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PROGRESS REPORT

February 6, 1942

to

WATERTOWN ARSENAL,
UNITED STATES ARMY

Research Investigation of Armor Plate Steels

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BATTELLE MEMORIAL INSTITUTE
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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

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FOREWORD

The program for the investigation of armor plate steels was revised somewhat at a conference in Watertown on December 9, 1941. The major changes suggested were as follows:

1. Increasing the ingot size to 55-lbs. so as to permit rolling three test plates from each heat.
2. Heat treating one plate from every composition to each of three different hardness levels including, (a) 310-330, (b) 350-370, and (c) 400-420 Brinell.
3. Decreasing the carbon content in all heats made subsequently to the 0.30-0.35% range.
4. Including two additional compositions simulating steels containing small percentages of "tramp" alloys, chromium, nickel, and molybdenum, which are normally present as carry-over constituents from steel scrap.

5. Determining hardenability characteristics of all steels made at Battelle.

Steps 1 and 2 originated from the thought that ballistic properties, determined on the same steel at three different hardness levels, would be of much more value than a single determination at one level in evaluating the characteristics of the steels. Cross-section hardness surveys from a location in the plates near the point at which the ballistic limits were determined will permit plotting actual hardness against ballistic limits. A curve drawn through the three points should facilitate comparisons of the steels since, within the limit of accuracy of the ballistic test, it will show what limits two plates would have if they were both tested at exactly the same hardness level.

The decision to lower the carbon content arose from a consideration of the increasing utilization of welded construction and the fact that higher carbon steels are somewhat difficult to handle.

Compositions based on the use of small percentages of alloys carried over from steel scrap were included because such elements are available without cost. The beneficial effect of residual elements such as chromium, nickel, and molybdenum, are to be augmented by the intentional addition of small amounts of the alloys so as to bring them up to a predetermined level.

The step involving hardenability tests does not really represent a change because these tests were intended in the beginning for some stage of the program. Hardenability characteristics of the various steels are an important subject in view of the fact that the substitution of less strategic alloys, or decreasing the amount of alloying elements in light armor plate, was the primary objective of the investigation. Some consideration should therefore be given to the nature of the test and the relation of the results to the major problem of selecting the best steels from the group.

There is some confusion in the minds of metallurgists as to whether the term "hardenability" includes both the ability of a given steel to reach a certain maximum hardness and the depth to which it will harden under stated conditions. In the armor plate problem it will be best to consider hardenability as having nothing to do with the intensity of hardening and relate the term to the extent or depth to which the steel hardens, the approximate maximum which may be expected for the carbon content. Cross-section hardness surveys of two armor plate specimens may serve to clarify this point.

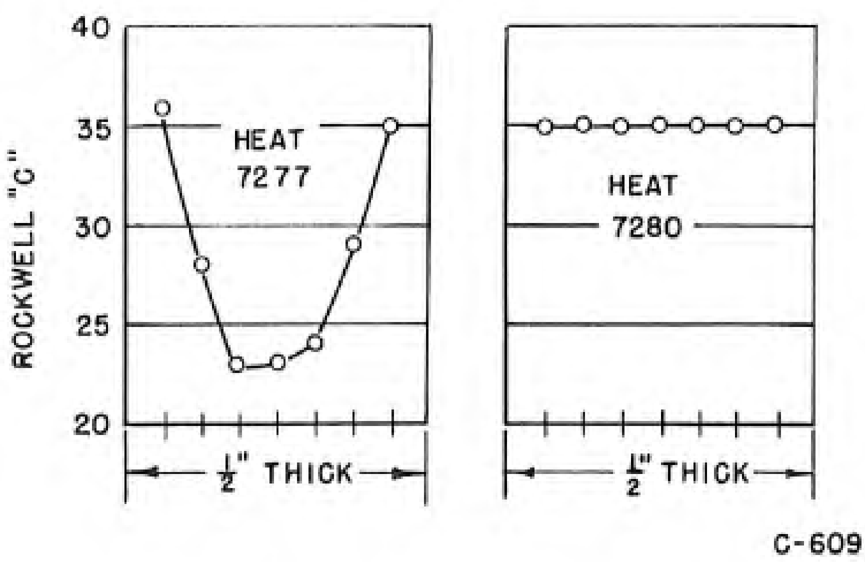

Fig. 1. Cross-section hardness surveys on two plates which had previously been tested for ballistic properties. The analyses of the two steels are as follows:

	C	Mn	Si	Ni	Cr	Mo
Heat No. 7277	.39	.35	.23	---	---	---
Heat No. 7280	.35	.92	.28	1.3/1.6	.70/.90	.20/.30

The illustrations shown above for two steels after quenching and drawing to the 310-330 Brinell level are examples of a marked difference in hardenability. The plate from Heat No. 7277 runs as high as 36 Rockwell C or 332 equivalent Brinell on the surface but the center hardness is only 23 Rockwell C or 245 equivalent Brinell. The plate from Heat No. 7280 has no higher surface hardness but that at the center is the same as the surface. Heat No. 7277 is shallow hardening or has low hardenability while Heat No. 7280 is, on a comparative basis, deep hardening or possesses high hardenability.

Extremely shallow hardening steels such as Heat No. 7277 would never constitute good armor plate material. It cannot be said, conversely, that all deep hardening steels would be good because other considerations including resistance to penetration and ductility, or freedom from spalling at high hardness have to be included. Hardenability sufficient for full hardening to the depth of the particular plate thickness being made, however, is a necessary requirement.

The Jominy end quench hardenability test is being used to rate the steels as regards depth of hardening. The procedure in making the test is described in detail in another section of this report. Briefly, a round specimen is drastically quenched, at one end only, from a temperature approximately 75° F. above the upper critical point. This produces all possible rates of cooling from an exceedingly rapid one at the quenched end to one almost as slow as air cooling at the other end. A hardness traverse from end to end is then made and the values are plotted against the distance from the quenched end.

The present progress report concerns only the making, heat treating, and hardenability testing of 27 heats which were produced since the meeting in Watertown.

SUMMARY

The method of making the series of 27 steels was similar to that described in previous reports. Larger ingots were cast, however, so as to permit rolling three test plates from each heat. The analyses of the steels produced are given in Table 1.

Coupons from the fish-tail ends of all heats were put through preliminary quenching treatments because the lowering of the carbon made data from the corresponding compositions, which were produced previously, rather unreliable for selecting heat treatments for the present low-carbon steels. After quenching the plates and drawing at 400° F., a 2" x 1" section was cut from two opposite corners for hardness determinations. These sections were replaced on the corresponding ends of the plates in the drawing furnace and used as test specimens in following the hardness drop at successively higher draws. When both ends were within the specified range, the remainder of the 1-in. sections was cut from the ends for an additional hardness check.

Final drawing temperatures and the hardness values reached are shown in Table 2. The two columns under the hardness headings represent the average Brinell of opposite ends of the plates.

Jominy hardenability tests were made on all the steels using a 1/2" diameter specimen. Curves showing hardness plotted against distance from the quenched end are given as Figures 5 - 31 inclusive. In an effort to bring the necessarily large amount of data together for purpose of comparison, the steels have been ranked as to hardness at given distances from the quenched end in Table 3.

This set of 81 plates is now at Watertown Arsenal for ballistic testing.

A selection of promising steels and the discarding of others is certainly not in order until both ballistic and hardenability test results are on hand from all of the 43 compositions being investigated. It is of interest, however, to note the relation between composition and hardenability of this particular group of 27 steels.

Figures 5 to 8 inclusive show that manganese alone does not increase hardenability appreciably until 1.73% is present. In general, the straight manganese series of steels is very shallow hardening.

Figures 9 to 11 inclusive show that 2.01% Ni has very little effect, 2.55% begins to make itself felt, and 5.15% imparts rather deep hardening properties.

Figures 12 and 13 emphasize the fact that nickel is most effective when used along with some chromium.

Figures 14 to 17 inclusive illustrate the deep hardening characteristics of the highly alloyed nickel-chromium-molybdenum steels. These are some of the compositions for which substitutes would be welcomed.

Figures 19 and 20 show a rather marked beneficial effect of the Grainal treatment.

Figures 21, 22, and 24 indicate that high hardenability can be obtained without nickel.

Figure 24 shows that Heat No. 7719 is the standout of the whole group so far as hardenability is concerned. This steel contains only 1.52% Mn and 0.39% Mo as alloying elements, yet Table 3 shows it to be the only heat which holds a No. 1 rank as to hardness throughout the traverse.

Figures 30 and 31 indicate that the "tramp" alloy heats are quite promising, especially No. 7736 which contains the higher percentage of silicon.

EXPERIMENTAL WORK

Melting Practice.

