Figure 37. Heat No. 7280. Back of plate after ballistic tests. Ballistic limit: 2291 feet per second, .30 cal. A. P. bullet. Average Brinell- 365. Photograph 1/2 Actual Size.

13702

Figure 38. Heat No. 7281. Back of plate after ballistic tests. Ballistic limit: 2275 feet per second, .30 cal. A. P. bullet. Average Brinell- 369. Photograph 1/2 Actual Size.

13718

Figure 39. Heat No. 7326. Back of plate after ballistic tests. Ballistic limit: 2264 feet per second, .30 cal. A. P. bullet. Average Brinell-368. Photograph 1/2 Actual Size.

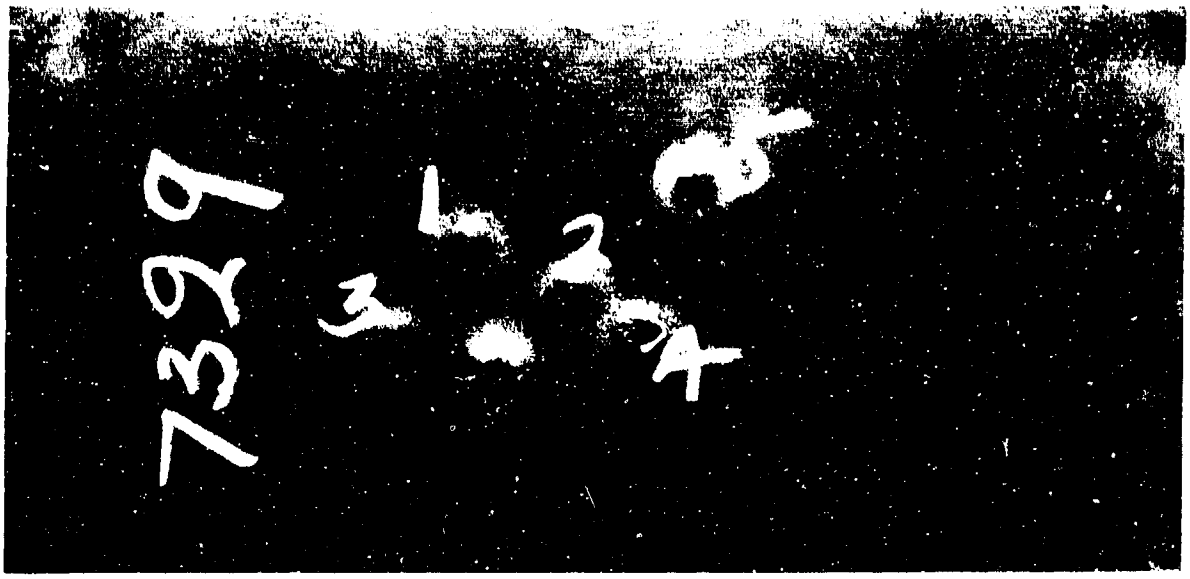


13712

Figure 40. Heat No. 7327. Back of plate after ballistic tests. Ballistic limit: 2209 feet per second, .30 cal. A. P. bullet. Average Brinell-370. Photograph 1/2 Actual Size.

13411

Figure 41. Heat No. 7328. Back of machined plate after ballistic tests. Ballistic limit: 2237 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 38, 38, 38, 38, 38, 38, 38. Average equivalent Brinell-352. Photograph 1/2 Actual Size.



13707

Figure 42. Heat No. 7329. Back of plate after ballistic tests. Ballistic limit: 2207 feet per second, .30 cal. A. P. bullet. Average Brinell-366. Photograph 1/2 Actual Size.

13719

Figure 43. Heat No. 7330. Back of plate after ballistic tests. Ballistic limit: 2203 feet per second, .30 cal. A. P. bullet. Average Brinell-369. Photograph 1/2 Actual Size.

13708

Figure 44. Heat No. 7340. Back of plate after ballistic tests. Ballistic limit: 2220 feet per second, .30 cal. A. P. bullet. Average Brinell-363. Photograph 1/2 Actual Size.

13704

Figure 45. Heat No. 7341. Back of plate after ballistic tests. Ballistic limit: 2181 feet per second, .30 cal. A. P. bullet. Average Brinell-355. Photograph 1/2 Actual Size.

13715

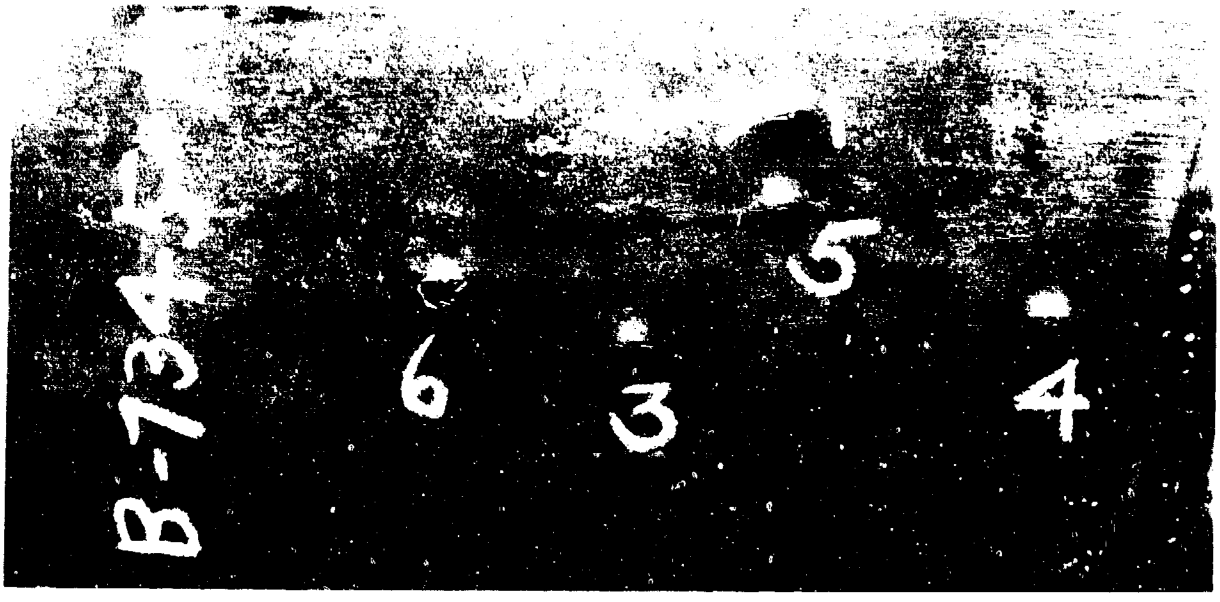
Figure 46. Heat No. 7342. Back of plate after ballistic tests. Ballistic limit: 2289 feet per second, .30 cal. A. P. bullet. Average Brinell-365. Photograph 1/2 Actual Size.

13410

Figure 47. Heat No. 7343. Back of machined plate after ballistic tests. Ballistic limit: 2293 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 36, 36, 36, 36, 37, 36, 36. Average equivalent Brinell-332. Photograph 1/2 Actual Size.

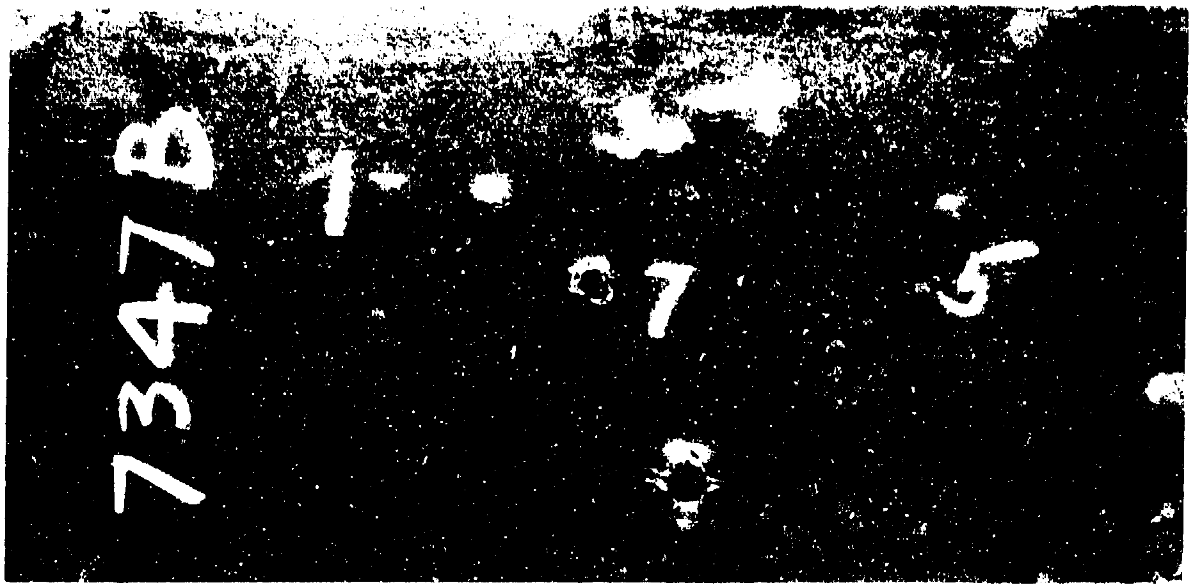
13717

Figure 48. Heat No. 7344. Back of plate after ballistic tests. Ballistic limit: 2235 feet per second, .30 cal. A. P. bullet. Average Brinell-351. Photograph 1/2 Actual Size.



13403

Figure 49. Heat No. 7345. Back of machined plate after ballistic tests. Ballistic limit: 2268 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 37, 37, 37, 37, 38, 36, 38. Average equivalent Brinell-342. Photograph 1/2 Actual Size.

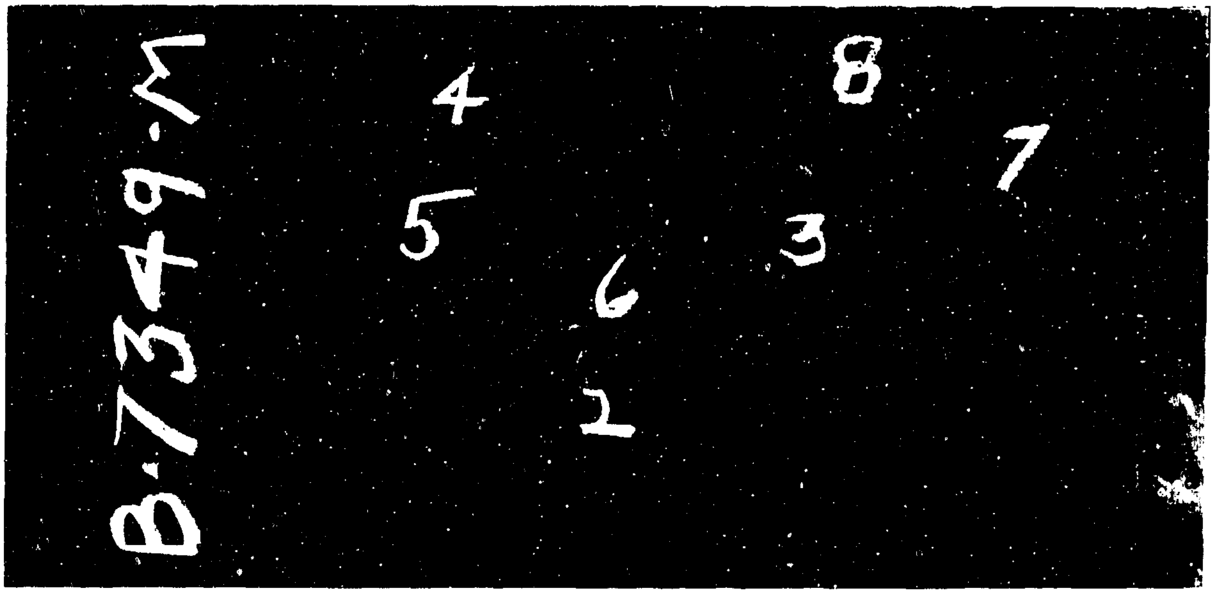


13714

Figure 50. Heat No. 7347. Back of plate after ballistic tests. Ballistic limit: 2150 feet per second, .30 cal. A. P. bullet. Average Brinell-363. Photograph 1/2 Actual Size.

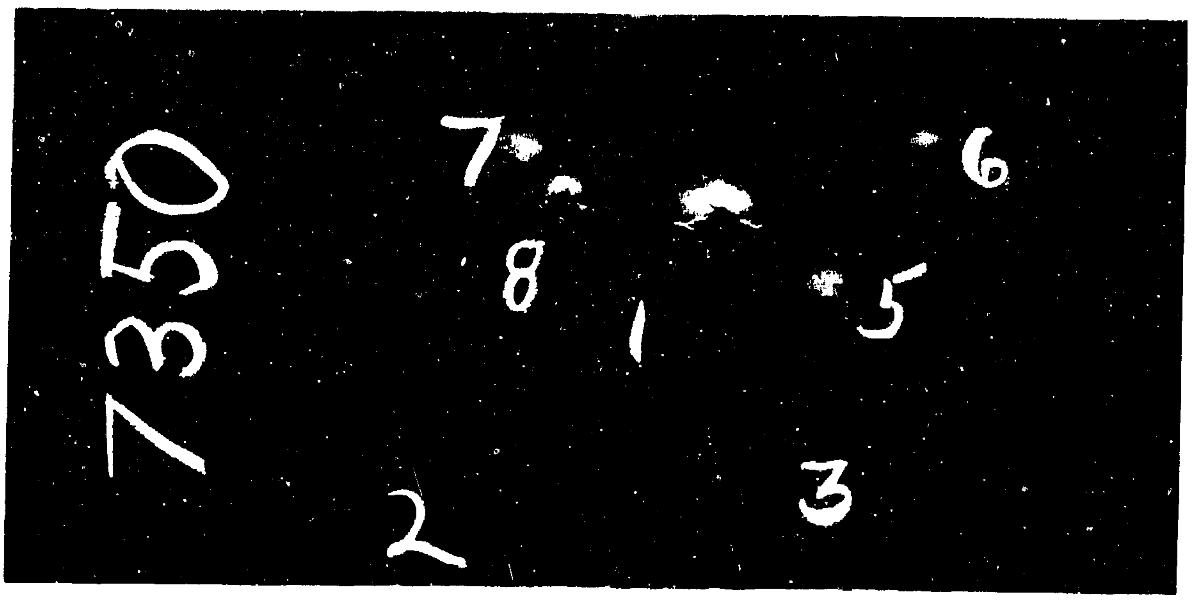
13705

Figure 51. Heat No. 7348. Back of plate after ballistic tests. Ballistic limit: 2170 feet per second, .30 cal. A. P. bullet. Avercge Brinell-369. Photograph 1/2 Actual Size.



13407

Figure 52. Heat No. 7349. Back of machined plate after ballistic tests. Ballistic limit: 2260 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 37, 36, 35, 37, 37, 35, 36. Average equivalent Brinell-332. Photograph 1/2 Actual Size.

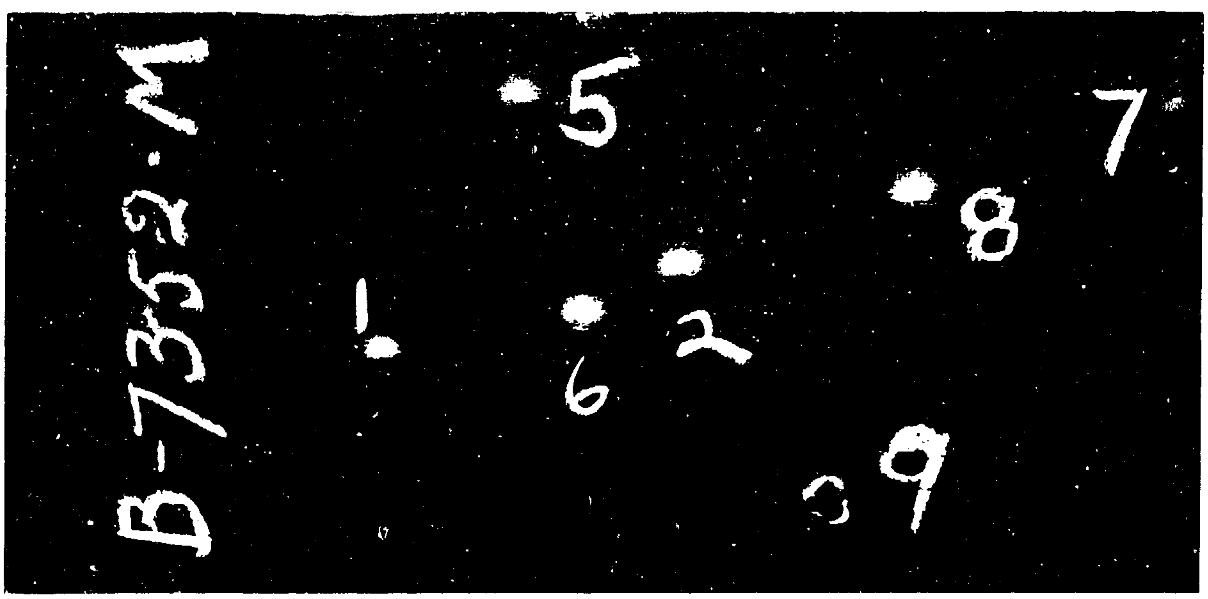


13711

Figure 53. Heat No. 7350. Back of plate after ballistic tests. Ballistic limit: 2246 feet per second, .30 cal. A. P. bullet. Average Brinell-375. Photograph 1/2 Actual Size.

13713

Figure 54. Heat No. 7351. Back of plate after ballistic tests. Ballistic limit: 2135 feet per second, .30 cal. A. P. bullet. Average Brinell-369. Photograph 1/2 Actual Size.