The group of 27 armor plate steels, which are described in this report, were made in a 60 lb. induction furnace using charges consisting of bar melting stock received from Watertown, Armco punchings, and ferro alloys as required. All heats were treated with .10 per cent aluminum except numbers 7714, 7715, and 7717 which were treated with Grainal or silicon-titanium. The heats were tapped in the temperature range of 2950 to 3000 degrees Fahrenheit, and poured directly from the melting unit into 55-lb. ingot molds of the fluted type. The ingot molds were equipped with core sand hot tops. The ingots were allowed to freeze in the molds, after which they were knocked out and allowed to cool in air. Chemical determinations for C, Mn, and Si were made on test coupons poured from each heat at the time of casting.

The intended compositions and some actual analyses of the heats are given in Table 1.

Forging and Rolling.

The forging and rolling procedure used in the processing of the 27 heats of armor plate steel was as follows. Hot tops were removed from all ingots by the use of either a power hacksaw or an abrasive cut-off wheel. The ingots were then heated to forging temperature, approximately 2200° Fahrenheit, in a gas fired heating unit and allowed to soak thoroughly before forging. The ingots were worked under the hammer to partially break up the cast structure and were then reheated and upset to 7 inches in length. This upsetting procedure was followed so as to permit subsequent cross rolling of the ingot. Two to three heatings were required to complete the operation. Longitudinal seams appearing in the surface of some of the

TABLE 1. INTENDED AND ACTUAL COMPOSITIONS OF TWENTY SEVEN ARMOR PLATE STEELS

Heat Number	Intended Composition %C	%Mn	%Si	%Ni	%Cr	%Mo	%V	%Cu	%Ti	Actual Composition %C	%Mn	%Si	%Ni	%Cr	%Mo	%V	%Cu	%Ti
7688	.30/.35	.30/.40	.20/.30							.33	.43	.24						
7689	.30/.35	.60/.90	.20/.30							.33	.81	.26						
7690	.30/.35	1.0/1.3	.20/.30							.32	1.24	.28						
7691	.30/.35	1.5/1.8	.20/.30							.31	1.73	.29						
7692	.30/.35	.50/.80	.20/.30	1.8/2.0						.31	.75	.26	2.01					
7693	.30/.35	.50/.80	.20/.30	3.3/3.7						.30	.70	.25	3.55					
7694	.30/.35	.50/.80	.20/.30	4.8/5.2						.31	.73	.27	5.13					
7695	.30/.35	1.0/1.3	.20/.30	1.8/2.0						.30	1.24	.24	2.01					
7696	.30/.35	.60/.90	.20/.30	1.3/1.6	.70/.80					.31	.81	.27		.83				
7697	.30/.35	.60/.90	.20/.30	3.6/3.9	2.4/2.6					.28	.79	.24		2.61				
7702	.30/.35	.60/.90	.20/.30	1.3/1.6	.70/.90	.20/.30				.31	.82	.26			.25			
7703	.30/.35	.60/.90	.20/.30	3.3/3.7	.90/1.1	.35/.45				.34	1.56	.46			.34			
7712	.30/.35	1.4/1.6	.20/.30	1.3/1.6	.75/.90	.25/.35				.28	1.49	.26			.30			
7713	.30/.35	.60/.90	.20/.30	1.3/1.6			.10/.15			.32	.90	.25				.18		
7714	.30/.35	1.4/1.6	.20/.30						.10/.20	.31	1.46	.24						.16
7715	.30/.35	1.4/1.6	.20/.30						Grainal	.32	1.42	.24						
7716	.30/.35	1.4/1.6	.60/.80		.90/1.1		.10/.20			.31	1.44	.63		1.08		.18		
7717	.30/.35	1.4/1.6	.60/.80		.90/1.1				Grainal	.32	1.46	.69		1.07				
7718	.30/.35	1.4/1.6	.35/.60		.90/1.1	.25/.35				.33	1.53	.27			.40			
7719	.30/.35	1.4/1.6	.20/.30			.35/.45				.32	1.52	.27			.39			
7731	.30/.35	.60/.90	.20/.30		1.3/1.7	.35/.45				.34	.81	.30		1.53	.40			
7732	.30/.35	.60/.90	.20/.30		1.1/1.3	.60/.80	.20/.30			.31	.73	.21		1.32		.27		
7733	.30/.35	1.4/1.6	.20/.30					1.4/1.6		.31	1.51	.26					1.49	
7734	.30/.35	.60/.90	.20/.30			.40/.50		.30/.50		.35	1.52	.27					.45	
7735	.30/.35	.90/1.2	.90/1.2					1.3/1.6		.32	.84	.26					.42	
7736	.30/.35	.90	.60	.50	.50	.30				.33	.88	.63		.50				
7737	.30/.35	.90	.30	.50	.50	.30				.31	.77	.22		.49				

Heat No. 7735 is off specification in Mn, Si, and Cu. Heat No. 7703 is off specification in Si
Heat No. 7734 is off specification in Mn.

plates are due to folds being formed during upsetting. After upsetting was completed, the ingots were worked down to slabs approximately 7 inches wide and 1-1/2 inches thick. The forged slabs were then shot blasted and chipped to remove surface defects.

The slabs were rolled to 1/2 inch by 7 inch plates, approximately 46 inches in length. The temperature range used for rolling was 1750 to 1800° Fahrenheit, and twelve passes of .084 inch were required to reduce the plates to finish size. The plates were shot blasted and inspected for surface defects before being given the final four passes in the mill.

After rolling, the plates were cut into three pieces 14 inches in length, with the ends being used for hardenability test specimens, preliminary quenching tests, and for drillings for final analysis.

Heat Treatment of Plates.

The lowering of the carbon content to the .30-.35% range was known to raise the critical points somewhat, hence, the quenching temperatures worked out previously from the dilatometer curves for higher-carbon steels of otherwise like analysis were too low. Coupons from the fish-tail ends of the plates were used in preliminary tests to determine the minimum quenching temperature from which approximately full hardness could be obtained.

Maximum hardness obtainable on 3/8" rounds for a .32% carbon steel was shown to be about 57 Rockwell C or 578 equivalent Brinell by Burns, Moore and Archer (Quantitative Hardenability, Trans. Amer. Soc. for Metals, Vol. XXVI, 1938, p. 14). In view of the mass effect of the large plates, a hardness of about 500 Brinell was thought to be reasonable. Quenching temperatures employed are listed in Table 2. All the steels were quenched

TABLE 2. RESPONSE OF ARMOR PLATE STEELS TO HEAT TREATMENT AND THE FINAL HARDNESS OF THE PLATES.

		GROUP 410 PLATES			GROUP 360 PLATES			GROUP 310 PLATES		
Heat Number	Quenching Temp., °F.	Hardness after quench and 400°F. draw.	Final drawing treatment.	Final Brinell hardness.	Hardness after quench and 400°F. draw.	Final drawing treatment.	Final Brinell hardness.	Hardness after quench and 400°F. draw.	Final drawing treatment.	Final Brinell hardness.
7688*	1700	470 - 415	550°F,1 hr.	416 - 417	415 - 445	650°F,1 hr.	362 - 361	415 - 435	850°F,1 hr.	300 - 285
7689	1700	477 - 477	625°F,½ hr.	415 - 415	470 - 477	750°F,1 hr.	366 - 360	469 - 467	825°F,1 hr.	326 - 315
7690	1650	493 - 490	650°F,1 hr.	415 - 415	481 - 477	800°F,½ hr.	359 - 363	485 - 488	850°F,1 hr.	323 - 323
7691	1600	514 - 507	700°F,½ hr.	415 - 415	507 - 495	800°F,1 hr.	363 - 363	504 - 493	875°F,1 hr.	326 - 321
7692	1650	502 - 502	650°F,½ hr.	406 - 406	485 - 481	750°F,1 hr.	363 - 360	488 - 485	850°F,½ hr.	329 - 323
7693	1500	493 - 490	650°F,1 hr.	401 - 409	485 - 487	750°F,1 hr.	363 - 368	479 - 486	850°F,½ hr.	326 - 331
7694	1500	482 - 482	650°F,1 hr.	415 - 415	481 - 477	750°F,1 hr.	363 - 370	483 - 488	875°F,1 hr.	317 - 317
7695	1550	506 - 497	700°F,¼ hr.	415 - 415	485 - 485	800°F,¼ hr.	363 - 368	492 - 485	875°F,1 hr.	321 - 317
7696	1550	514 - 508	725°F,½ hr.	412 - 415	512 - 499	900°F,½ hr.	352 - 361	488 - 491	950°F,1 hr.	321 - 315
7697	1600	485 - 495	800°F,½ hr.	415 - 420	481 - 488	1000°F,1 hr.	354 - 359	485 - 481	1100°F,1 hr.	325 - 319
7702	1650	510 - 514	750°F,1 hr.	409 - 412	495 - 505	950°F,1 hr.	359 - 356	495 - 495	1050°F,½ hr.	323 - 323
7703	1550	526 - 524	850°F,½ hr.	412 - 415	516 - 497	1050°F,¼ hr.	359 - 354	514 - 507	1100°F,1 hr.	326 - 323
7712	1600	477 - 495	750°F,½ hr.	420 - 415	481 - 485	900°F,1 hr.	363 - 366	481 - 485	1075°F,1 hr.	311 - 311
7713	1600	495 - 490	650°F,1 hr.	412 - 415	479 - 485	800°F,1 hr.	368 - 366	477 - 481	950°F,¼ hr.	326 - 323
7714	1550	495 - 495	650°F,1 hr.	415 - 415	499 - 495	800°F,1 hr.	352 - 356	508 - 490	875°F,1 hr.	315 - 323
7715	1600	490 - 490	650°F,1 hr.	415 - 412	481 - 478	800°F,1 hr.	370 - 368	488 - 492	900°F,½ hr.	321 - 323
7716	1650	488 - 505	825°F,½ hr.	409 - 409	495 - 499	950°F,1 hr.	363 - 366	504 - 510	1200°F,1 hr.	315 - 324
7717	1650	510 - 514	825°F,½ hr.	409 - 406	503 - 510	950°F,1 hr.	363 - 363	514 - 512	1100°F,1 hr.	326 - 323
7718	1600	495 - 514	750°F,1 hr.	415 - 401	514 - 517	900°F,1 hr.	356 - 356	514 - 517	1075°F,1 hr.	323 - 313
7719	1600	500 - 517	750°F,1 hr.	415 - 420	506 - 514	1075°F,½ hr.	366 - 363	514 - 514	1150°F,1 hr.	318 - 313
7731	1600	516 - 520	850°F,1 hr.	409 - 415	526 - 534	1000°F,½ hr.	368 - 370	532 - 530	1100°F,2 hr.	315 - 321
7732	1650	510 - 514	850°F,1 hr.	420 - 415	514 - 511	1225°F,1 hr.	363 - 373	522 - 507	1250°F,3 hr.	315 - 319
7733	1600	507 - 508	750°F,1 hr.	415 - 406	494 - 504	850°F,1 hr.	363 - 366	495 - 507	975°F,½ hr.	325 - 321
7734	1600	512 - 509	800°F,½ hr.	401 - 401	492 - 495	850°F,1 hr.	360 - 360	495 - 495	1100°F,1 hr.	326 - 321
7735	1600	498 - 490	800°F,½ hr.	406 - 406	490 - 485	850°F,½ hr.	363 - 363	507 - 503	1000°F,½ hr.	325 - 323
7736	1600	506 - 490	800°F,¼ hr.	415 - 420	499 - 494	900°F,½ hr.	363 - 363	490 - 499	1075°F,1 hr.	321 - 321
7737	1600	479 - 481	725°F,½ hr.	409 - 409	495 - 483	850°F,1 hr.	363 - 363	479 - 485	1000°F,1 hr.	325 - 325

* This steel was quenched in a 10% salt solution- the other steels were quenched in water, using the submerged spray head described in the first Progress Report.

in water with the exception of the low manganese steel, Heat No. 7688, which had to be quenched in brine.

The 14-in. plates were too long for uniform heating in the salt bath furnace which has been used previously. A sheet metal box was made up in which to heat the plates. Graphite slabs were used as spacers between the plates and to close the end of the box. This material also produced a non-scaling atmosphere inside the box and served to minimize decarburization of the plates.

Following the preliminary tests on coupons from all heats, the plates were quenched and immediately drawn at 400° F. A 1" x 2" section was then cut from both ends of each plate for hardness determinations. The results are listed in Table 2.

The sections cut off for determining hardness after the quench and 400° F. draw were placed on top of the respective plates in the furnace for the purpose of checking the hardness during successive draws. After the plates were drawn to the proper hardness level, the remainder of the 1-in. strip was cut from each end and tested for hardness. In most cases the hardness of the strip finally cut off the plate was identical to that shown by the separate sections. The few plates which showed slight differences were subsequently adjusted so as to have both ends fall within the intended range.

The final drawing temperatures and hardness values obtained from both ends of each plate are listed in Table 2. Complete data showing the hardness drop for successively higher drawing temperatures are on file. This information is not thought to be of interest to the sponsor but can be supplied upon request.

Jominy Hardenability Investigation.

Since all of the ingots made were rolled to plates 1/2" in thickness, hardenability specimens had to be restricted to 1/2" round bars instead of the standard 1" round. However, Gordon T. Williams (Hardenability Variations in Alloy Steels - Some Investigations With the End Quench Test, Trans. of the Amer. Soc. for Metals, Vol. XXVIII, 1940, page 163) has shown that results from 1/2" round specimens are comparable to those from the standard 1" round bar.

Blanks were cut from the fish-tail ends of the 1/2" plates and normalized from 1700° F. to eliminate the effect of prior microstructure and then machined to size as shown in Figure 2. Several of the steels, which were prone to air harden, had to be drawn at a sufficiently high temperature to make them machinable.

Graphite blocks were drilled to a depth to completely hide the specimen for the purpose of preventing scaling and to minimize surface decarburization. (Figure 3.) The specimens in the graphite holders were held at approximately 75° F. above the Ac_3 point for 20 minutes and then quickly transferred to the quenching fixture. In order that too much heat would not be lost in transferring, the graphite protection tube was not removed from the specimen until it was clamped in the fixture.

The quenching fixture (see Fig. 4) consists of a column of water directed against the bottom of the hot test piece. Water at 70-80°F. is passed through a 1/4" diameter opening under sufficient pressure to rise to an unimpeded height of 2-1/2". A quick-opening valve permits turning the water supply on immediately after the specimen is placed in the fixture with its bottom 1/2" above the orifice. The specimen is kept in the fixture for at least 10 minutes and can then be handled with bare hands.

After the quenching treatment, two flats are ground 0.015" deep, 180° apart along the sides of the specimen. It was found that grinding these surfaces at the rate of 0.002" for the first five passes and 0.001" each for the last five, under a plentiful supply of coolant, did not temper or work the ground surface to any detectable degree which would affect the hardness readings taken at 1/16" intervals. Average hardness values of the ground surfaces are plotted against the distance from the quenched end and these hardenability curves are shown in Figures 5 to 31 inclusive.

For purpose of comparison, the hardness test results have been tabulated and the different steels rated as to hardness in Table 3. Heats 7697, 7703, and 7719, for example, show a hardness of 52 Rockwell C at a distance of 1-1/2" from the quenched end. These three heats are ranked in the highest or No. 1 position while Heat 7717 shows 51 Rockwell C and stands second in the list,

DISCUSSION

The method of taking hardness readings employed in processing this series of plates is by far the most satisfactory one tried. In the majority of cases the hardness obtained from the coupon cut off the plate after final drawing was very close to that of the small specimen used as a guide throughout the successive drawing treatments. Subsequent adjustments were made when the final hardness specimen was out of the intended range.

Difficulty was experienced in hardening heat number 7688 which contains a low percentage of manganese. The plates had to be quenched in brine from a rather high temperature. This material is extremely shallow hardening and can only be of use as a basis of comparison.

TABLE 3. RANKING OF THE TWENTY-SEVEN STEELS AS TO HARDNESS AT VARIOUS DISTANCES FROM THE QUENCHED END.