13395

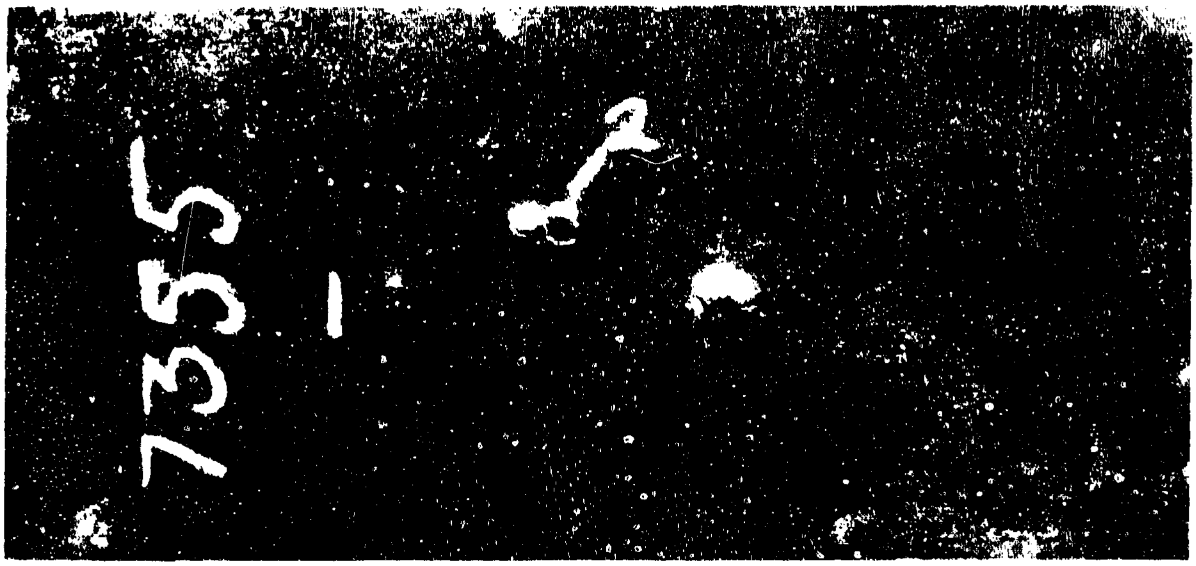
Figure 55. Heat No. 7352. Back of machined plate after ballistic tests. Ballistic limit: 2242 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 38, 38, 38, 37, 38, 38, 38. Average equivalent Brinell-352. Photograph 1/2 Actual Size.

13701

Figure 56. Heat No. 7353. Back of plate after ballistic tests. Ballistic limit: 2220 feet per second, .30 cal. A. P. bullet. Average Brinell-349. Photograph 1/2 Actual Size.

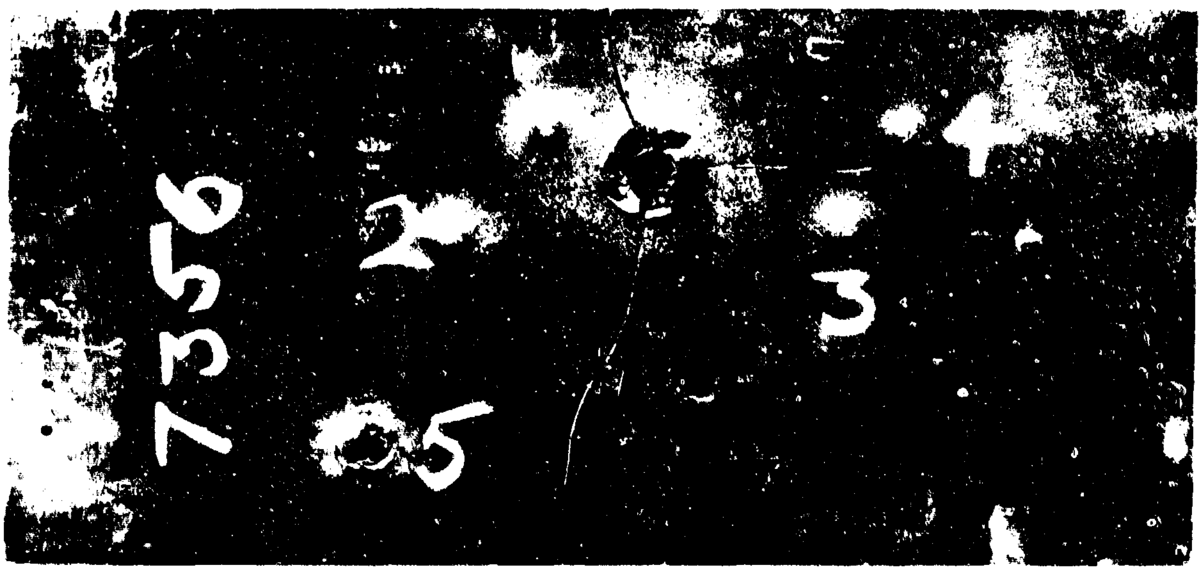
13709

Figure 57. Heat No. 7354. Back of plate after ballistic tests. Ballistic limit: 2300 feet per second, .30 cal. A. P. bullet. Average Brinell-358. Photograph 1/2 Actual Size.



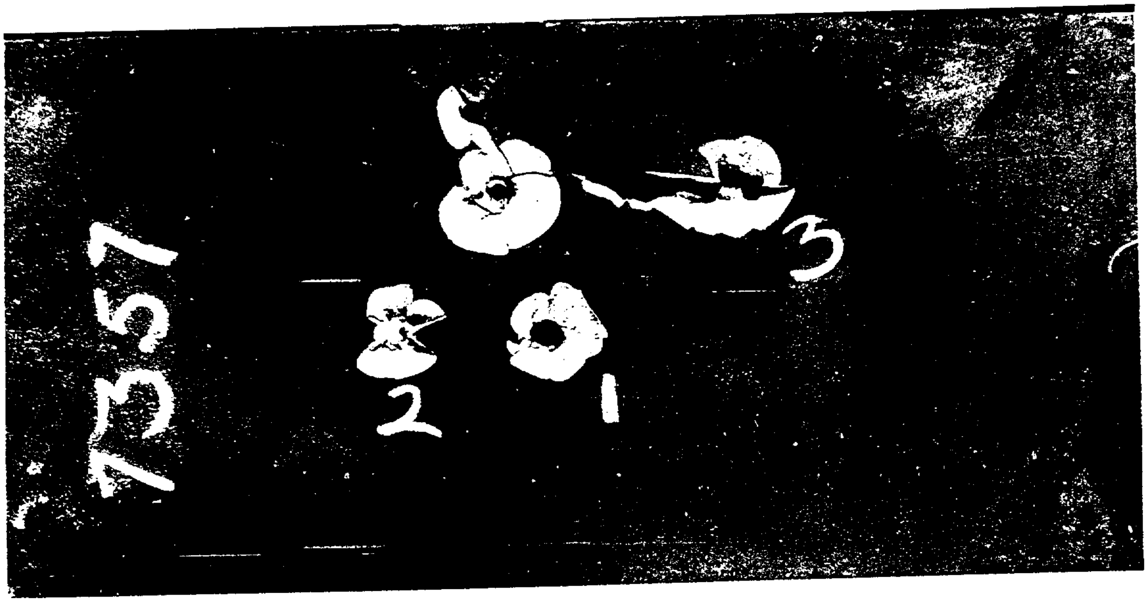
13716

Figure 58. Heat No. 7355. Back of plate after ballistic tests. Ballistic limit: 2215 feet per second, .30 cal. A. P. bullet. Average Brinell-362. Photograph 1/2 Actual Size.



13693

Figure 59. Heat No. 7356. Back of plate after ballistic tests. Ballistic limit: 2300 feet per second, .30 cal. A. P. bullet. Average Brinell-365. Photograph 1/2 Actual Size.

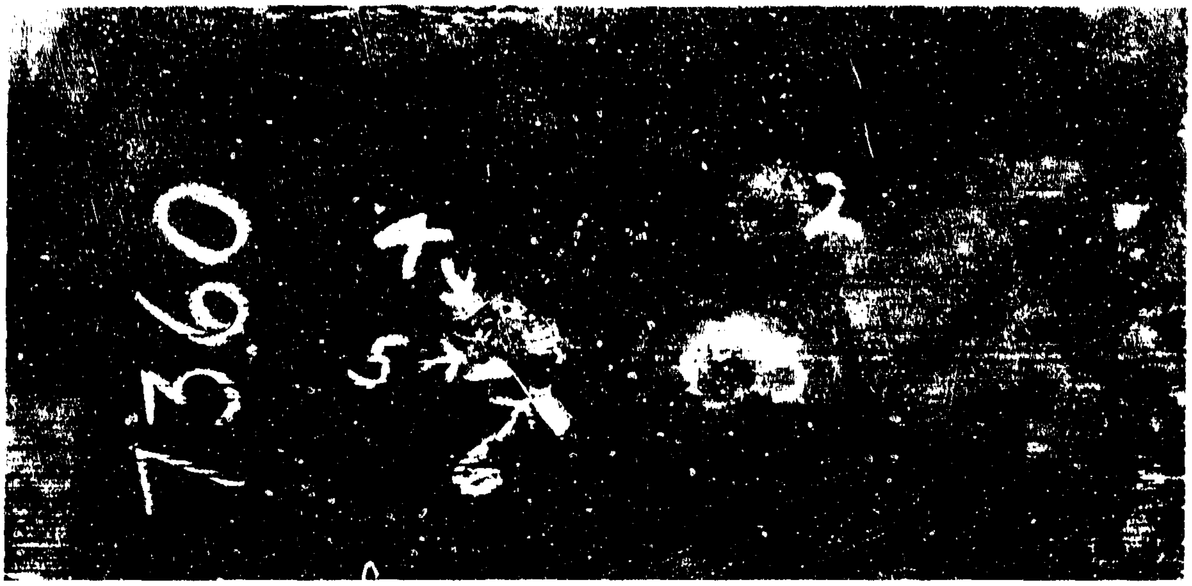


13695

Figure 60. Heat No. 7357. Back of plate after ballistic tests. Ballistic limit not determined, .30 cal. A. P. bullet. Average Brinell - 363. Photograph 1/2 Actual Size.

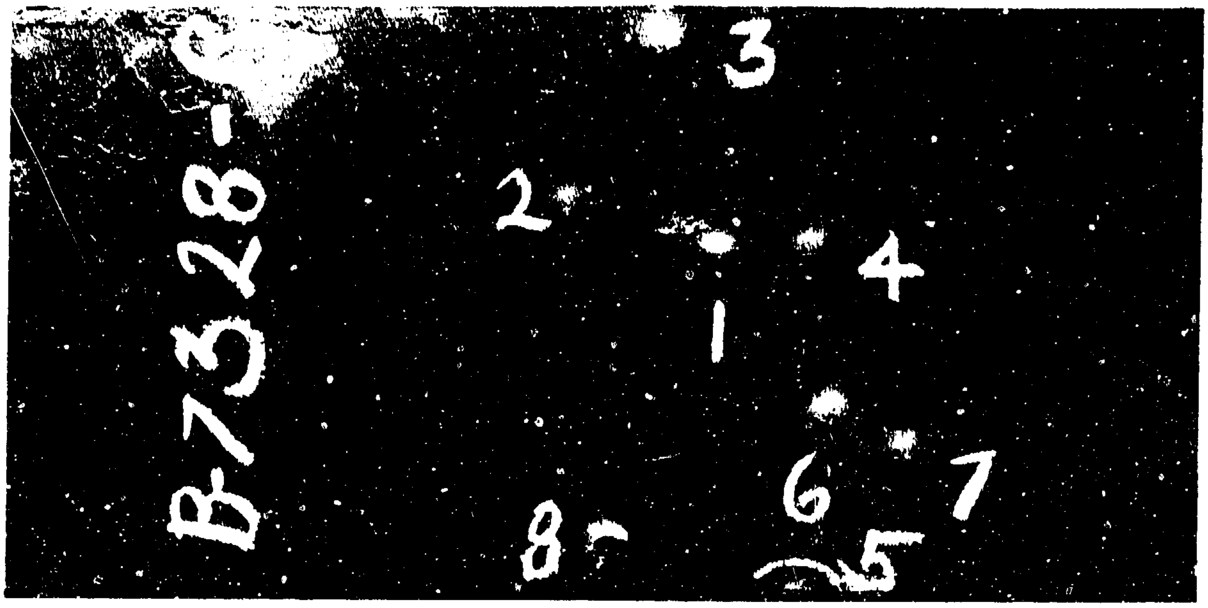
13694

Figure 61. Heat No. 7358. Back of plate after ballistic tests. Ballistic limit not determined, .30 cal. A. P. bullet. Average Brinell - 359. Photograph 1/2 Actual Size.



13703
Figure 62. Heat No. 7360. Back of plate after ballistic tests. Ballistic limit not determined, .30 cal. A P. bullet. Average Brinell- 363. Photograph 1/2 Actual Size.

13697
Figure 63. Heat No. 7476. Back of plate after ballistic tests. Ballistic limit not determined, .30 cal. A. P. Bullet. Average Brinell- 275. Photograph 1/2 Actual Size.

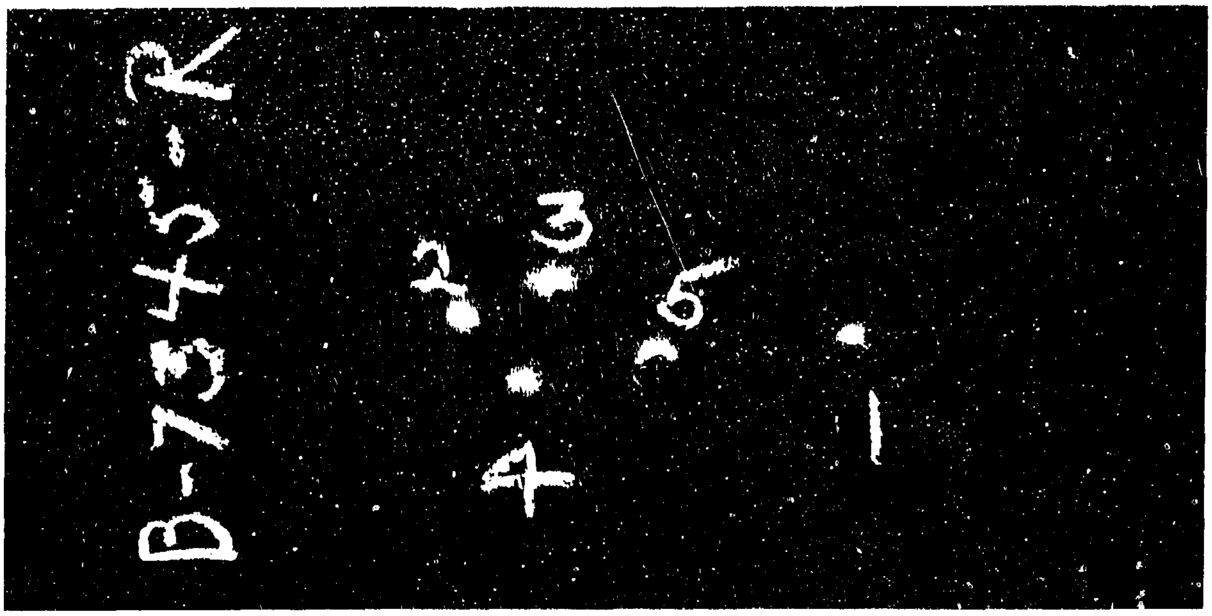


13397

Figure 64. Heat No. 7328. Back of as rolled plate after ballistic tests. Ballistic limit 2229 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 38, 38, 38, 38, 38, 38, 38. Average equivalent Brinell-352. Photograph 1/2 Actual Size.

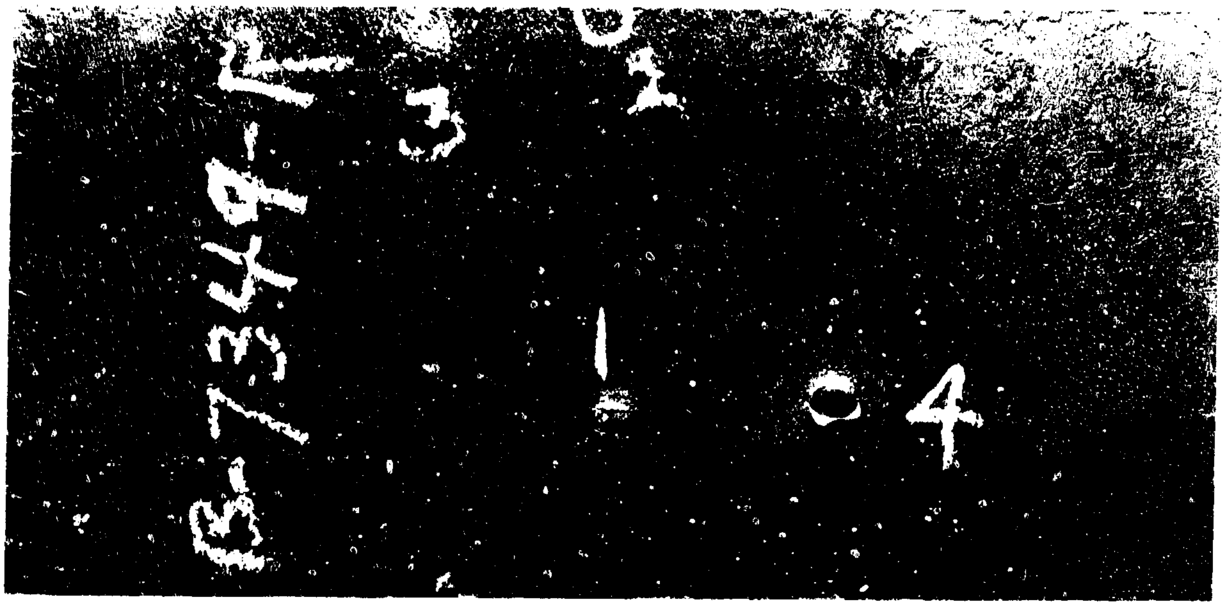
13401

Figure 65. Heat No. 7343. Back of as rolled plate after ballistic tests. Ballistic limit 2312 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 39, 39, 39, 39, 38, 39, 38. Average equivalent Brinell-362. Photograph 1/2 Actual Size.