Heat	1/16"		1/4"		1/2"		3/4"		1"		1-1/4"		1-1/2"		2"		2-1/2"	
No.	RC	Rank	RC	Rank	RC	Rank	RC	Rank	RC	Rank	RC	Rank	RC	Rank	RC	Rank	RC	Rank
7688	50	6	22	12	14	19	10	19	7	21	4	24	3	17	0	21	-1	22
7689	51	5	23	11	17	18	14	18	11	20	10	23	8	16	5	20	5	21
7690	52	4	39	9	20	17	18	16	16	18	14	22	13	15	11	19	11	20
7691	53	3	49	6	38	12	28	14	24	16	22	14	20	14	18	17	17	19
7692	52	4	44	8	21	16	18	16	16	18	14	22	13	15	12	18	11	20
7693	53	3	51	4	45	8	35	11	27	13	23	13	20	14	18	17	17	19
7694	54	2	53	2	51	3	50	4	49	5	47	6	45	5	41	6	38	8
7695	53	3	50	5	41	10	30	13	25	15	23	13	21	13	19	16	18	18
7696	53	3	51	4	49	5	45	8	40	9	37	8	35	7	33	7	33	9
7697	54	2	54	1	53	1	53	1	52	2	52	2	52	1	52	1	52	1
7702	52	4	51	4	50	4	50	4	50	4	50	4	48	4	45	4	44	4
7703	54	2	53	2	53	1	52	2	52	2	52	2	52	1	52	1	52	1
7712	52	4	50	5	50	4	49	5	49	5	49	5	49	3	49	3	49	3
7713	51	5	49	6	43	9	32	12	27	13	25	12	24	11	23	12	22	13
7714	50	6	37	10	22	15	17	17	15	19	14	22	13	15	12	18	11	20
7715	51	5	50	5	49	5	44	9	35	11	28	10	24	11	21	14	21	14
7716	50	6	49	6	48	6	48	6	47	6	46	7	44	6	41	6	40	7
7717	53	3	51	4	51	3	51	3	51	3	51	3	51	2	50	2	50	2
7718	52	4	51	4	50	4	47	7	42	7	37	8	33	8	28	10	27	11
7719	56	1	54	1	53	1	53	1	53	1	53	1	52	1	52	1	52	1
7731	54	2	52	3	52	2	52	2	52	2	51	3	49	3	45	4	43	5
7732	52	4	51	4	51	3	51	3	50	4	47	6	45	5	42	5	42	6
7733	52	4	51	4	48	6	43	10	38	10	34	9	31	9	29	9	27	11
7734	52	4	49	6	36	13	28	14	25	15	23	13	22	12	22	13	21	14
7735	51	5	48	7	32	14	25	15	23	17	21	15	21	13	20	15	19	15
7736	50	6	49	6	47	7	44	9	41	8	37	8	35	7	32	8	31	10
7737	53	3	50	5	40	11	32	12	28	12	26	11	25	10	24	11	24	12

The Jominy hardenability tests were made on 1/2 inch rounds instead of the standard 1-inch bar because heats previously produced had been rolled to 1/2-inch plate. Williams, (Hardenability Variations in Alloy Steels - Some Investigations With the End Quench Test. Trans. American Society for Metals, Vol. 28, 1940, page 165,) has pointed out the fact that end area and bar volume have a constant ratio and, within reasonable limits, should not influence the results. Curves are shown by this author from 1/2-inch, 1-inch, and 1-1/2- inch bars. A slightly higher hardness through the transition zone, shown in the 1/2-inch specimen, was attributed to water creeping up the sides because the outlet was not properly reduced in cross-section. Some tests on standard 1-inch and 1/2-inch bars should be made on one or two of the armor plate steels for the purpose of comparison.

The Jominy test is not suitable for distinguishing between steels which are extremely deep hardening. If the steels are air hardening, both ends may be approximately the same and, hence, no rating can be applied to two such steels. Air hardening steel, however, would certainly not be difficult to harden by even a mild quench when in the form of light armor plate.

PLANS FOR FUTURE WORK.

Cross section hardness surveys are now being run on the set of 38 plates returned from Watertown. The surveys are being made close to the location at which the ballistic limit was determined. Curves will be drawn by plotting hardness against ballistic limits.

Hardenability tests have been completed and a report including all test results on the 38 plates will be sent out within a few days.

Hardness surveys will be made on the group of 81 plates now at Watertown as soon as ballistic limit determinations are completed and the plates returned. It should then be possible to select a few promising compositions for further study.

Data from which this report was written are recorded in Notebook No. 799, pages 61 to 100, and Notebook No. 849, pages 4 to 47.

MLS-CHL:DW
2/13/42

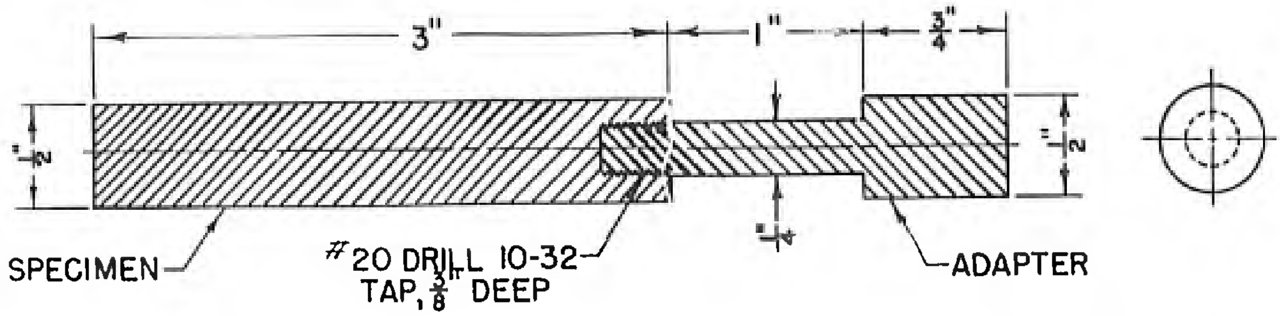

Fig. 2. Specimen and adaptor for Jominy hardenability test.

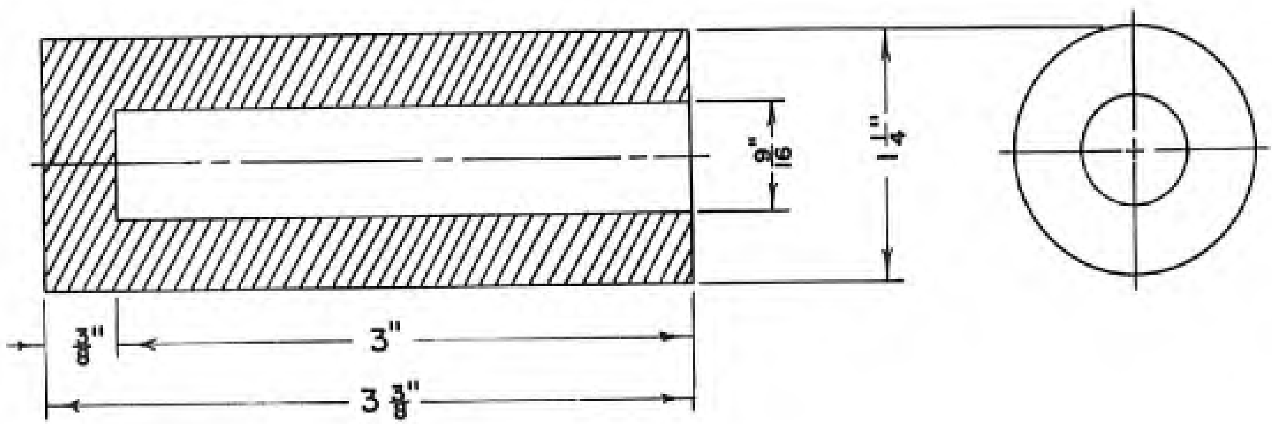

Fig. 3. Graphite protection thimble in which the specimens were heated.

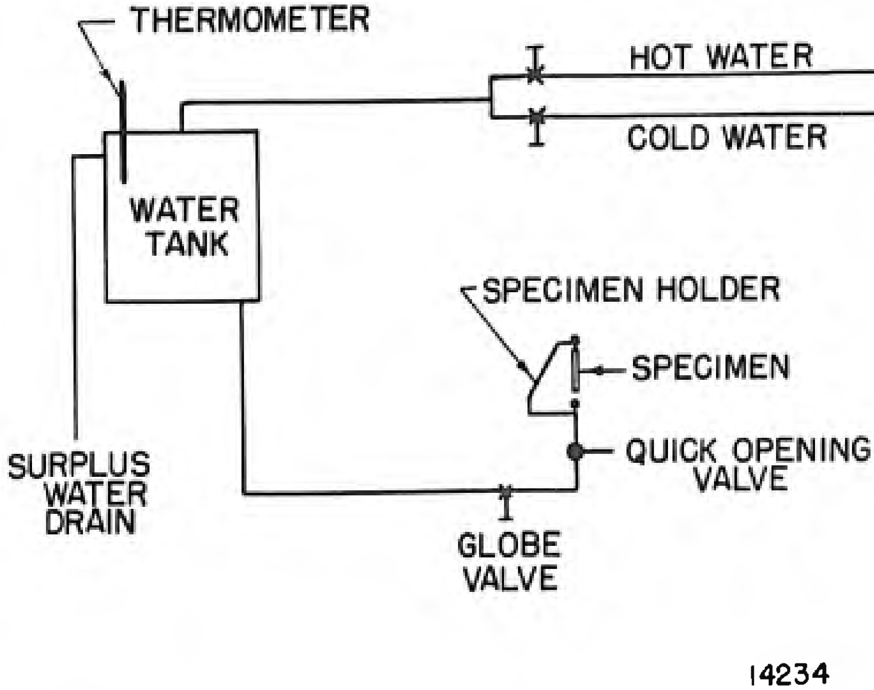

Fig. 4. Schematic drawing of the quenching apparatus for the Jominy test.

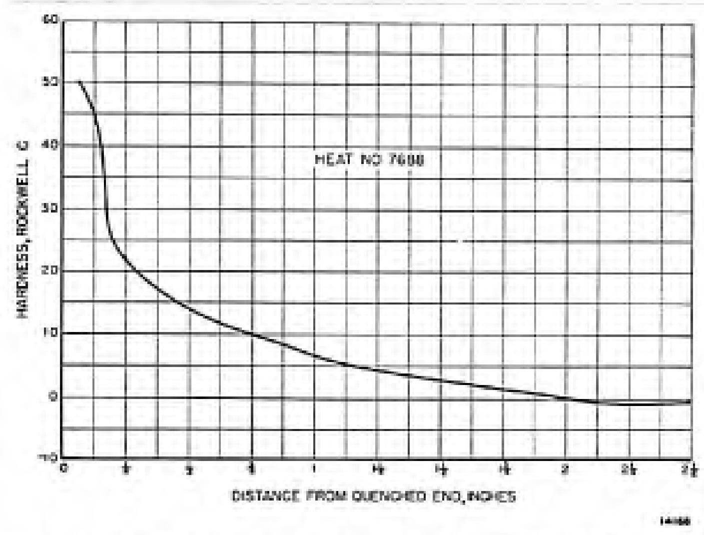

Fig. 5. Heat No. 7688. C-.33, Mn-.43, Si-.24.

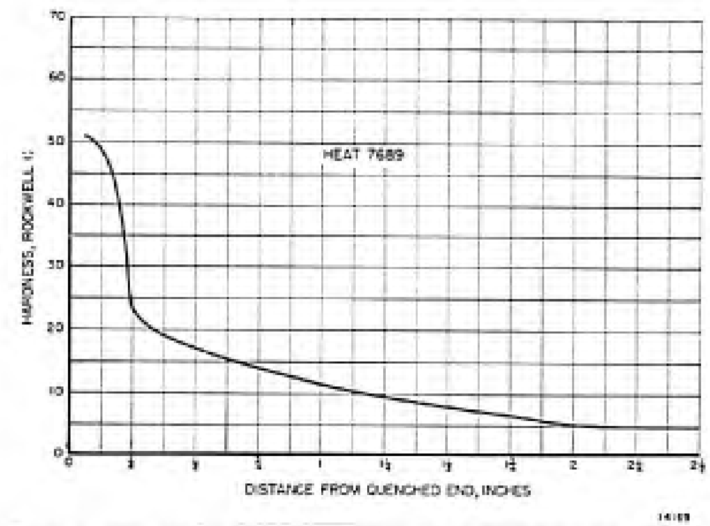

Fig. 6. Heat No. 7689. C-.33, Mn-.81, Si-.26.

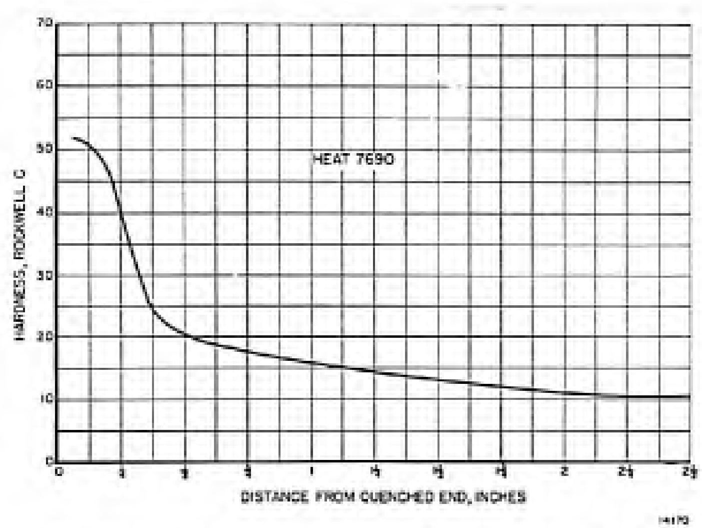

Fig. 7. Heat No. 7690. C-.32, Mn-1.24, Si-.28.

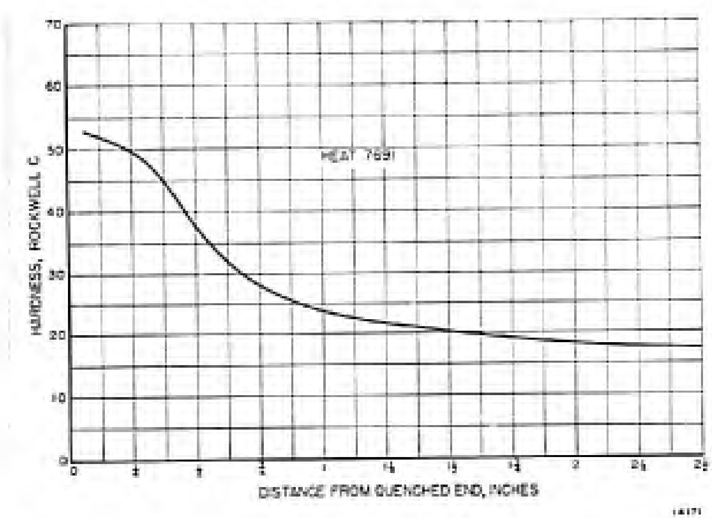

Fig. 8. Heat No. 7691. C-.31, Mn-1.73, Si-.29.

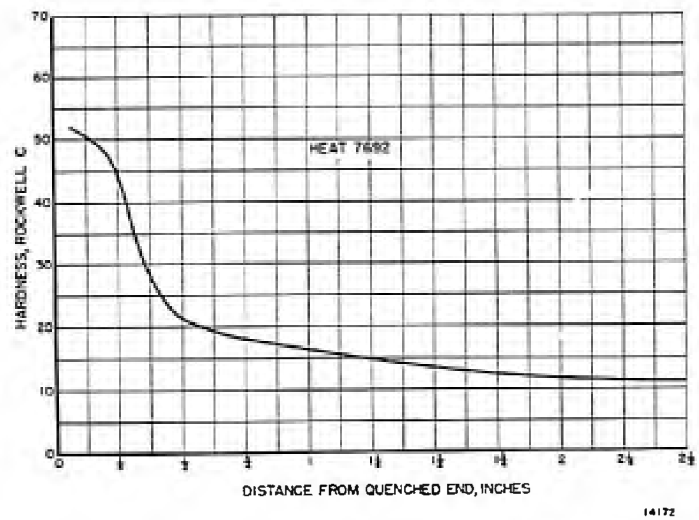

Fig. 9. Heat No. 7692. C-.31, Mn-.75, Si-.26, Ni-2.01.

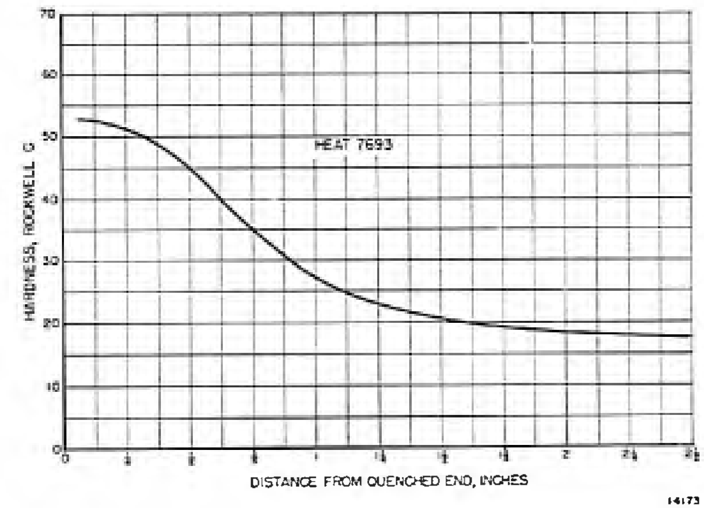

Fig. 10. Heat No. 7693. C-.30, Mn-.70, Si-.25, Ni-2.55.

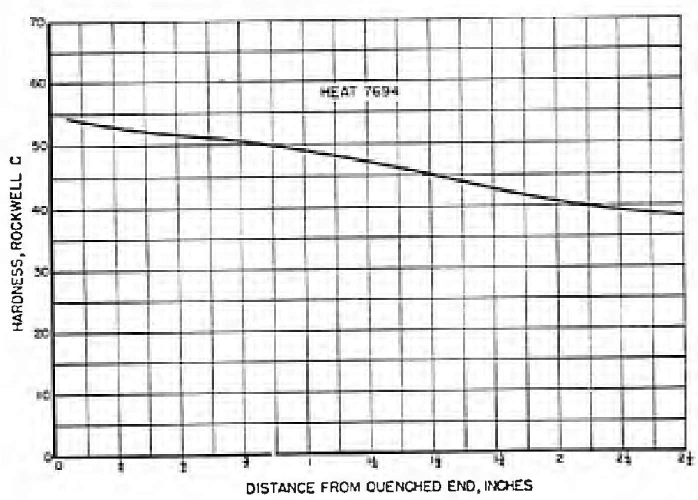

Fig. 11. Heat No. 7694. C-.31, Mn-.73, Si-.27, Ni-5.15.