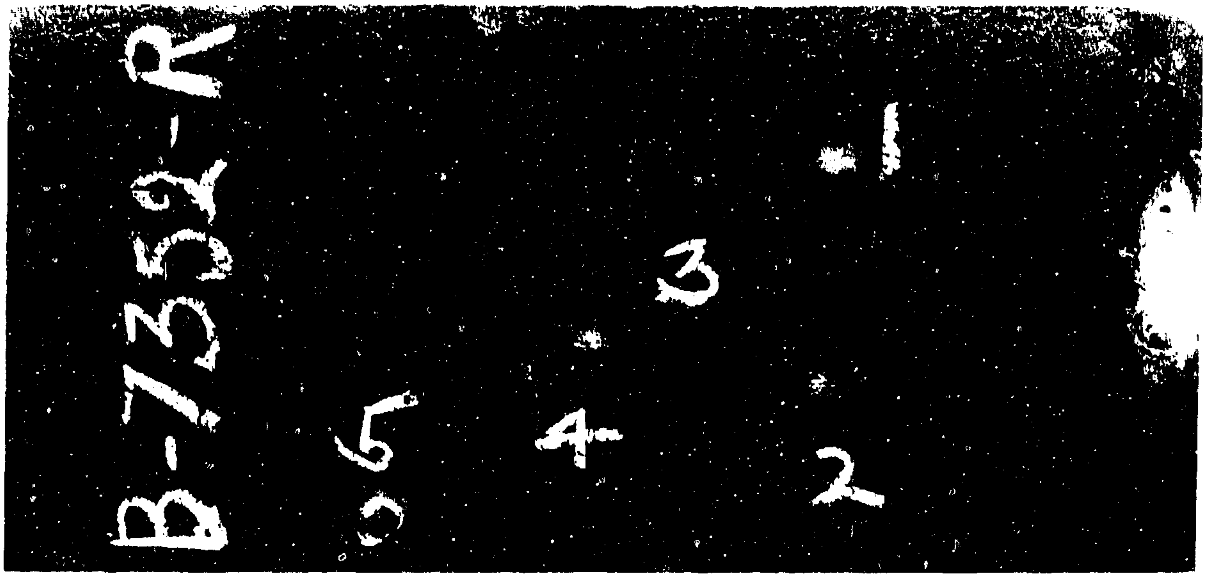
13393

Figure 66. Heat No. 7345. Back of as rolled plate after ballistic tests. Ballistic limit 2287 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 36, 37, 37, 37, 37, 37, 36. Average equivalent Brinell-342. Photograph 1/2 Actual Size.



13405

Figure 67. Heat No. 7349. Back of plate after ballistic tests. Ballistic limit: 2309 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 39, 39, 39, 39, 39, 39, 39. Average equivalent Brinell-362. Photograph 1/2 Actual Size.



13399

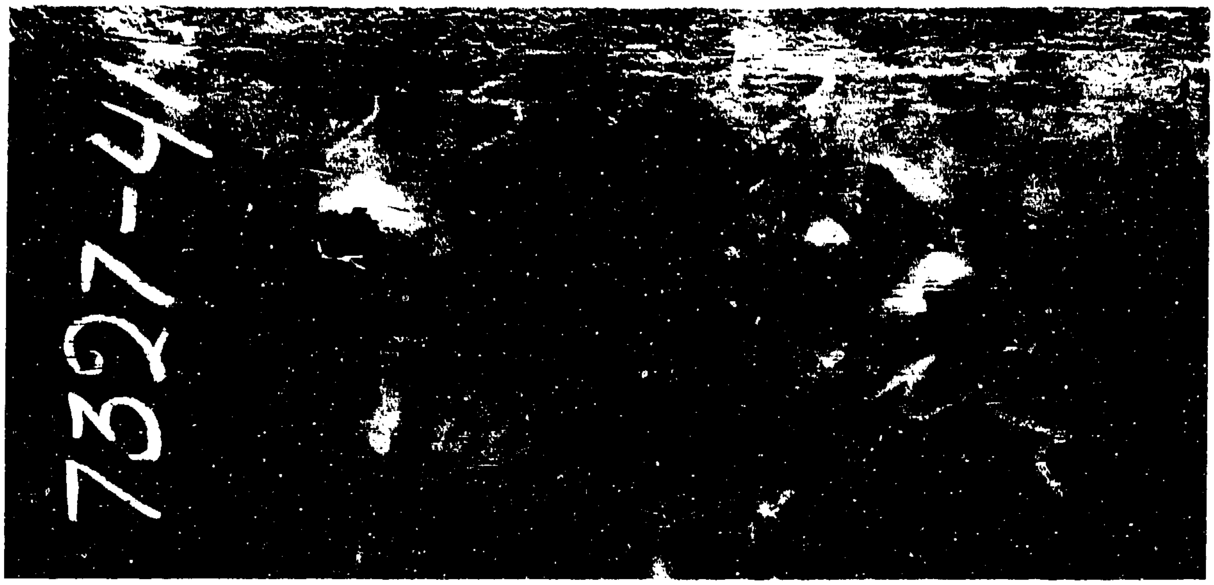
Figure 68. Heat No. 7352. Back of plate after ballistic tests. Ballistic limit: 2285 feet per second, .30 cal. A. P. bullet. Rockwell "C" cross-section hardness survey: 36, 36, 37, 37, 37, 37, 36. Average equivalent Brinell-332. Photograph 1/2 actual size.

14279

Figure 69. Heat No. 7111:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2445 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 43, 43, 43, 43, 43, 43,. Composition: Carbon .46% Silicon .20% Manganese 1.58% Vanadium .10/.20%. Average equivalent Brinell 404. Photograph 1/2 actual size.

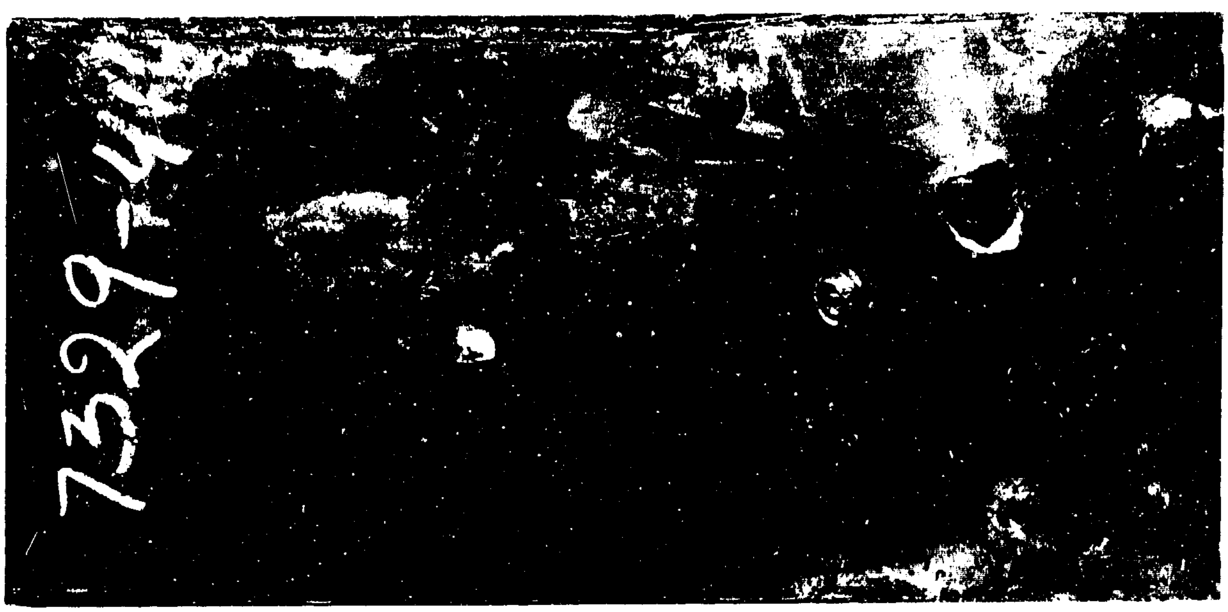
14280

Figure 70. Heat No. 7326:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2245 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 44, 45, 45, 45, 45, 44. Composition: Carbon .30% Manganese .73% Silicon .20% Chromium .90/1.10%. Average equivalent Brinell 420. Photograph 1/2 actual size.



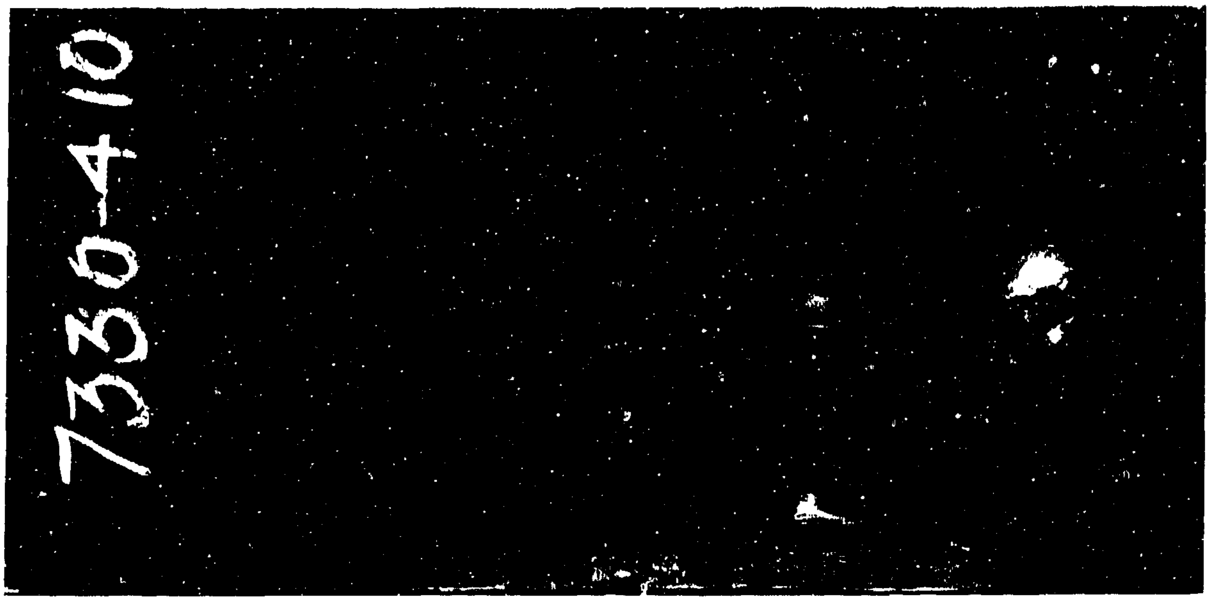
14276

Figure 71. Heat No. 7327:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2362 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 43, 44, 44, 44, 44, 44. Composition: Carbon .35% Manganese .88% Silicon .26% Chromium 2.3/2.7%. Average equivalent Brinell 412. Photograph 1/2 actual size.



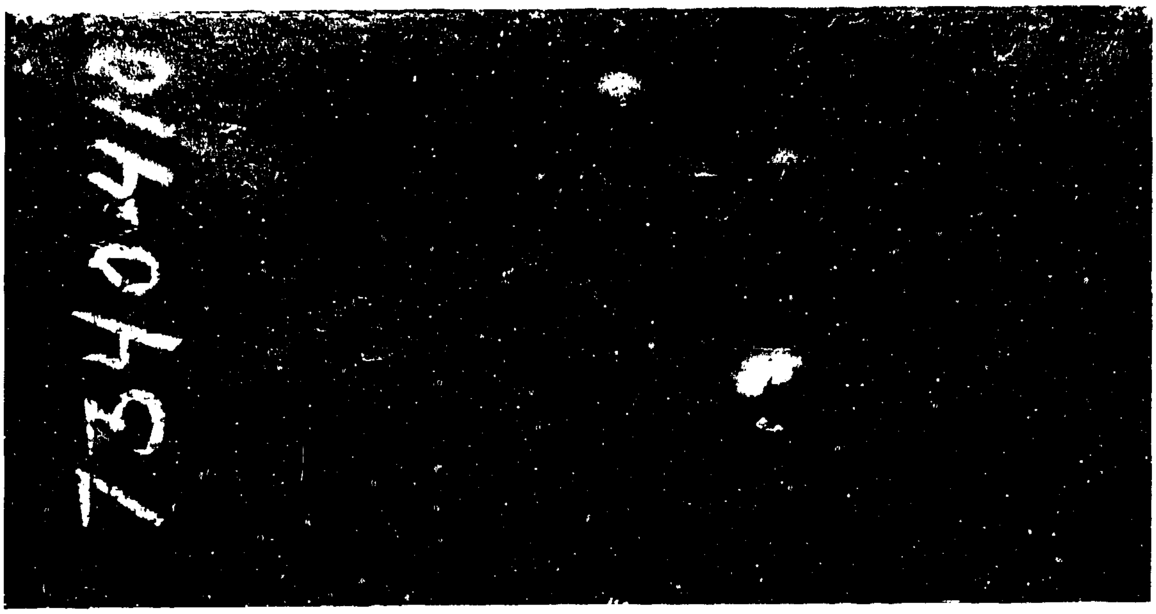
14282

Figure 72. Heat No. 7329:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2455 ft. per sec. Cal. .30 AP bullet. Rockwell "C" cross-section hardness survey: 44, 45, 45, 45, 45, 44. Composition: Carbon .34% Manganese .88% Silicon .25% Chromium 1.3/1.7% Vanadium .10/.20 Average equivalent Brinell 421. Photograph 1/2 actual size.



14286

Figure 73. Heat No. 7330:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2412 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 43, 42, 43, 43, 43, 44. Composition: Carbon .46% Manganese .86% Silicon .24% Molybdenum .25/.35% Vanadium .10/.20%. Average equivalent Brinell 404. Photograph 1/2 actual size.

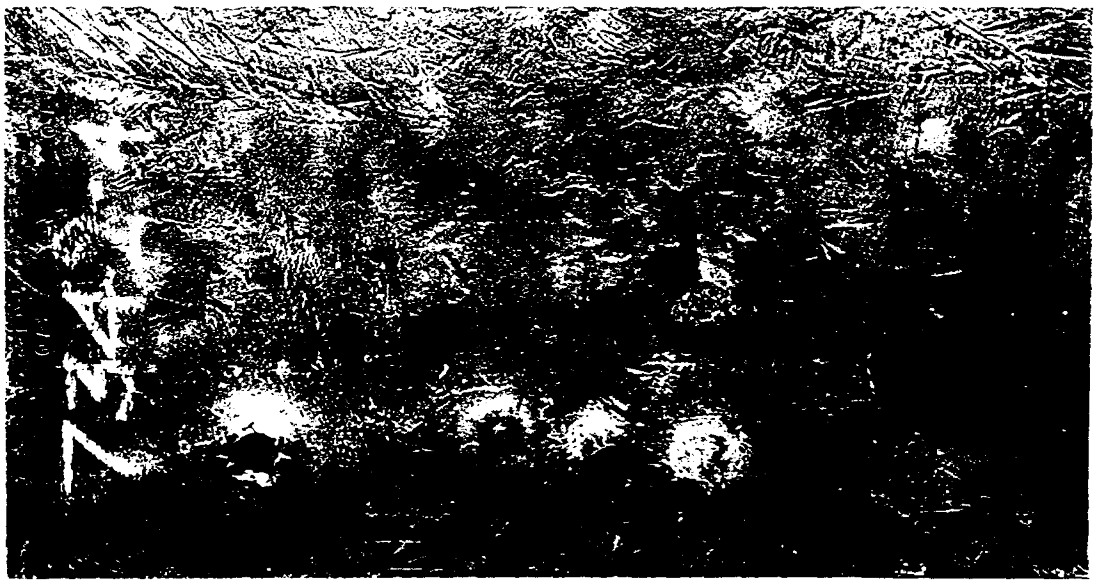


14271

Figure 74. Heat No. 7340:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2383 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 45, 44, 44, 45, 44, 44, 44,. Composition: Carbon .46% Manganese .84% Silicon .29% Molybdenum .25/.35. Average equivalent Brinell 418. Photograph 1/2 actual size.

14272

Figure 75. Heat No. 7341:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2230 ft. per sec. Cal . .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 44, 44, 44, 44, 44, 44,. Composition: Carbon .34% Manganese .94% Silicon 1.06% Chromium .90/1.10% Molybdenum .35/.45% Avera ge equivalent Brinell 413. Photograph 1/2 actual size.



14277

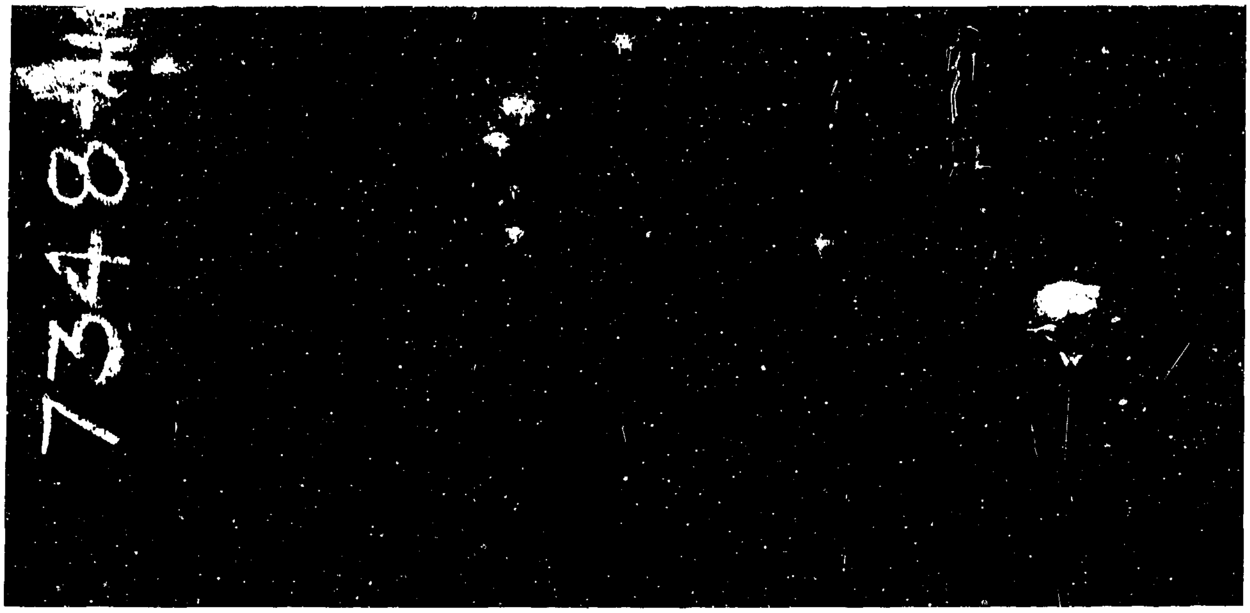
Figure 76. Heat No. 7342:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2410 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 44, 44, 43, 43, 44, 43. Composition: Carbon .46% Manganese .77% Silicon .25% Chromium .90/1.10% Molybdenum .25/.35 Vanadium .10/.20%. Average equivalent Brinell 409. Photograph 1/2 actual size.

14285

Figure 77. Heat No. 7344:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2267 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 42, 43, 44, 42, 41, 41. Composition: Carbon .46% Manganese .75% Silicon .20% Vanadium .20/.30% Average equivalent Brinell 390. Photograph 1/2 actual size.

14284

Figure 78. Heat No. 7347:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2274 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 34, 38, 33, 33, 34, 34, 34. Composition: Carbon .34% Manganese .83% Silicon .26% Chromium .90/1.10% Copper 1.4/1.6%. Average equivalent Brinell 410. Photograph 1/2 actual size.



14283

Figure 79. Heat No. 7348:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2345 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 41, 41, 42, 43, 44, 44, 45. Composition: Carbon .47% Manganese 1.48% Silicon .32% Molybdenum .40/.50% Copper .30/.50% Average equivalent Brinell 402. Photograph 1/2 actual size.

14281

Figure 79a. Heat No. 7350:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2356 ft. per sec. Cal. .30 AP. bullet. Rockwell"C" cross-section hardness survey: 44, 44, 44, 45, 45, 44, 44. Composition: Carbon .46% Manganese .80% Silicon .23% Molybdenum .40/.50% Copper 1.0/1.5% Average equivalent Brinell 418. Photograph 1/2 actual size.

14275

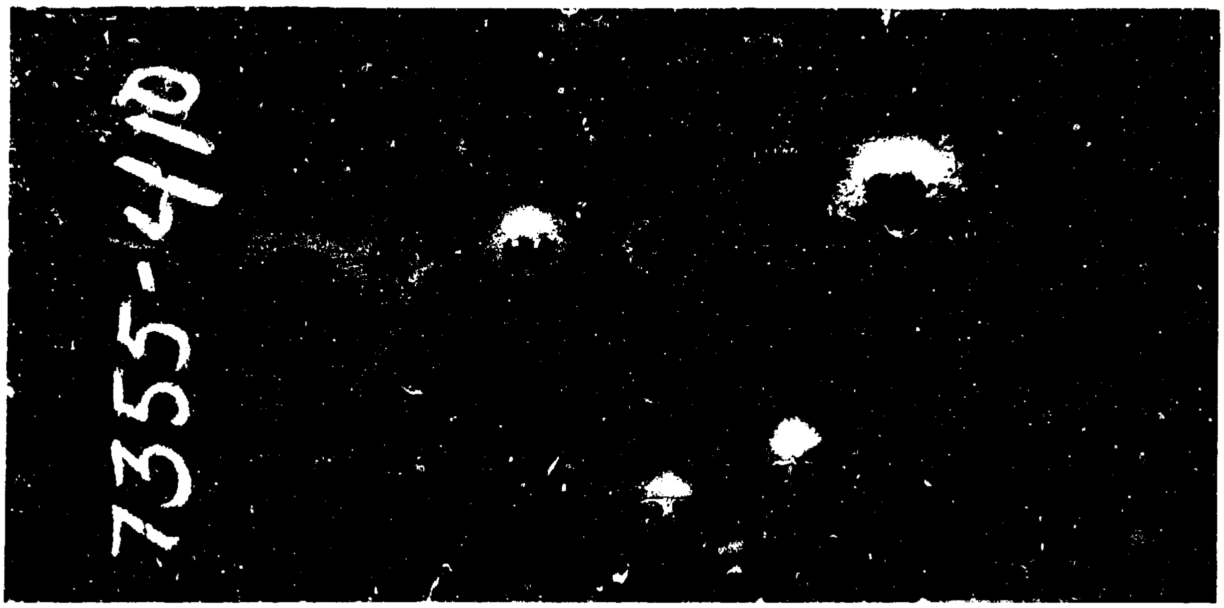
Figure 80. Heat No. 7351:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2426 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 44, 44, 44, 43, 43, 44. Composition: Carbon .46% Manganese 1.49% Silicon .29% Molybdenum .40/.50% Copper 1.0/1.5%. Average equivalent Brinell 410. Photograph 1/2 actual size.

14274

Figure 81. Heat No. 7353:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2328 ft. per sec. Cal. .30 AP. bullet Rockwell "C" cross-section hardness survey: 41, 41, 41, 41, 40, 41, 40. Composition: Carbon .45% Manganese .84% Silicon .73%. Average equivalent Brinell 379. Photograph 1/2 actual size.

14273

Figure 82. Heat No. 7354:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2417 ft. per sec. Cal. .30 AP. bullet. Rockwell "C" cross-section hardness survey: 43, 43, 43, 43, 43, 43, 43 Composition Carbon .45% Manganese .88% Silicon 1.71%. Average equivalent Brinell 404. Photograph 1/2 actual size.



14278

Figure 83. Heat No. 7355:410. Back of as rolled plate after ballistic tests. Ballistic limit: 2427 ft. per sec. Cal. .30 AP bullet. Rockwell "C" cross-section hardness survey: 45, 44, 45, 43, 44, 45, 44. Composition Carbon .46% Manganese .78% Silicon 1.06% Molybdenum .40/.50%. Average equivalent Brinell 417. Photograph 1/2 actual size.

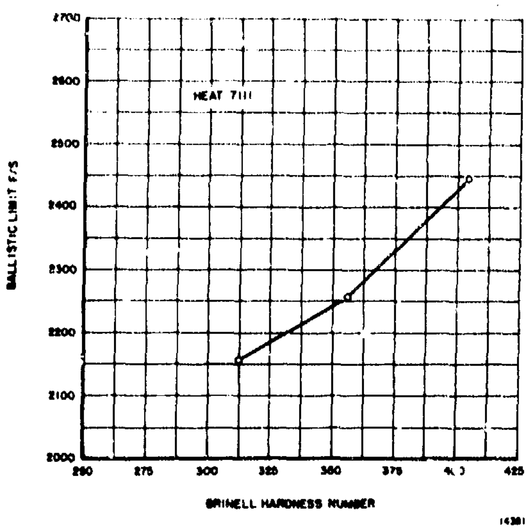


Figure 84. Heat No. 7111. Relationship of ballistic limit to Brinell hardness.

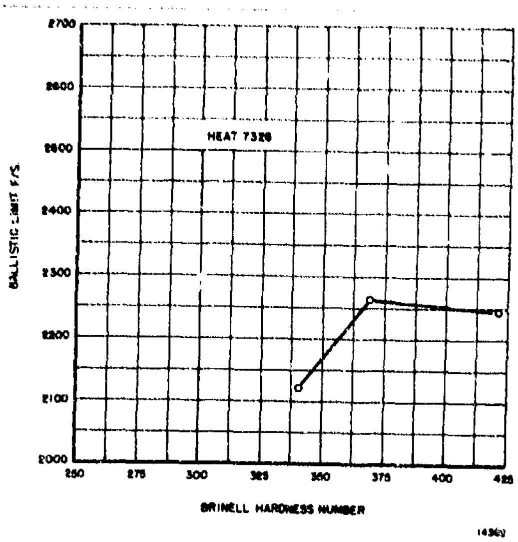


Figure 85. Heat No. 7326. Relationship of ballistic limit to Brinell hardness.

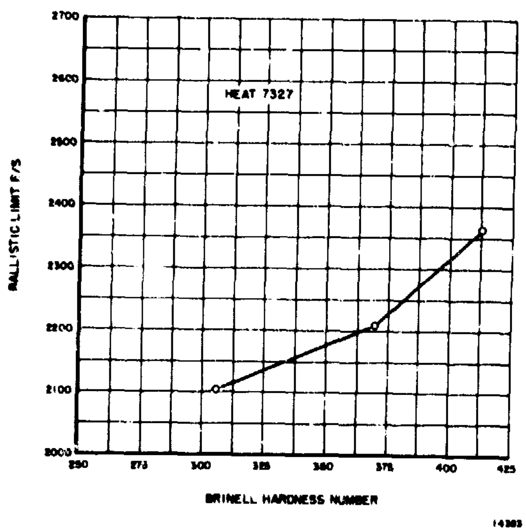


Figure 86. Heat No. 7327. Relationship of ballistic limit to Brinell hardness.

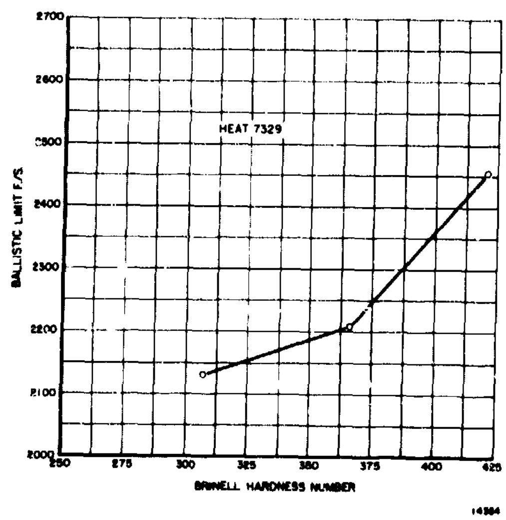


Figure 87. Heat No. 7329. Relationship of ballistic limit to Brinell hardness.

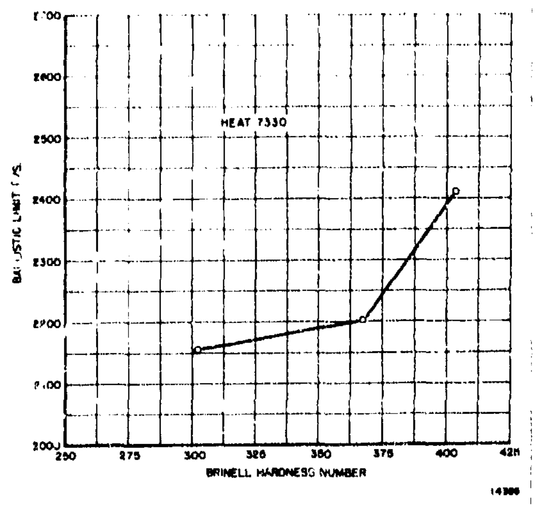


Figure 88. Heat No. 7330. Relationship of ballistic limit to Brinell hardness.

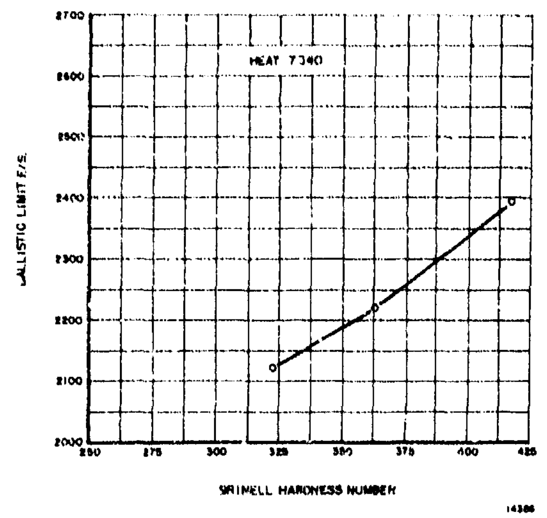


Figure 89. Heat No. 7340. Relationship of ballistic limit to Brinell hardness.

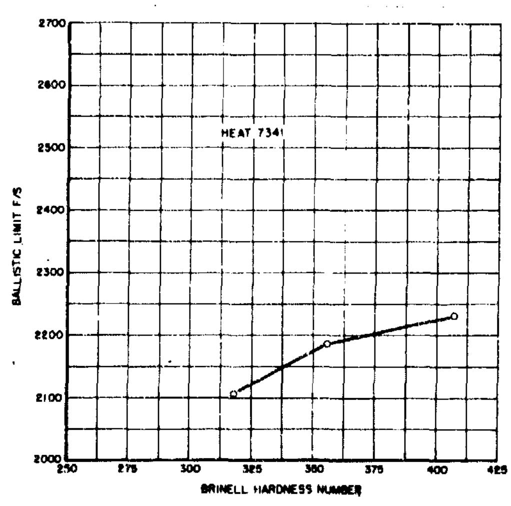


Figure 90. Heat No. 7341. Relationship of ballistic limit to Brinell hardness.

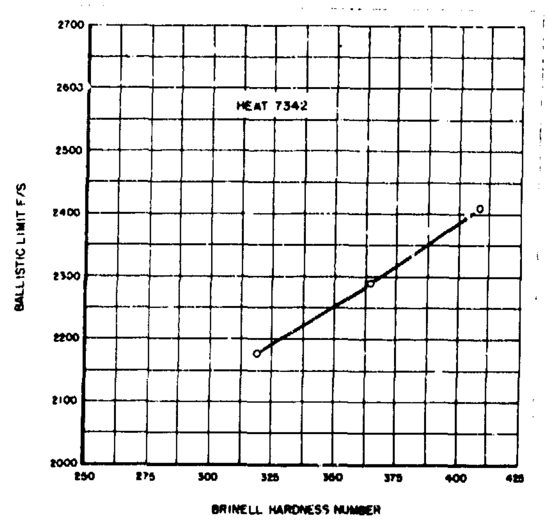


Figure 91. Heat No. 7342. Relationship of ballistic limit to Brinell hardness.

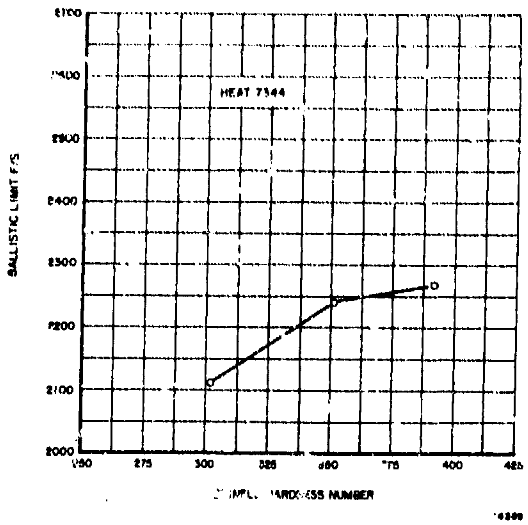


Figure 92. Heat No. 7344. Relationship of ballistic limit to Brinell hardness.

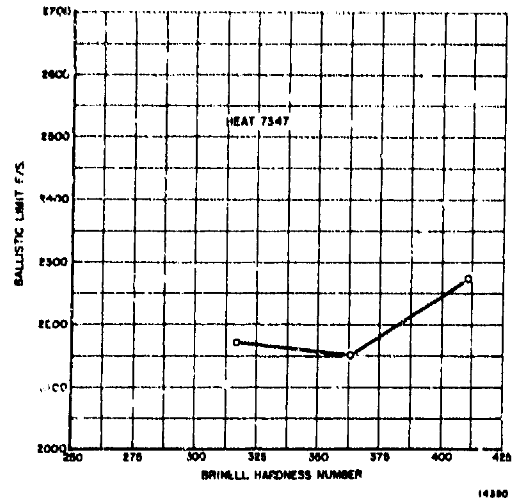


Figure 93. Heat No. 7347. Relationship of ballistic limit to Brinell hardness.

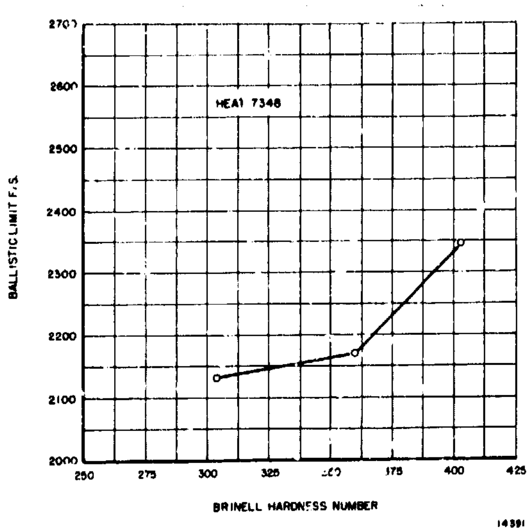


Figure 94. Heat No. 7348. Relationship of ballistic limit to Brinell hardness.

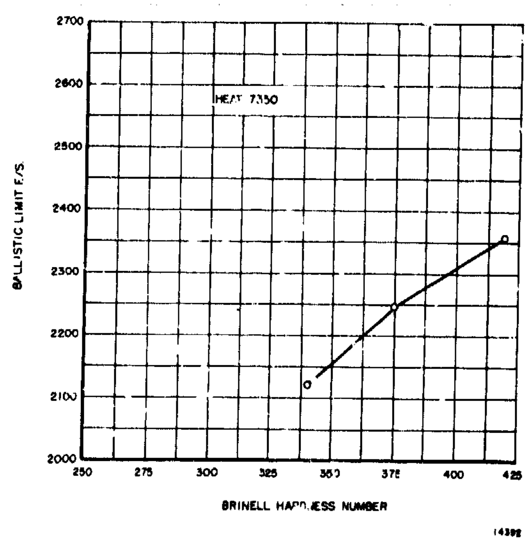


Figure 95. Heat No. 7350. Relationship of ballistic limit to Brinell hardness.

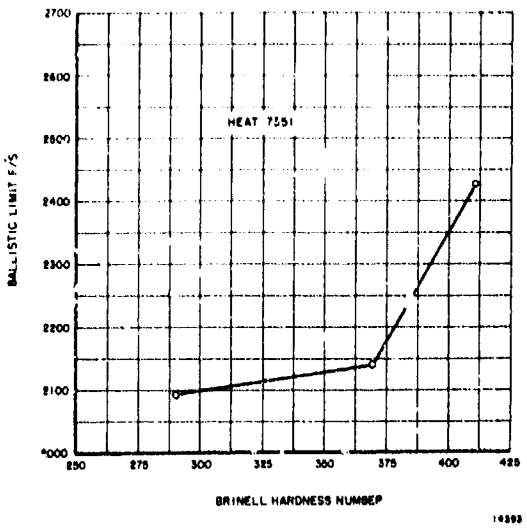


Figure 96. Heat No. 7351.
Relationship of ballistic limit
to Brinell hardness.

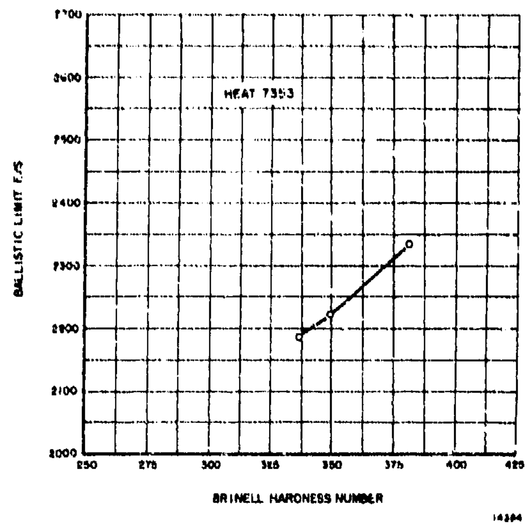


Figure 97. Heat No. 7353.
Relationship of ballistic limit
to Brinell hardness.