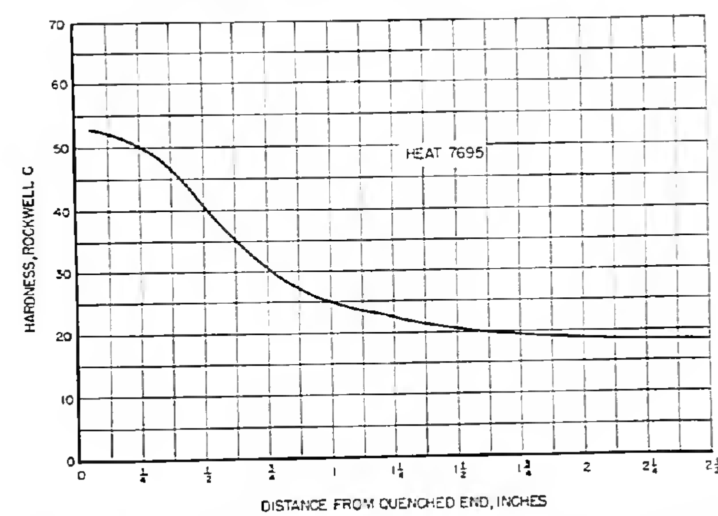

Fig. 12. Heat No. 7695. C-.30, Mn-1.24, Si-.24, Ni-2.01

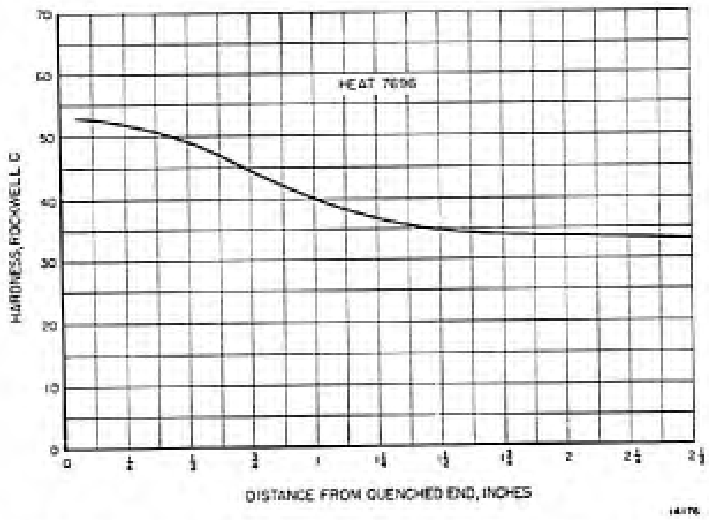

Fig. 13. Heat No. 7696. C-.31, Mn-.81, Si-.27, Ni-1.3/1.6, Cr-.83.

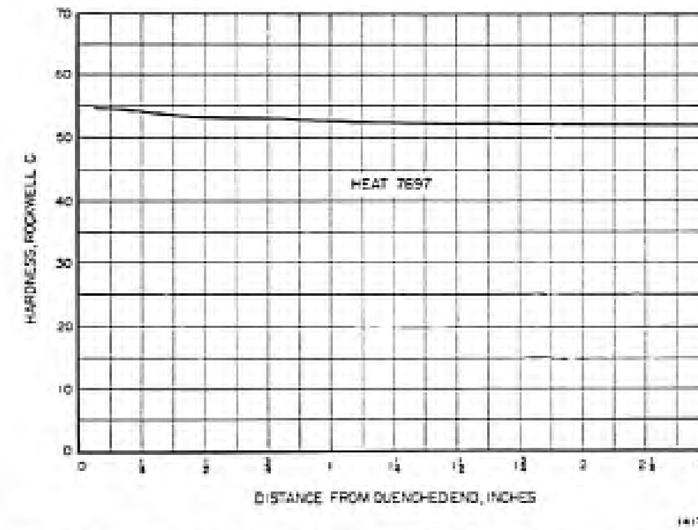

Fig. 14. Heat No. 7697. C-.28, Mn-.79 Si-.24, Ni-3.6/3.9, Cr-2.61.

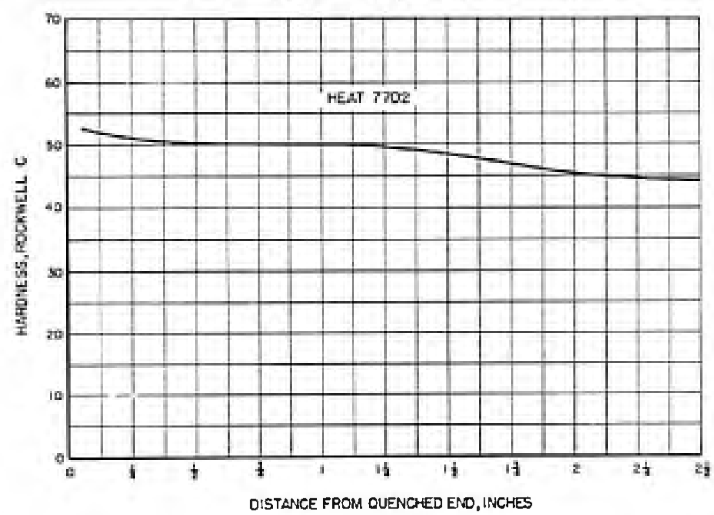

Fig. 15. Heat No. 7702. C-.31, Mn-.82, Si-.26, Ni-1.3/1.6, Cr-.70/.90, Mo-.25.

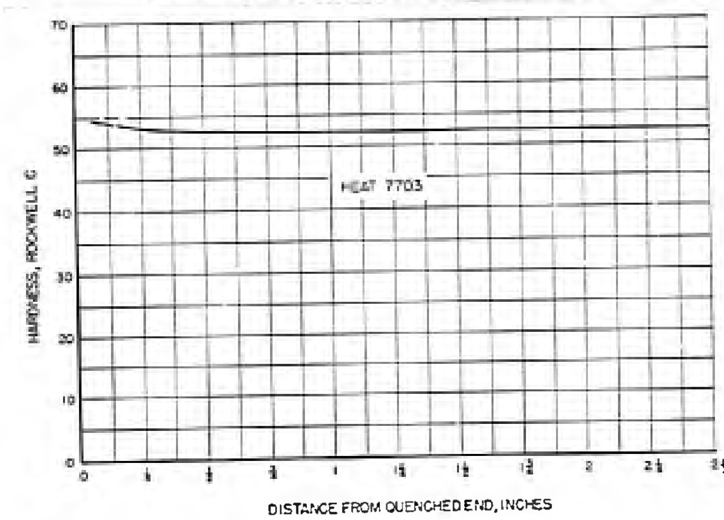

Fig. 16. Heat No. 7703. C-.34, Mn-1.56, Si-.46, Ni-3.3/3.7, Cr-.90/1.10, Mo-.34.

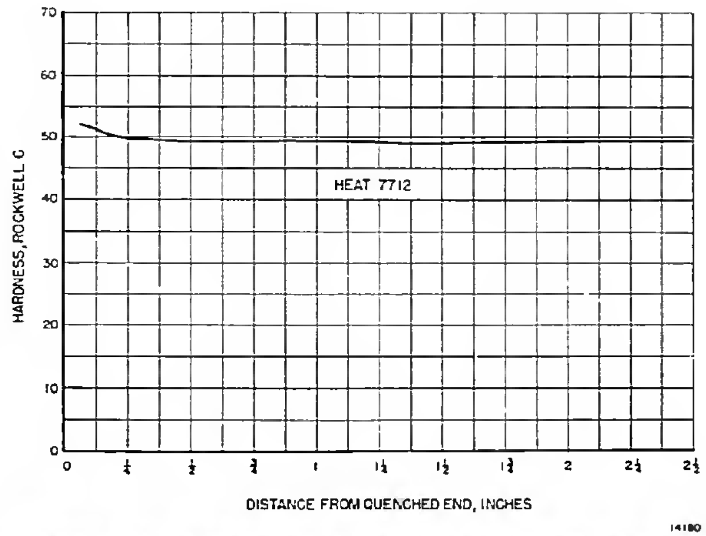

Fig. 17. Heat No. 7712. C-.28, Mn-1.49, Si-.26, Ni-1.3/1.6, Cr-.75/.90, Mo-.30.

Fig. 18. Heat No. 7713. C-.32, Mn-.90, Si-.25, Ni-1.3/1.6, V-.18.