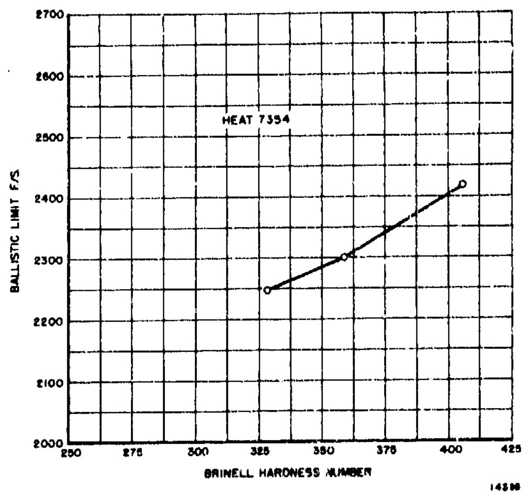


Figure 98. Heat No. 7354.
Relationship of ballistic limit
to Brinell hardness.

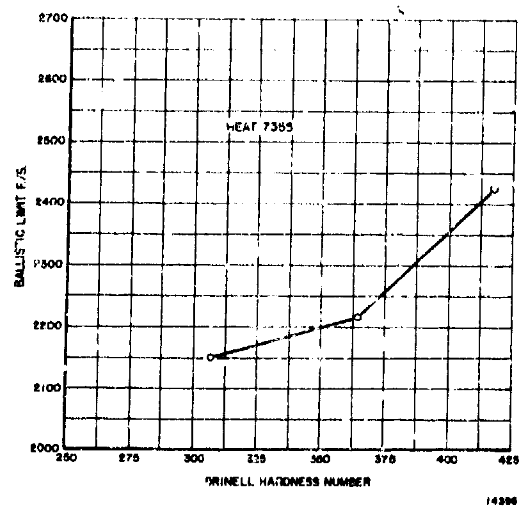


Figure 99. Heat No. 7355.
Relationship of ballistic limit
to Brinell hardness.

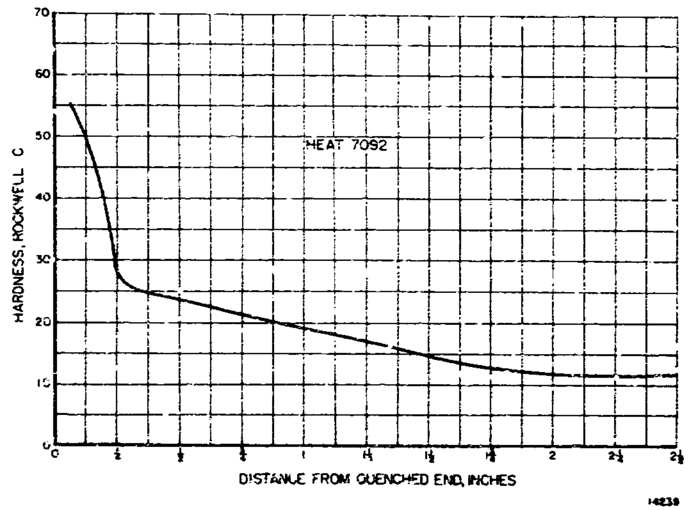


Figure 100. Heat No. 7092. Jominy end quench hardenability curve.

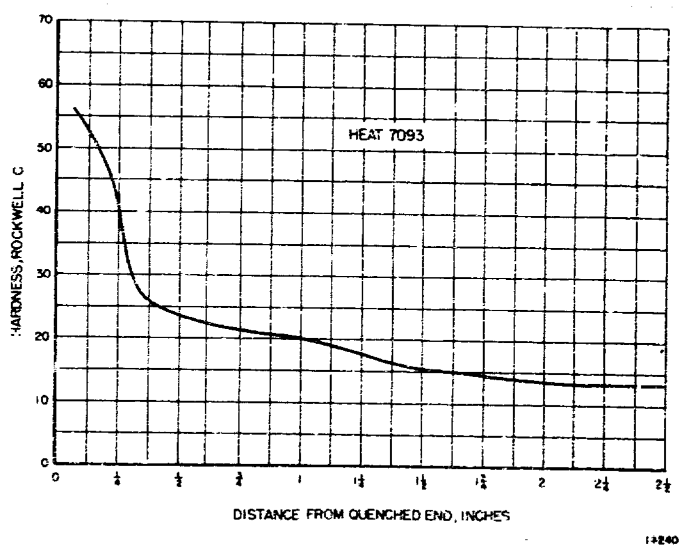


Figure 101. Heat No. 7093. Jominy end quench hardenability curve.

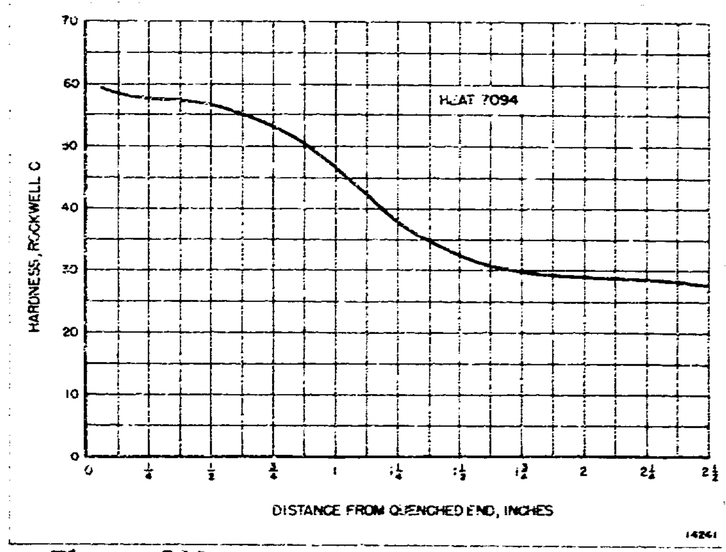


Figure 102. Heat No. 7094. Jominy end quench hardenability curve.

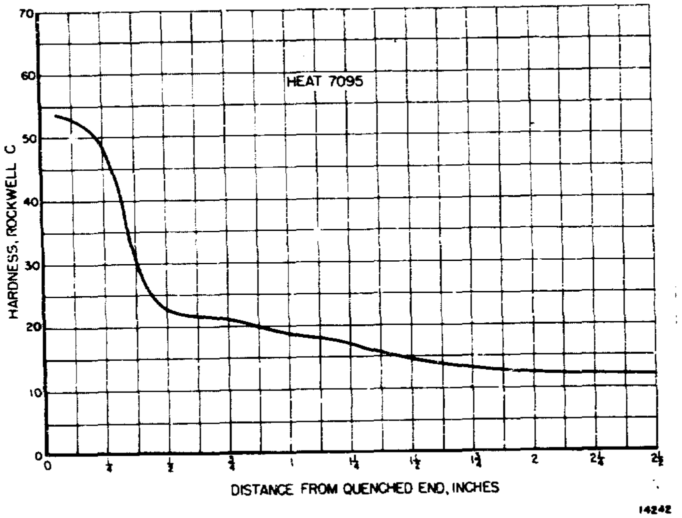


Figure 103. Heat No. 7095. Jominy end quench hardenability curve.

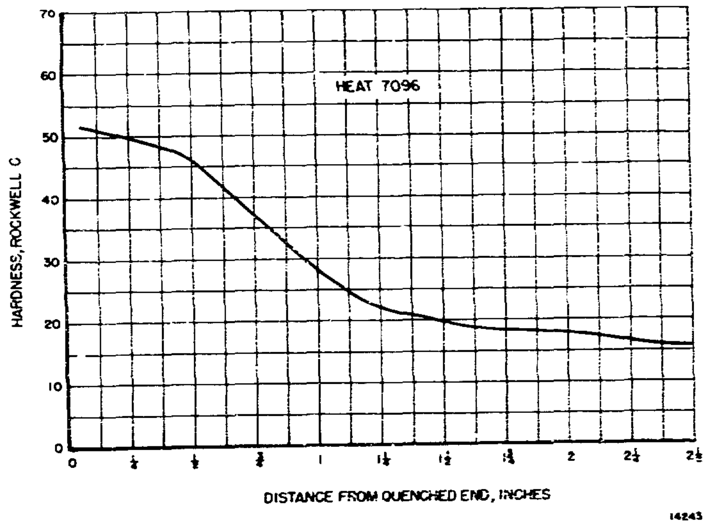


Figure 104. Heat No. 7096. Jominy end quench hardenability curve.

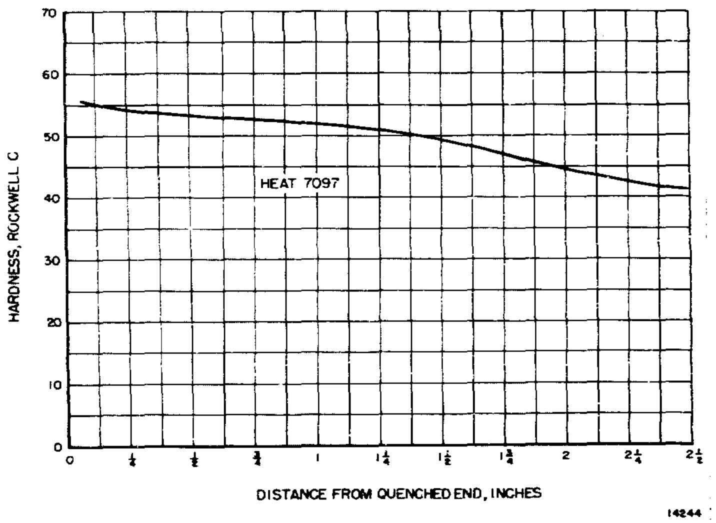


Figure 105. Heat No. 7097. Jominy end quench hardenability curve.

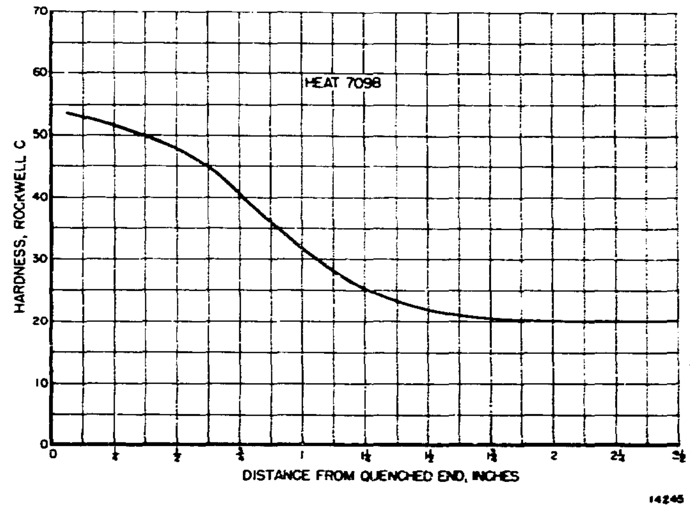


Figure 106. Heat No. 7098. Jominy end quench hardenability curve.

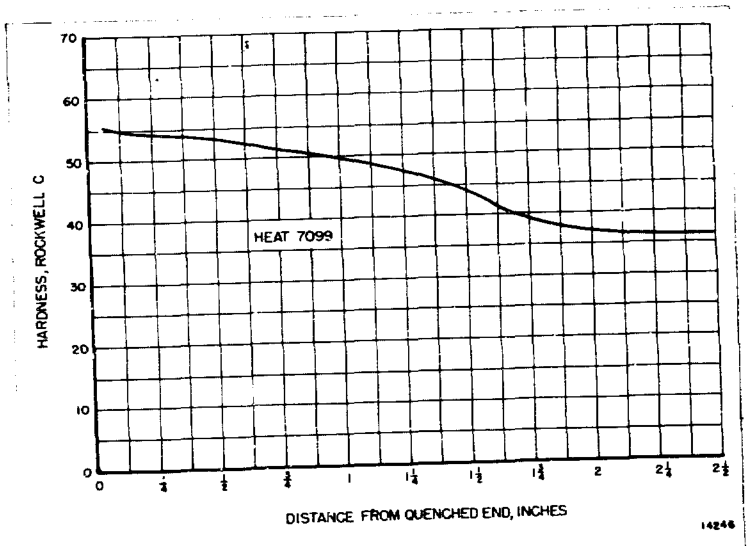


Figure 107. Heat No. 7099. Jominy end quench hardenability curve.

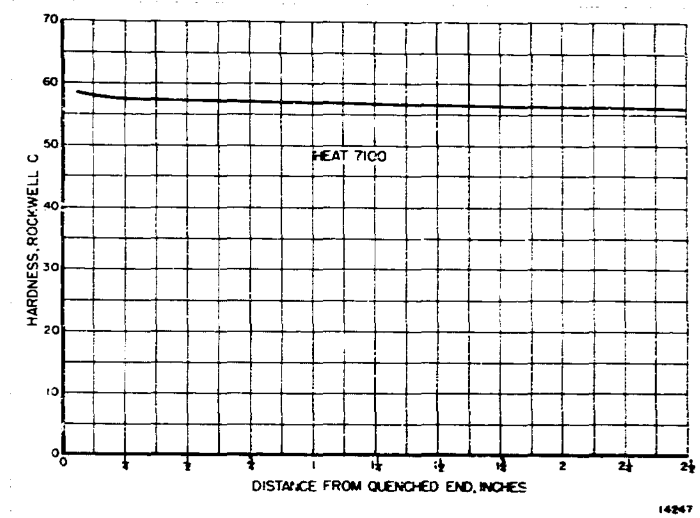


Figure 108. Heat No. 7100. Jominy end quench hardenability curve.

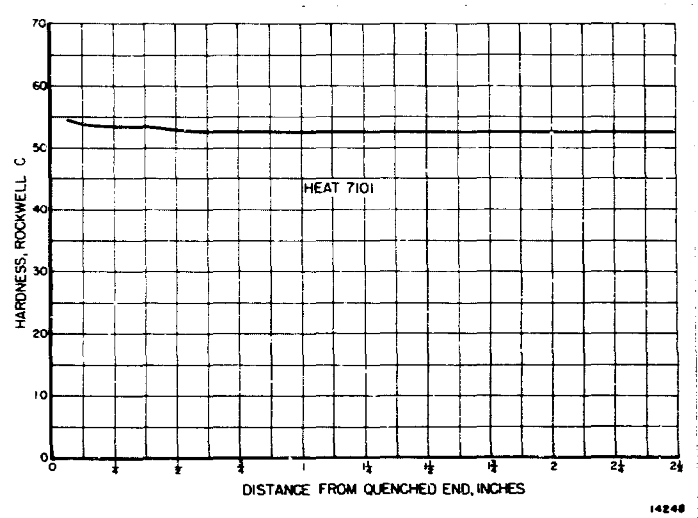


Figure 109. Heat No. 7101. Jominy end quench hardenability curve.

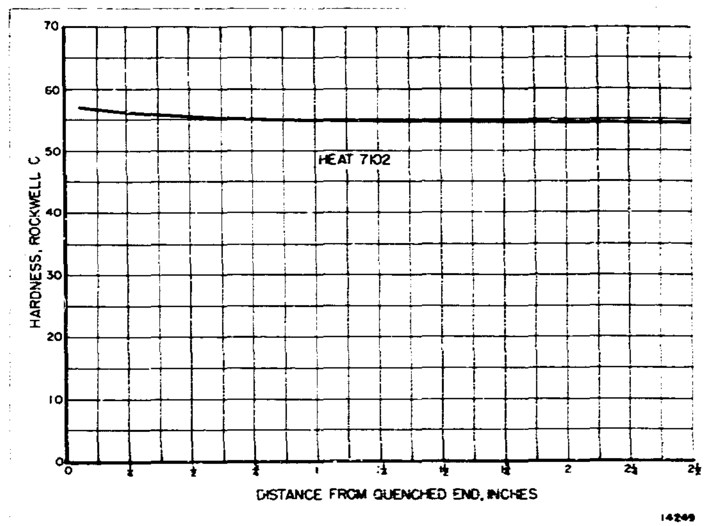


Figure 110. Heat No. 7102. Jominy end quench hardenability curve.

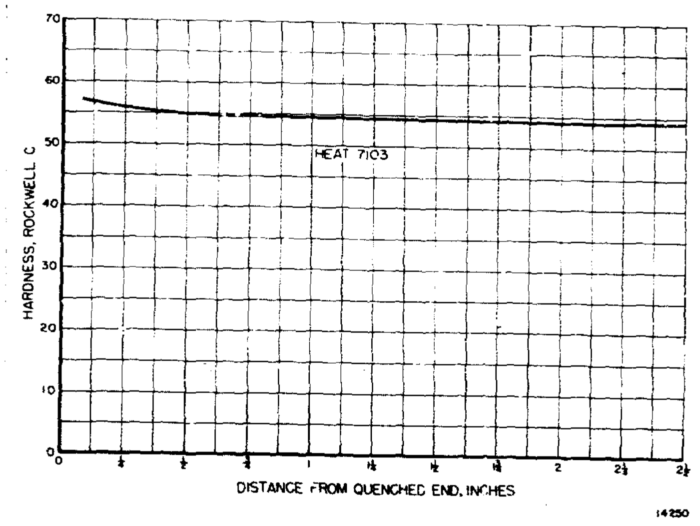


Figure 111. Heat No. 7103. Jominy end quench hardenability curve.

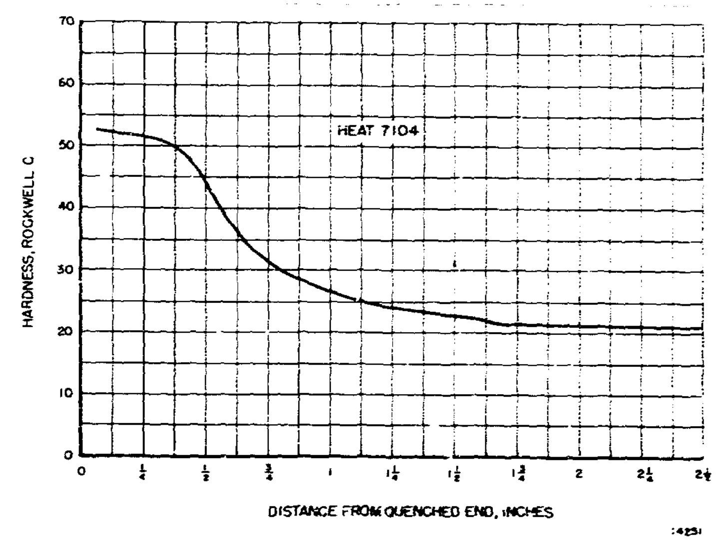


Figure 112. Heat No. 7104. Jominy end quench hardenability curve.

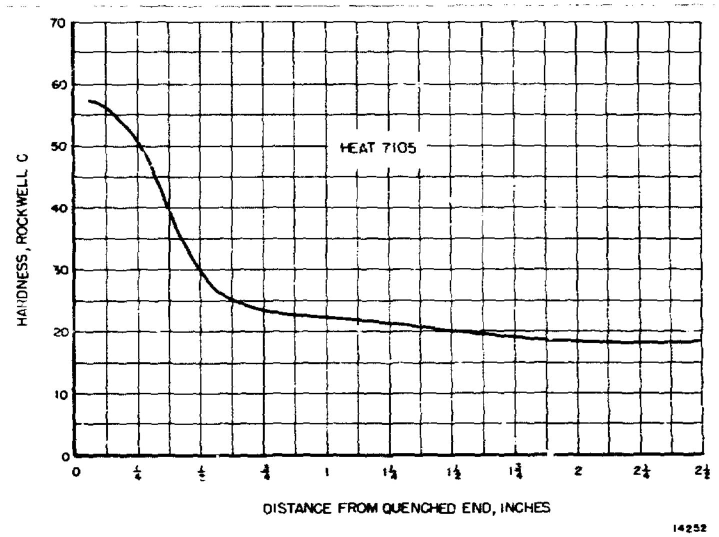


Figure 113. Heat No. 7105. Jominy end quench hardenability curve.

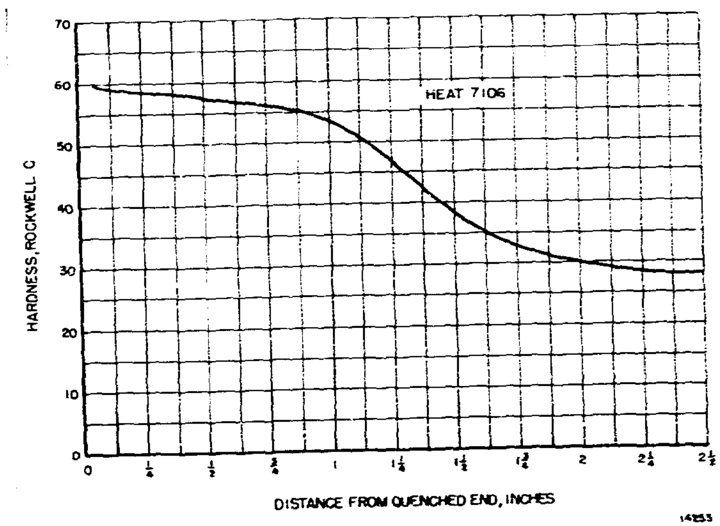


Figure 114. Heat No. 7106. Jominy end quench hardenability curve.

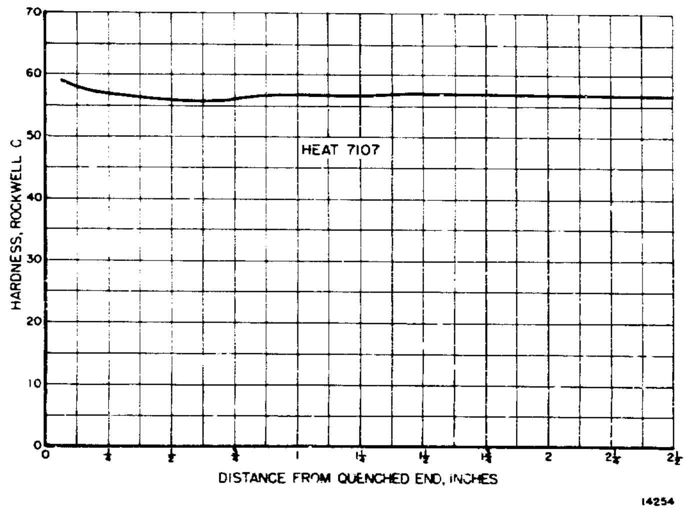


Figure 115. Heat No. 7107 Jominy end quench hardenability curve.

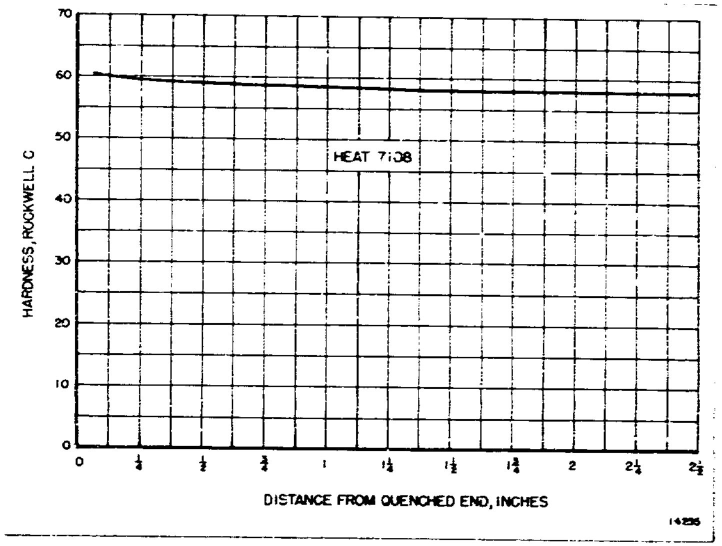


Figure 116. Heat No. 7108. Jominy end quench hardenability curve.

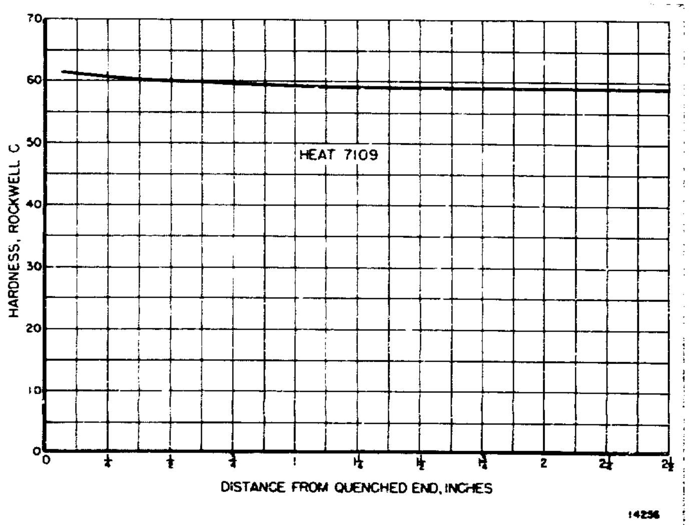


Figure 117. Heat No. 7109. Jominy end quench hardenability curve.

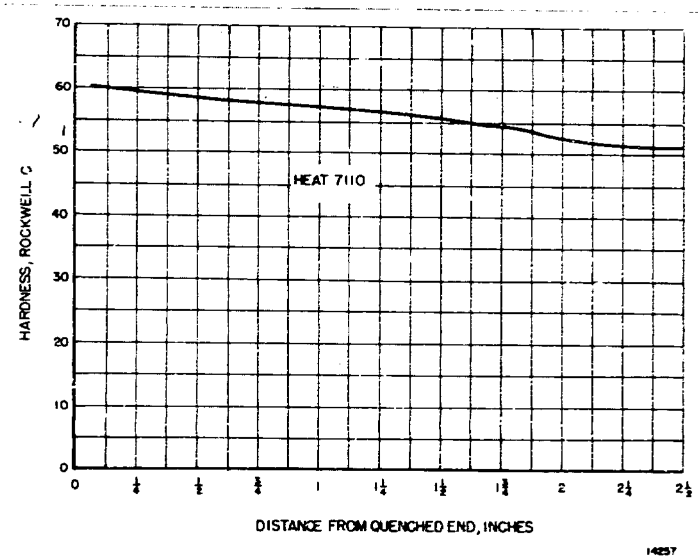


Figure 118. Heat No. 7110. Jominy end quench hardenability curve.

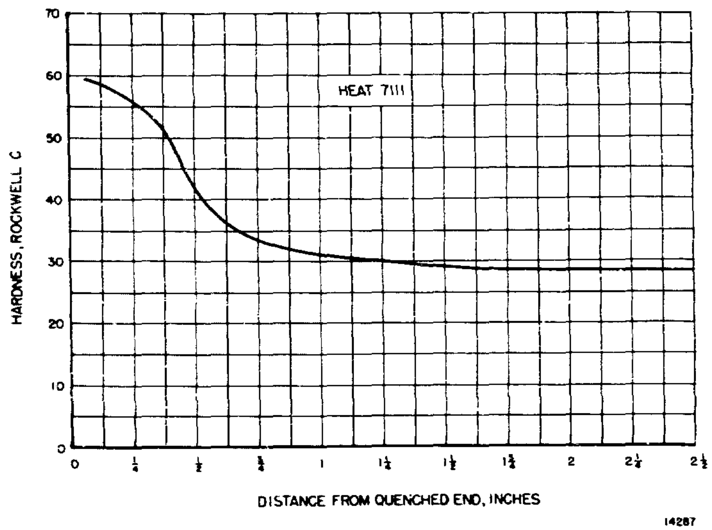


Figure 119. Heat No. 7111. Jominy end quench hardenability curve.

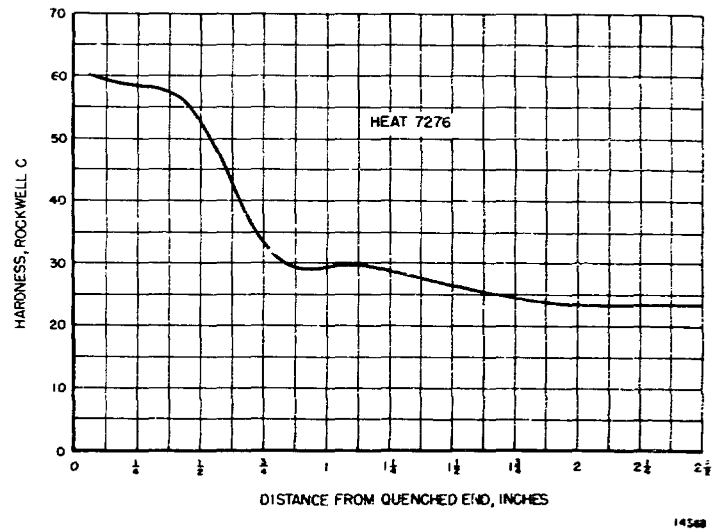


Figure 120. Heat No. 7276. Jominy end quench hardenability curve.

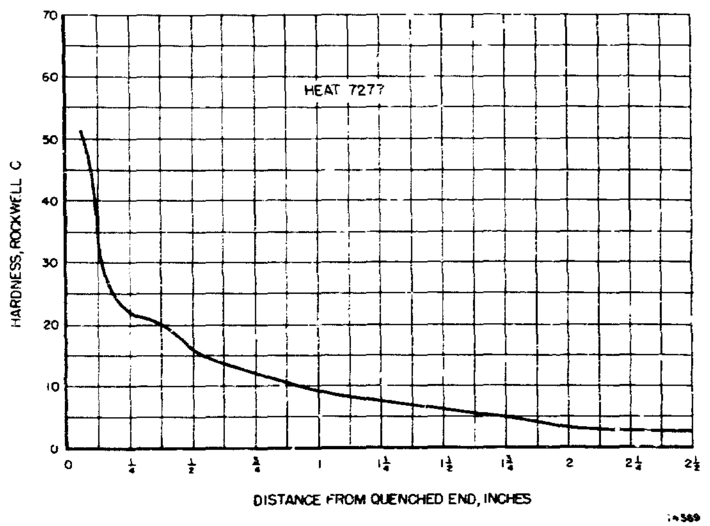


Figure 121. Heat No. 7277. Jominy end quench hardenability curve.

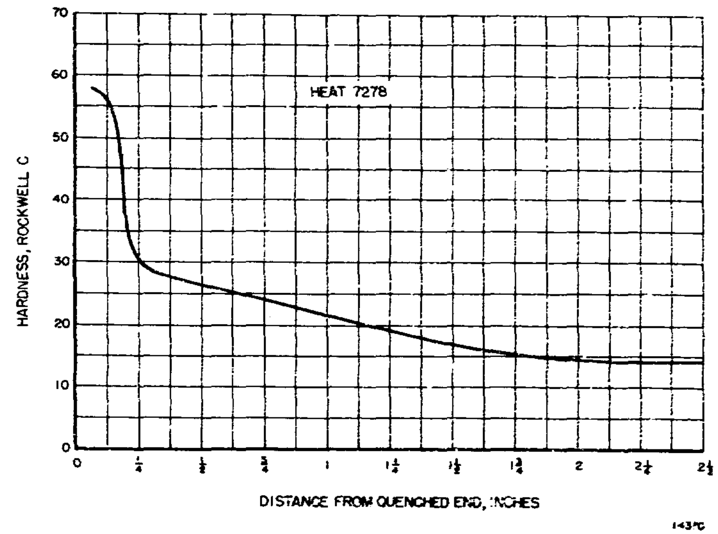


Figure 122. Heat No. 7278. Jominy end quench hardenability curve.

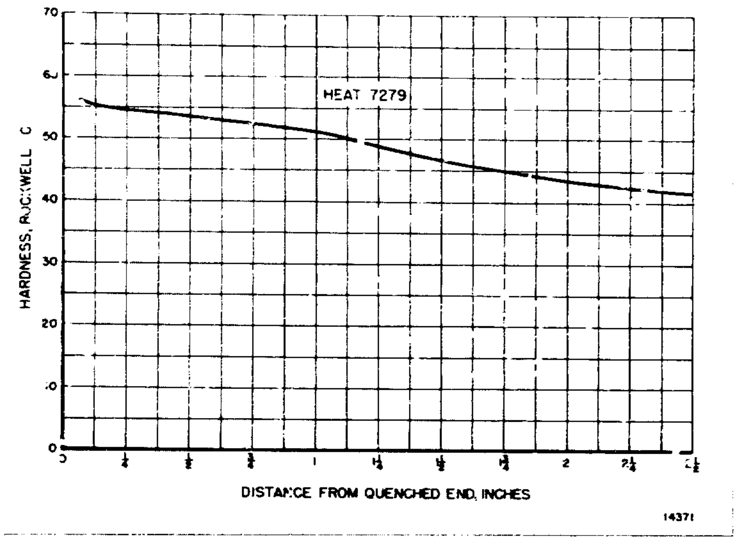


Figure 123. Heat No. 7279. Jominy end quench hardenability curve.

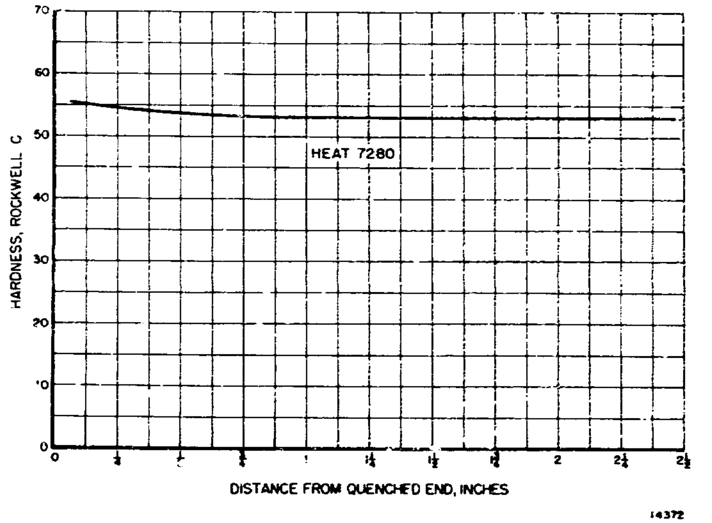


Figure 124. Heat No. 7280. Jominy end quench hardenability curve.

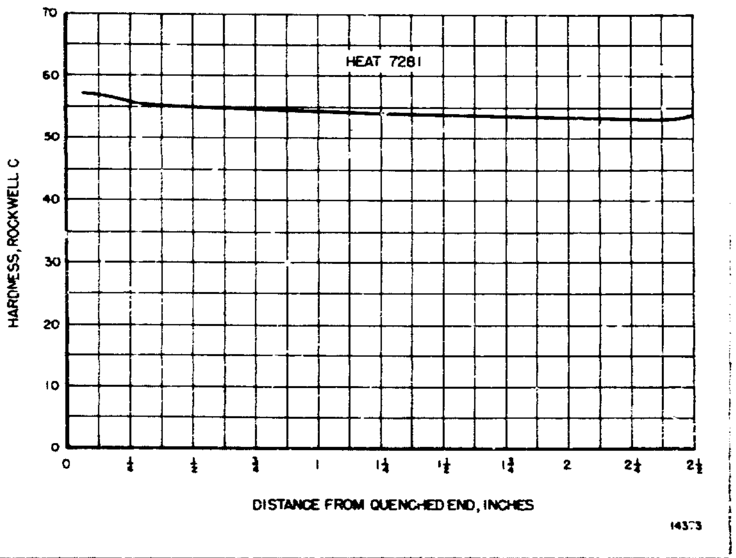


Figure 125. Heat No. 7281. Jominy end quench hardenability curve.

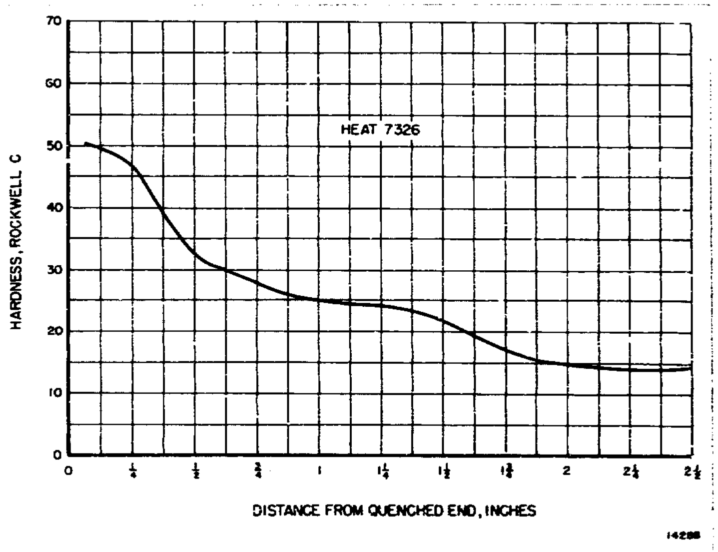


Figure 126. Heat No. 7326. Jominy end quench hardenability curve.