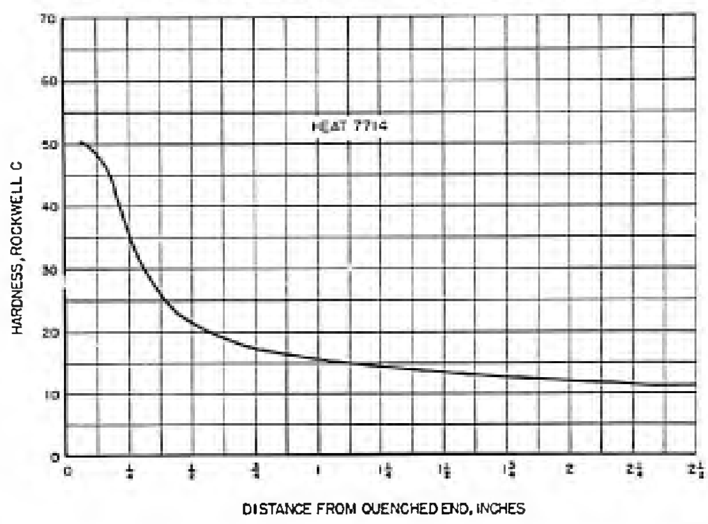

Fig. 19. Heat No.7714. C-.31, Mn-1.46, Si-.24, Ti-.16.

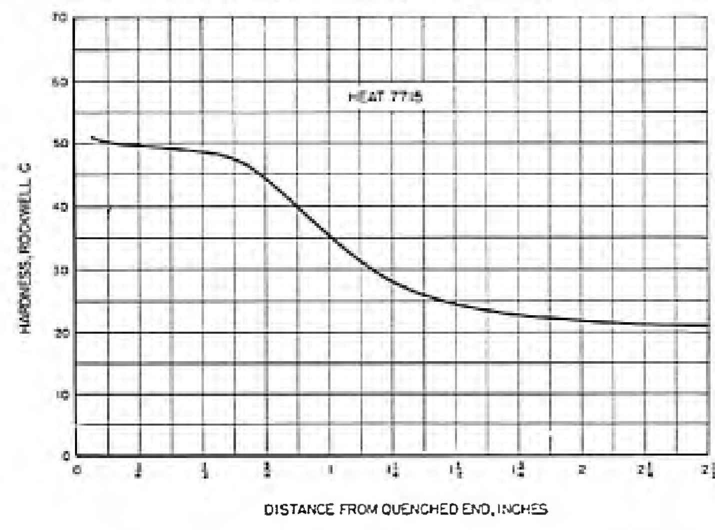

Fig. 20. Heat No. 7715. C-.32, Mn-1.42, Si-.24, Grainal treated.

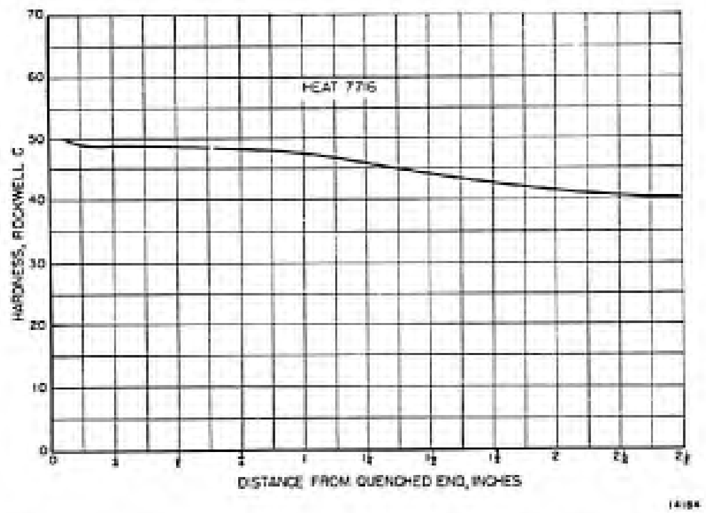

Fig. 21. Heat No. 7716. C-.31, Mn-1.44, Si-.63, Cr-1.08, V-.18.

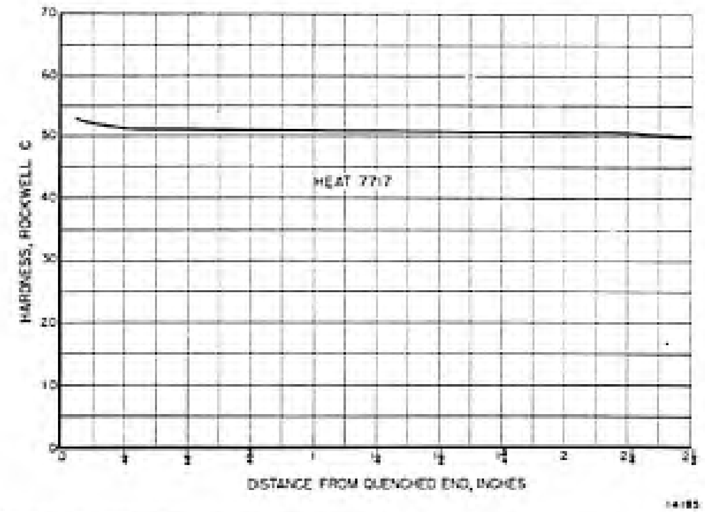

Fig. 22. Heat No. 7717. C-.32, Mn-1.46, Si-.69, Cr-1.07, Grainal treated.

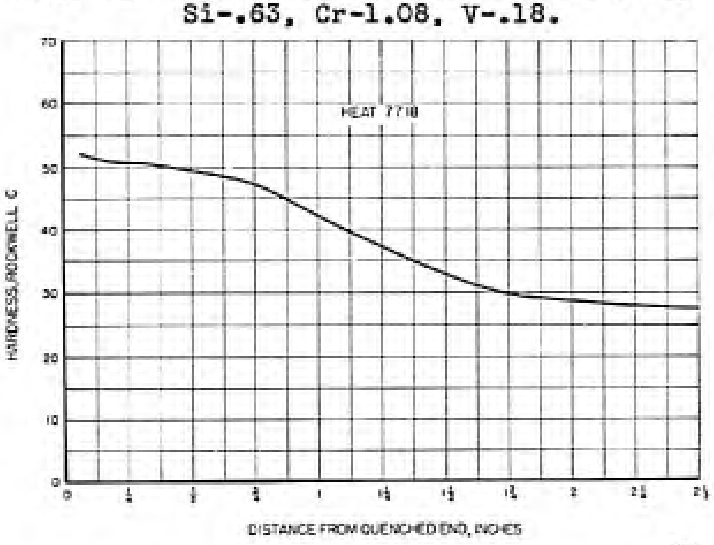

Fig. 23. Heat No. 7718. C-.33, Mn-1.53, Si-.27, Cr-.90/1.10, Mo-.40.

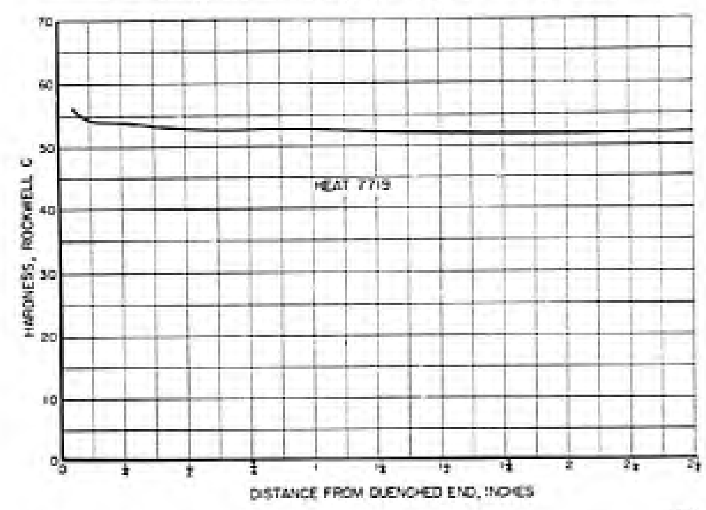

Fig. 24. Heat No. 7719. C-.32, Mn-1.52, Si-.27, Mo-.39.

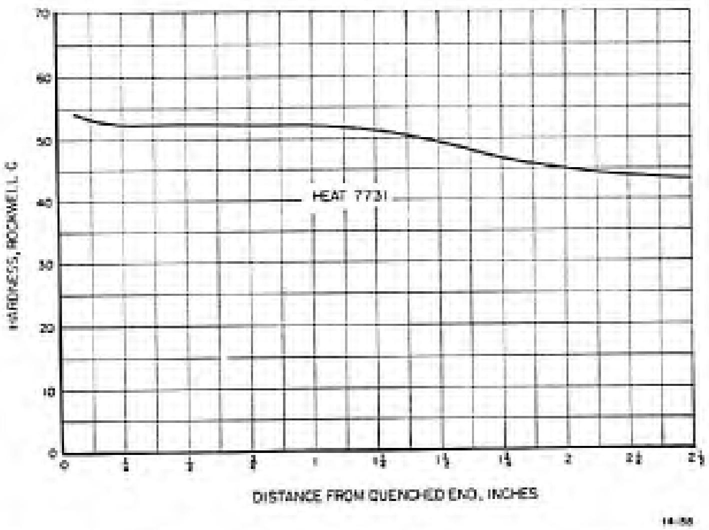

Fig. 25. Heat No. 7731. C-.34, Mn-.81, Si-.30, Cr-1.53, Mo-.40.