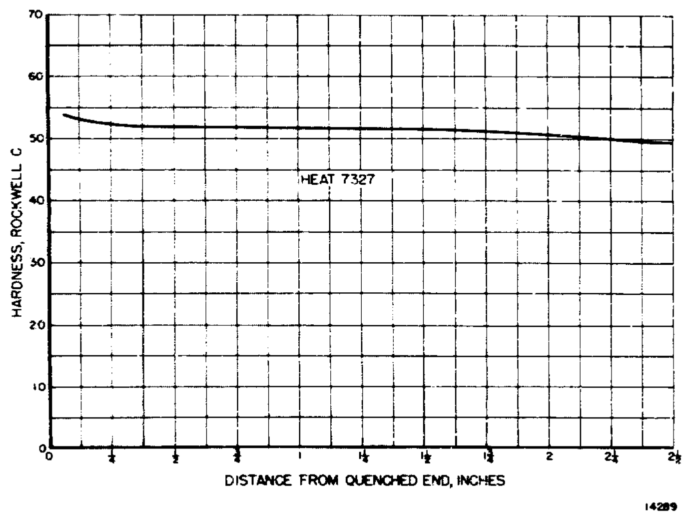


Figure 127. Heat No. 7327. Jominy end quench hardenability curve.

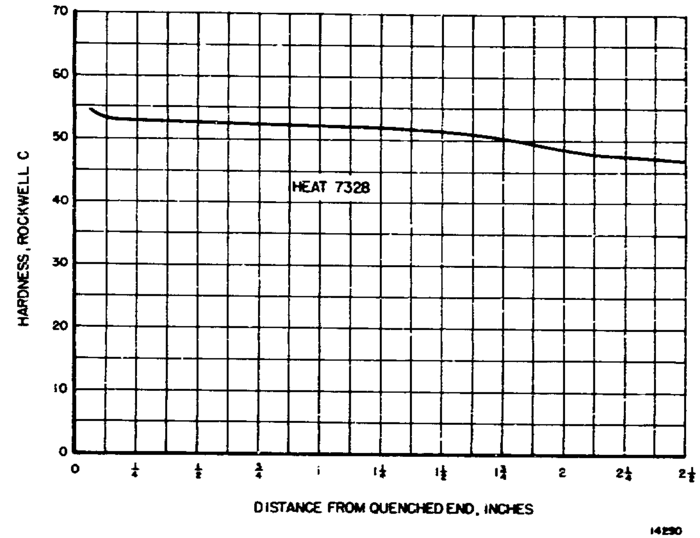


Figure 128. Heat No. 7328. Jominy end quench hardenability curve.

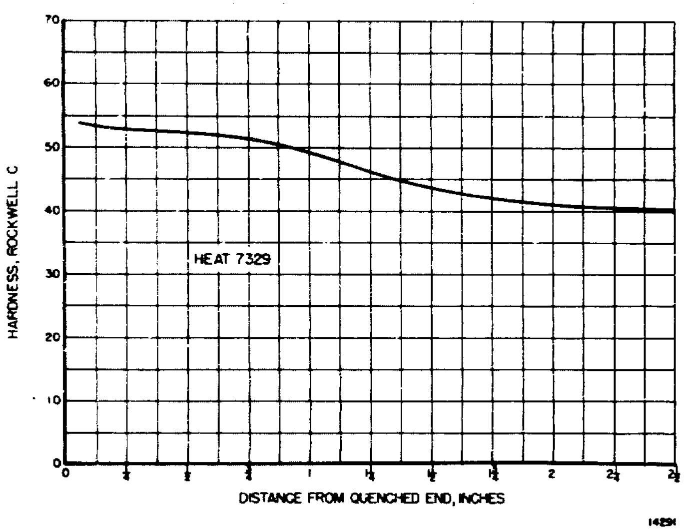


Figure 129. Heat No. 7329. Jominy end quench hardenability curve.

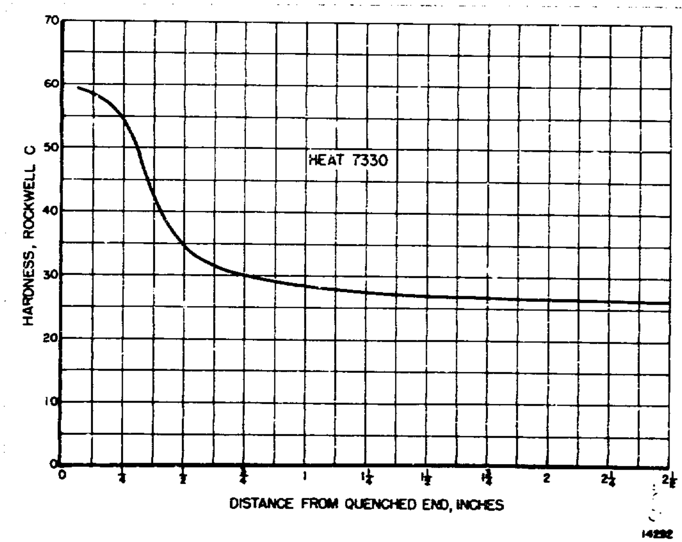


Figure 130. Heat No. 7330. Jominy end quench hardenability curve.

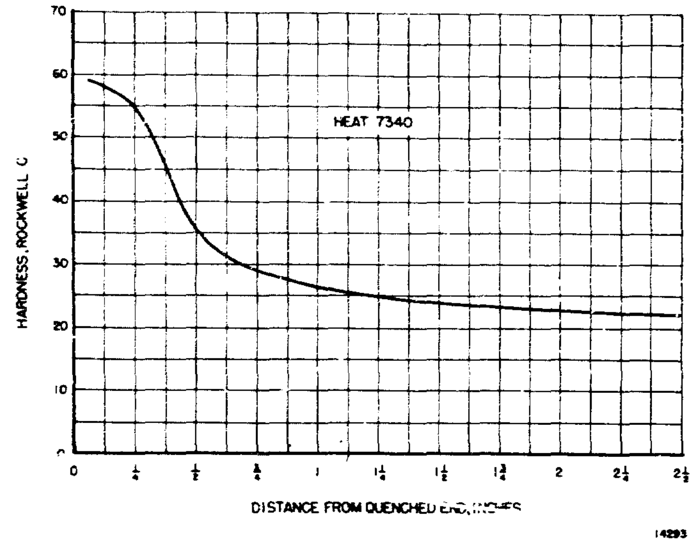


Figure 131. Heat No. 7340. Jominy end quench hardenability curve.

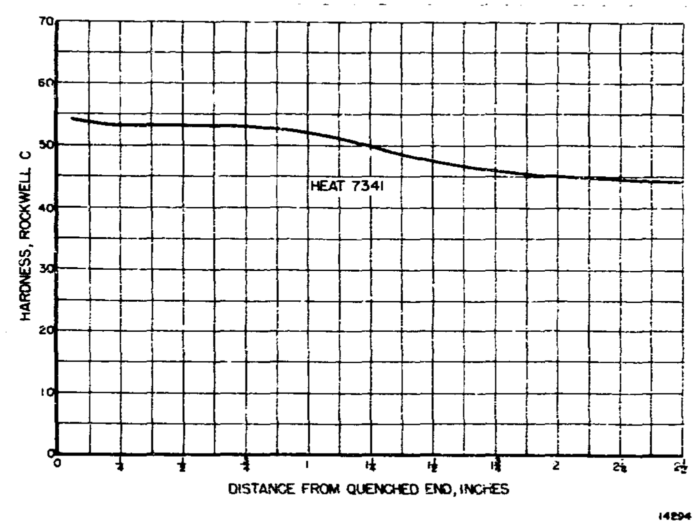


Figure 132. Heat No. 7341. Jominy end quench hardenability curve.

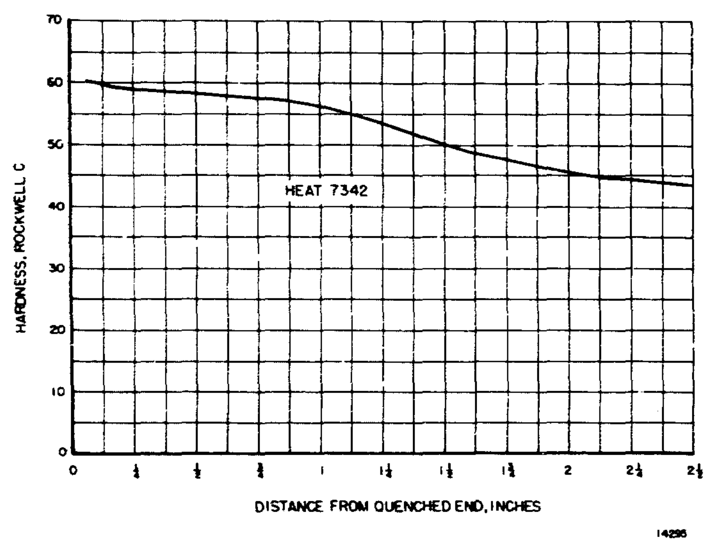


Figure 133. Heat No. 7342. Jominy end quench hardenability curve.

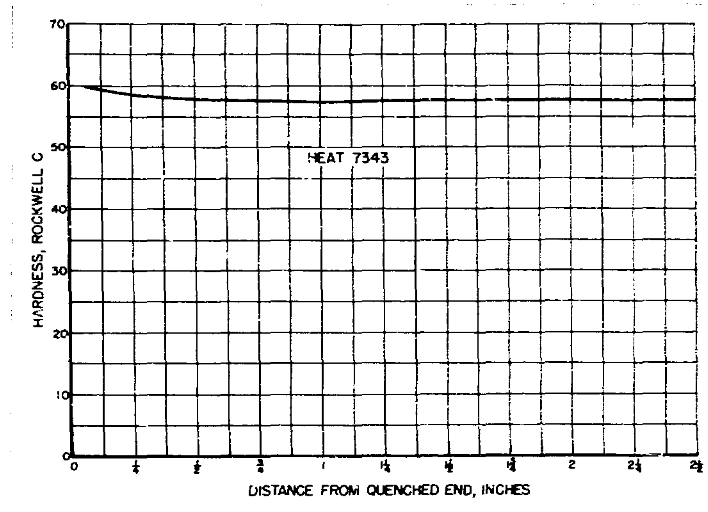


Figure 134. Heat No. 7343. Jominy end quench hardenability curve.

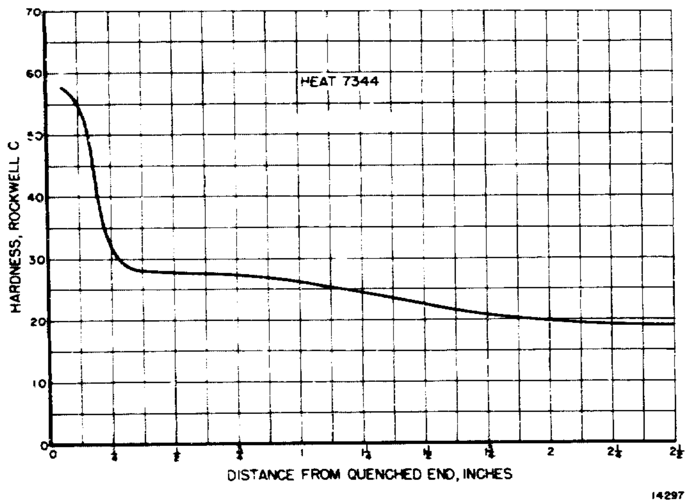


Figure 135. Heat No. 7344. Jominy end quench hardenability curve.

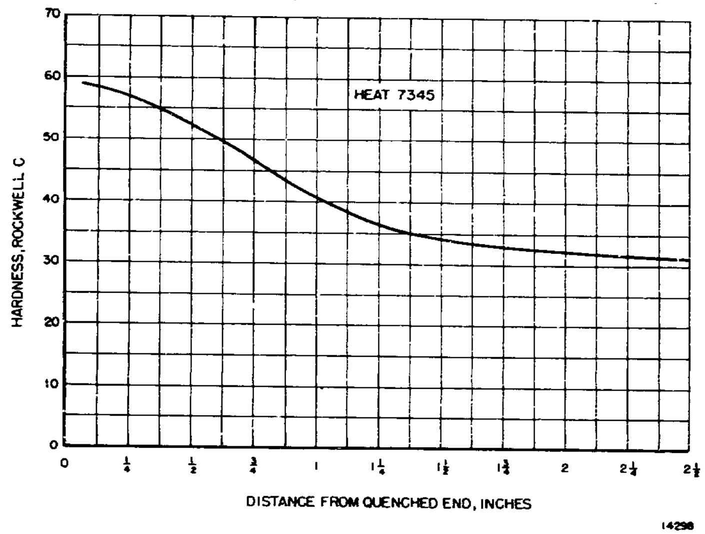


Figure 136. Heat No. 7345. Jominy end quench hardenability curve.

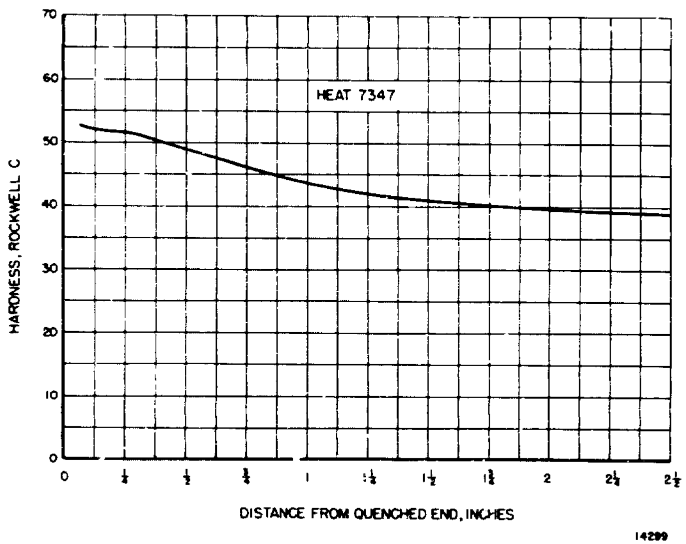


Figure 137. Heat No. 7347. Jominy end quench hardenability curve.

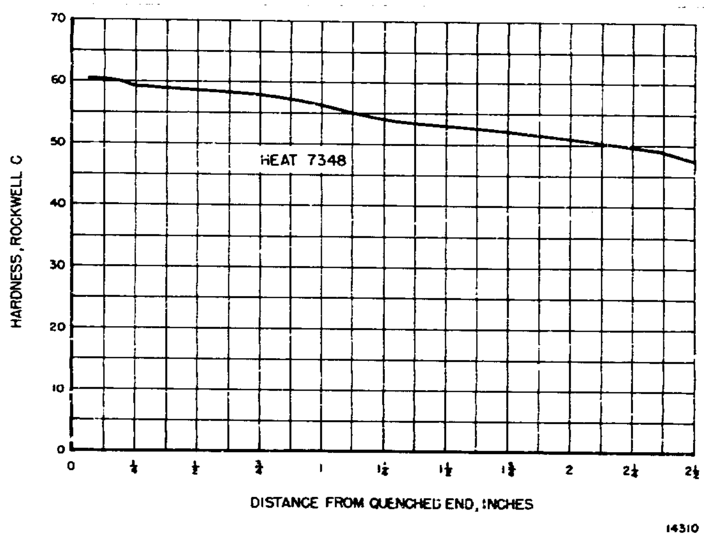


Figure 138. Heat No. 7348. Jominy end quench hardenability curve.

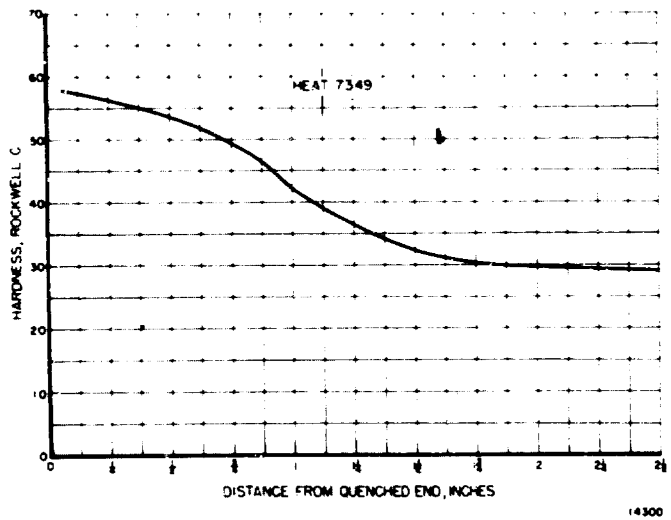


Figure 139. Heat No. 7349. Jominy end quench hardenability curve.

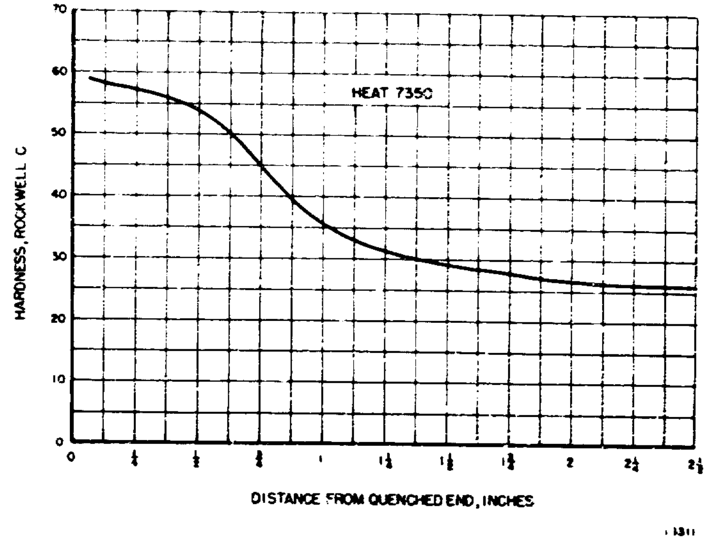


Figure 140. Heat No. 7350. Jominy end quench hardenability curve.

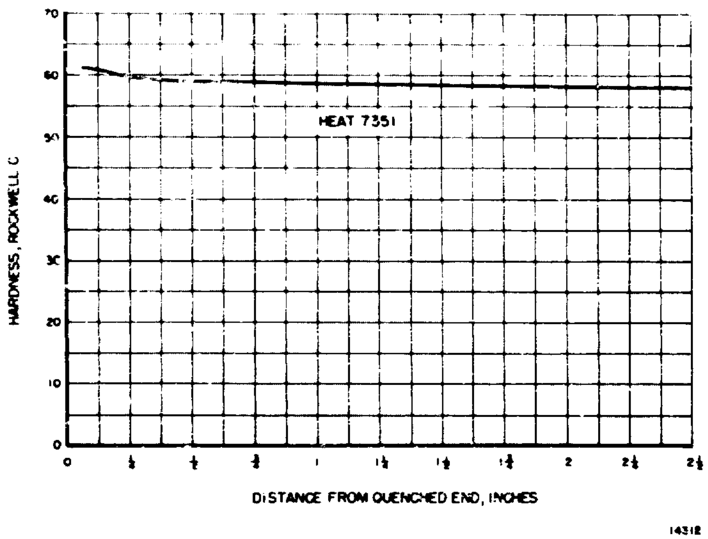


Figure 141. Heat No. 7351. Jominy end quench hardenability curve.

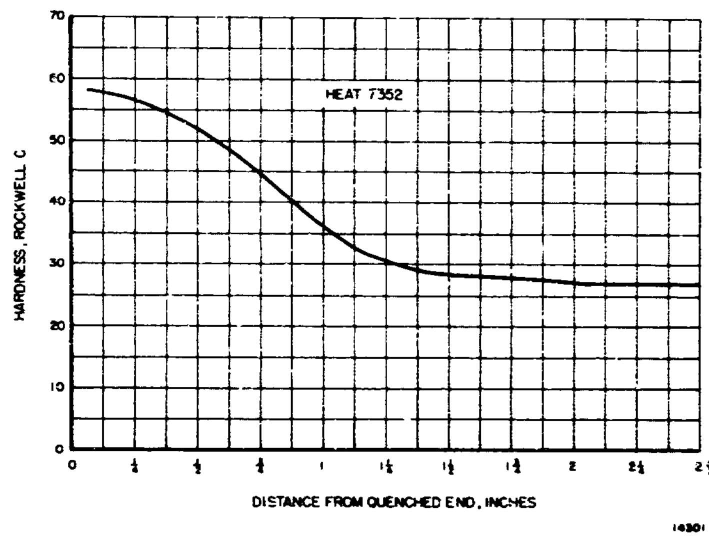


Figure 142. Heat No. 7352. Jominy end quench hardenability curve.

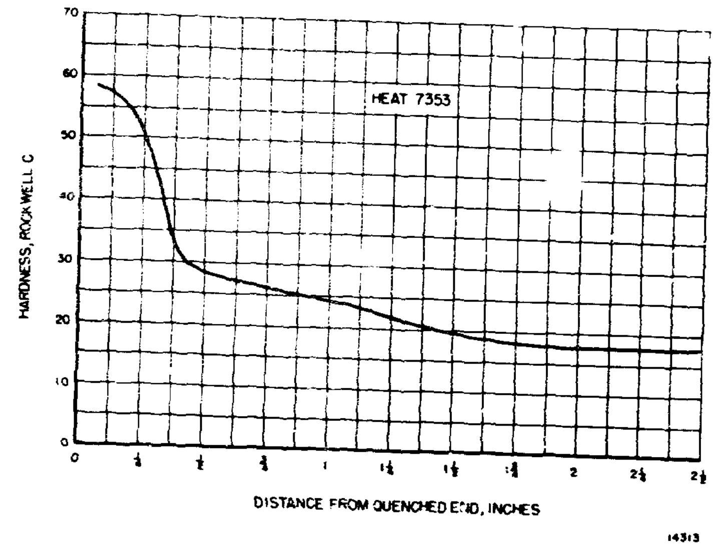


Figure 143. Heat No. 7353. Jominy end quench hardenability curve.

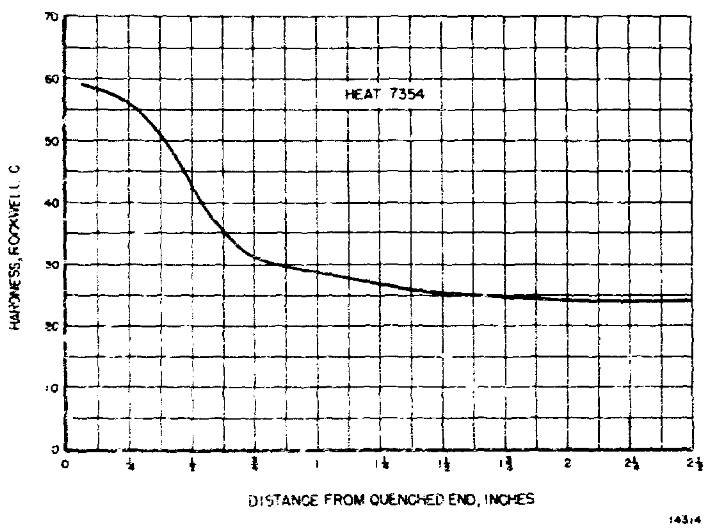


Figure 144. Heat No. 7354. Jominy end quench hardenability curve.

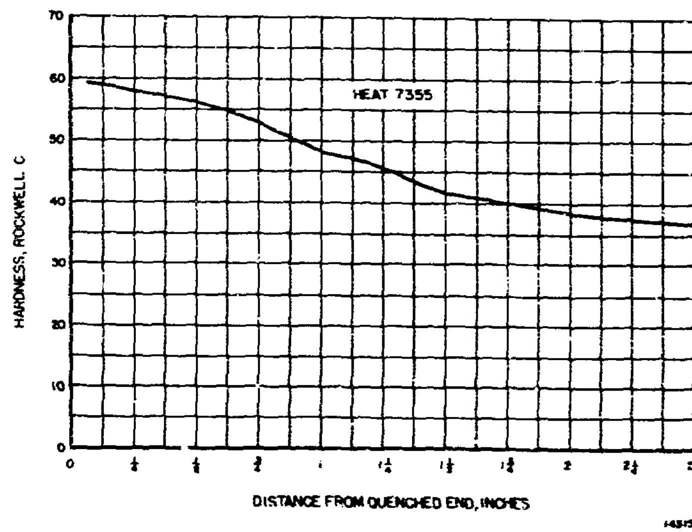


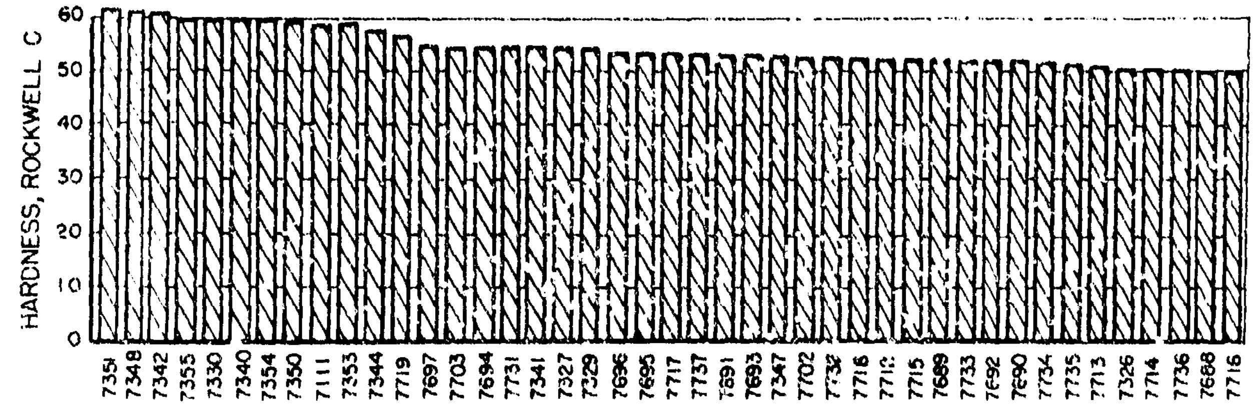
Figure 145. Heat No. 7355. Jominy end quench hardenability curve.

Compositions of Heats Appearing in Bar Graphs

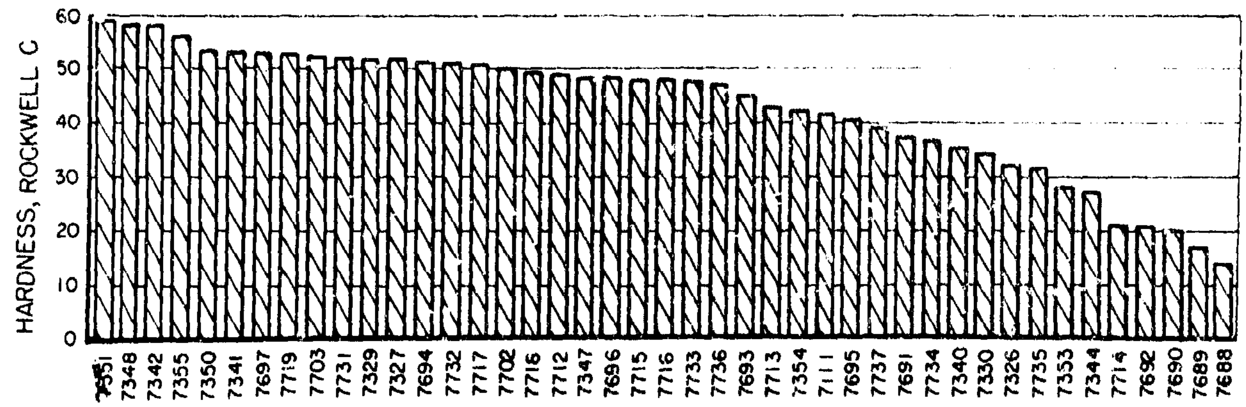
Heat Number	C	Mn	Si	Ni	Cr	Mo	V	Cu	Ti
7111	.46	1.58	.20				.10/.20		
7326	.30	.73	.20		.90/1.1				
7327	.35	.88	.26		2.3/2.7				
7329	.34	.88	.25		1.3/1.7		.10/.20		
7330	.46	.86	.24			.25/.35	.10/.20		
7340	.46	.84	.29			.25/.35			
7341	.34	.94	1.06		.90/1.1	.35/.45			
7342	.46	.77	.25		.90/1.1	.25/.35	.10/.20		
7344	.46	.75	.20				.20/.30		
7347	.34	.83	.26		.90/1.1			1.4/1.6	
7348	.47	1.48	.32			.40/.50		.30/.50	
7350	.46	.80	.23			.40/.50		1.0/1.5	
7351	.46	1.49	.29			.40/.50		1.0/1.5	
7353	.45	.84	.75						
7354	.45	.88	1.71						
7355	.46	.78	1.07			.40/.50			
7688	.33	.43	.24						
7689	.33	.81	.26						
7690	.32	1.24	.28						
7691	.31	1.73	.29						
7692	.31	.75	.26	2.01					
7693	.30	.70	.25	3.55					
7694	.31	.73	.27	5.13					
7695	.30	1.24	.24	2.01					
7696	.31	.81	.27	1.3/1.6	.83				
7697	.28	.79	.24	3.6/3.9	2.61				
7702	.31	.82	.26	1.3/1.6	.70/90	.25			
7703	.34	1.56	.46	3.3/3.7	.90/1.1	.34			
7712	.28	1.49	.26	1.3/1.6	.75/.90	.30			
7713	.32	.90	.25	1.3/1.6			.18		
7714	.31	1.46	.24						.16
7715	.32	1.42	.24						Grainal
7716	.31	1.44	.63		1.08		.18		
7717	.32	1.46	.69		1.07				Grainal
7718	.33	1.53	.27		.90/1.1	.40			
7719	.32	1.52	.27		•	.39			
7731	.34	.81	.30		1.53	.40			
7732	.31	.73	.21		1.32	.60/.80	.27		
7733	.31	1.51	.26					1.49	
7734	.35	1.52	.27			.40/.50		.45	
7735	.32	.84	.26					.42	
7736	.33	.88	.63	.50	.50	.30			
7737	.31	.77	.22	.50	.49	.30			

A COMPARISON OF THE HARDENABILITY OF 43 HEATS

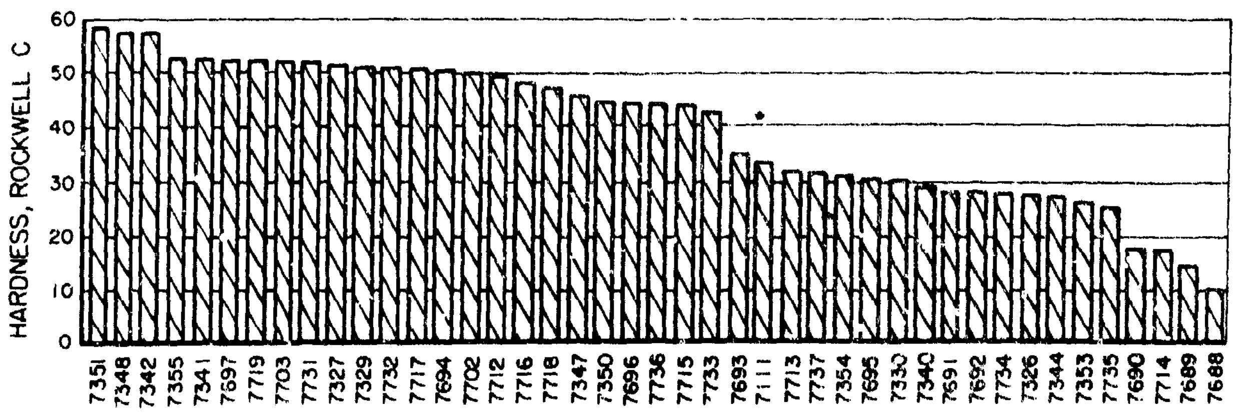
FIG. 146



HARDNESS AT 1/16" FROM THE QUENCHED END



HARDNESS AT 1/2" FROM THE QUENCHED END



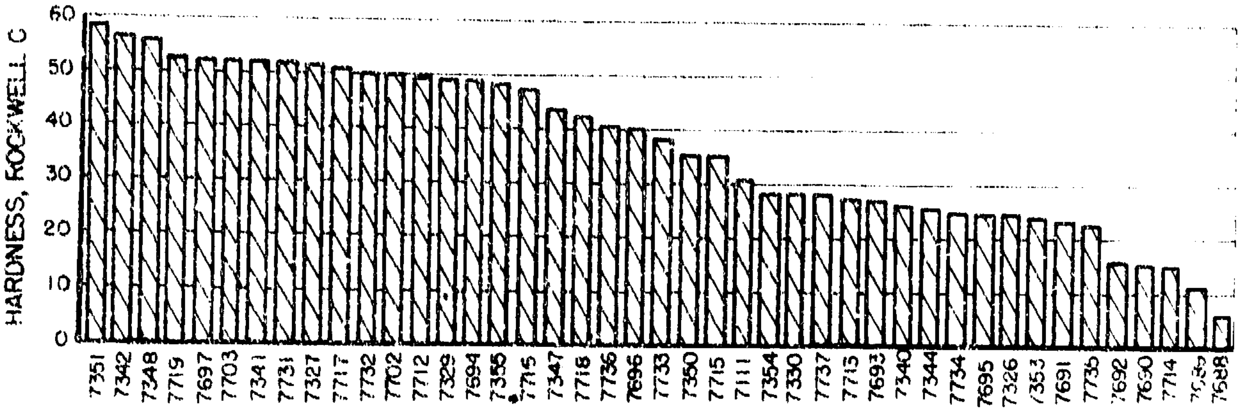
HARDNESS AT 3/4" FROM THE QUENCHED END

-CONTINUED-

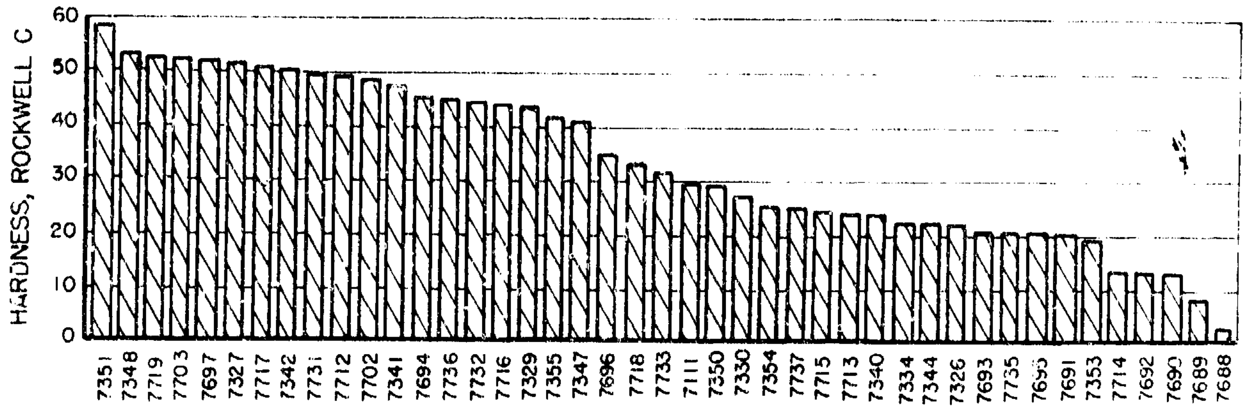
14403

A COMPARISON OF THE HARDENABILITY OF 43 HEATS

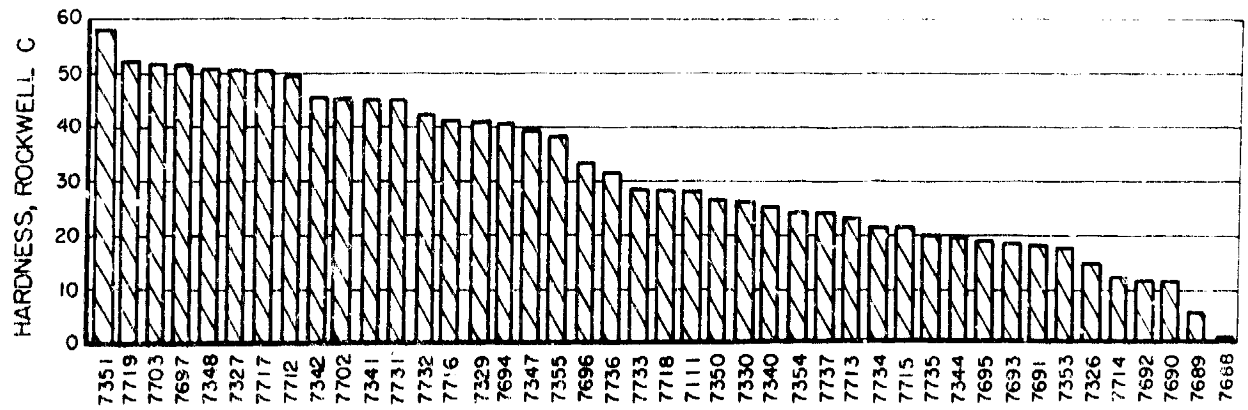
FIG. 146-CONTINUED



HARDNESS AT 1" FROM THE QUENCHED END



HARDNESS AT 1½" FROM THE QUENCHED END



HARDNESS AT 2" FROM THE QUENCHED END

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