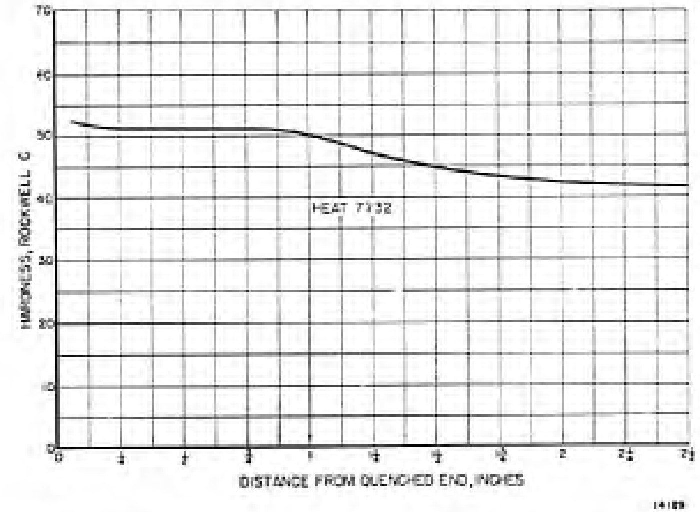

Fig. 26. Heat No. 7732. C-.31, Mn-.73, Si-.21, Cr-1.32, Mo-.60/.80, V-.27.

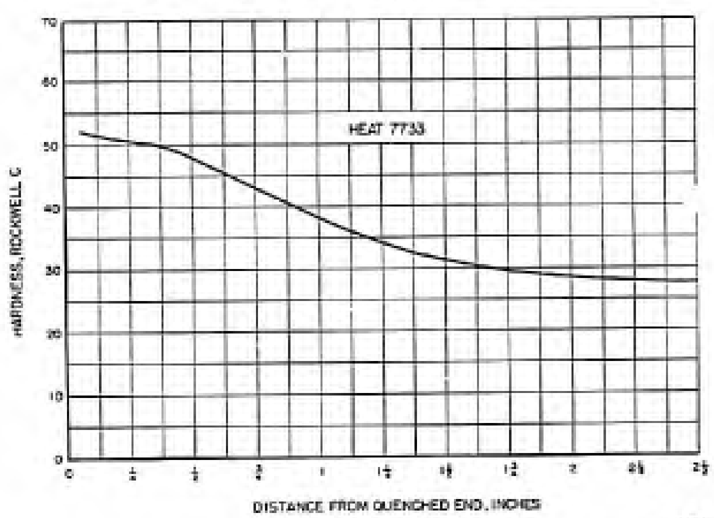

Fig. 27. Heat No. 7733. C-.31, Mn-1.51, Si-.26, Cu-1.49.

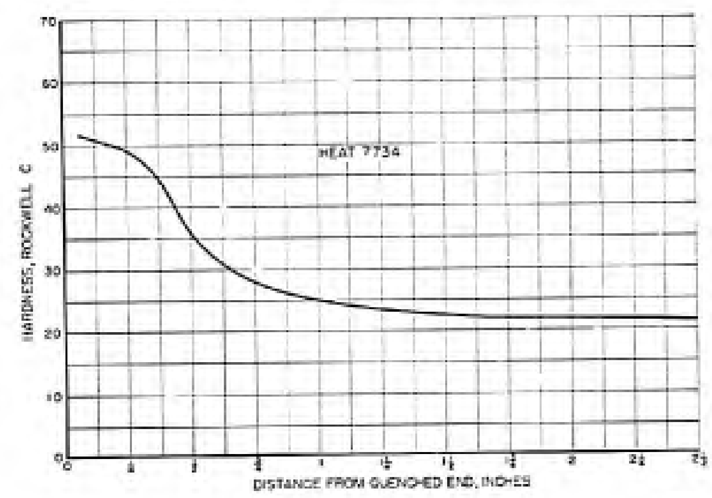

Fig. 28. Heat No. 7734. C-.35, Mn-1.52, Si-.27, Mo-.40/.50, Cu-.45.

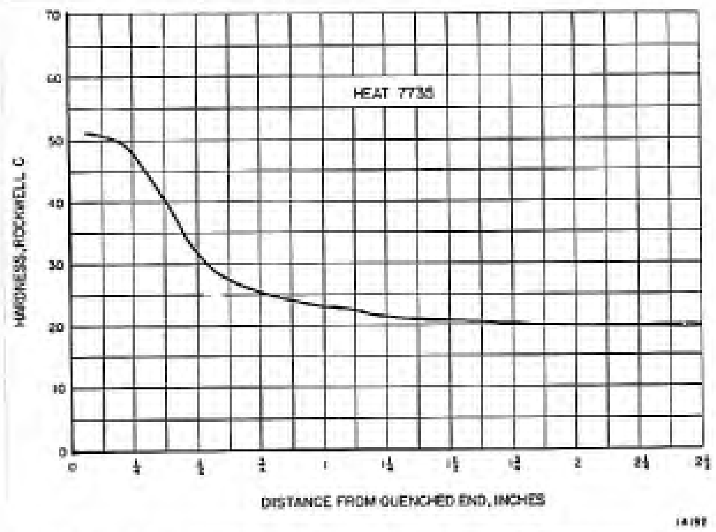

Fig. 29. Heat No. 7735. C-.32, Mn-.84, Si-.26, Cu-.42.

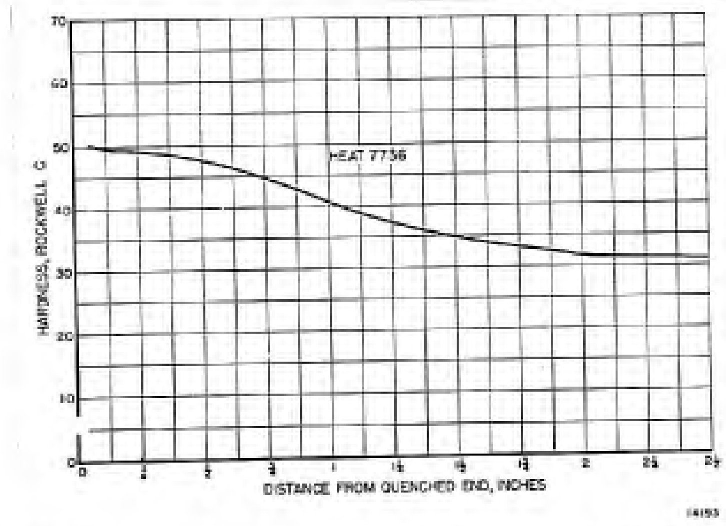

Fig. 30. Heat No. 7736. C-.33, Mn-.88, Si-.63. Ni-.50, Cr-.50, Mo-30.

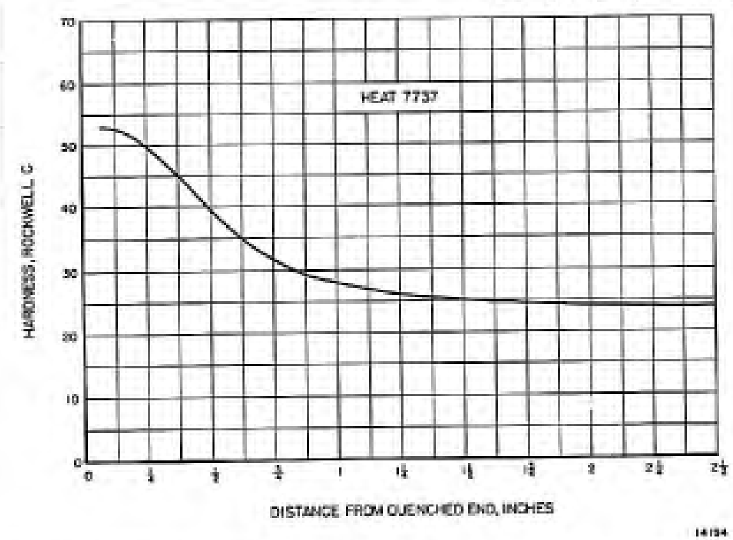

Fig. 31. Heat No. 7737. C-.31, Mn-.77, Si-.22, Ni-.50, Cr-.49, Mo-.30.