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HARDENING CHARACTERISTICS AND OTHER PROPERTIES OF COMMERCIAL ONE-PERCENT-CARBON TOOL STEELS

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ABSTRACT

Widely used brands of 1-percent-carbon tool steels produced by one foreign and five domestic manufacturers were classified on the basis of their depths of hardening. Two of these steels, having widely different hardening characteristics, were selected for a study of the effect of initial structure on the austenitic grain size and grain growth and on the critical cooling rates. These data made possible a direct comparison of the relation between austenitic grain size and critical cooling rates over a range of quenching temperatures of 1,425 to 1,775° F. Comparisons of the two steels were also made with respect to their behavior in the transformation temperature range during thermal analysis, relative rates of spheroidization, Charpy impact strengths, relative susceptibility to grinding cracks, hardness values on quenching with different rates, structural normality, performance as lathe tools and the effect of rate of heating to the hardening temperatures on depth of hardening.

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I. INTRODUCTION

Plain carbon tool steels of apparently the same composition often have widely different hardening characteristics. This important fact has been recognized for many years but definite progress in explaining the fundamental causes of this difference in behavior has been made only in the last decade. Recent investigations have at least partially explained this anomaly by showing the marked influence exerted by the austenitic grain size on the hardenability of steel.

The influence of initial structure (structure prior to hardening) upon the austenitic grain size and hence upon hardenability was also recognized by those most active in developing the theories of effects of grain size. This factor has, however, received less attention than many other phases of austenitic grain-size influence.

The experiments described in this report were made in the course of a study of the hardening characteristics of commercial 1-percent-carbon tool steels. Particular attention was given to the influence of initial structure of two selected steels (which had wide differences in their depth of hardening) upon the grain size and grain growth of their austenite in and above the usual range of hardening temperatures, and upon the critical cooling rates on quenching from a similar range of temperatures. Comparisons of these two steels were also made with respect to their behavior in the transformation temperature range during thermal analysis, relative rates of spheroidization, Charpy impact strengths, relative susceptibility to grinding cracks, Rockwell hardness values on quenching with different rates, structural normality, performance as lathe tools, and the effect of rate of heating to the hardening temperatures on the depth of hardening.

II. PREVIOUS INVESTIGATIONS

In 1922 McQuaid and Ehn [1] reported a difference in the hardening of carburized plain carbon steels. The ability to harden was related to the "normal" or "abnormal" structure of the steel. In the shallow-hardening or abnormal steel the grain size was usually small and, on slow cooling from the carburizing temperature, the cementite in the hypereutectoid zone existed as coalesced masses generally surrounded by ferrite. In the relatively deep-hardening or normal steel, the grain size was large and the pearlite grains in the hypereutectoid zone were inclosed by thin films of cementite. Abnormality was believed to be caused by oxides, either in solution or as submicroscopic particles.

Epstein and Rawdon [2] pointed out that abnormality in commercial carburizing steels seemed, in most cases, to be associated with the use of aluminum for deoxidizing and that the higher carbon tool steels had features of normality and abnormality similar to those met in carburizing steels.

Davenport and Bain [3] considered that the structure and hardness in a quenched steel depend primarily on the particular temperature at which austenite decomposes during the quenching. The rate at which the steel cools during the quenching is important only in determining to how low a temperature austenite can be cooled before its decomposition begins. They concluded that hardenability of a steel depends upon the stability of quenched austenite in the temperature range of 1,110 to 930° F, the upper range in which austenite is most prone to decompose and in which its decomposition products are relatively soft. If the austenite of a steel is relatively stable in this temperature range and can be cooled through this range by a mild quench, then it decomposes only in the range below about 300° F, the product of decomposition is martensite, and the steel is

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[1] W. H. McQuaid and E. W. Ehn, Trans. Am. Inst. Min. Met. Engrs. **67**, 341–391 (1922).

[2] S. Epstein and H. S. Rawdon, BS J. Research 1, 423–466 (1928) RP14.

[3] E. S. Davenport and E. C. Bain, Trans. Am. Inst. Min. Met. Engrs., Iron & Steel Div. **90**, 117–154 (1930).

fully hardened. Such a steel may, therefore, be called a "deep-hardening" steel as compared with another in which the austenite is less stable in the range, 1,110 to 930° F, and which, therefore, does not fully harden under identical quenching conditions.

Bain [4] further clarified the conception of hardenability by suggesting that the factors which determine the relative stability of austenite in the temperature range, 1,110 to 930° F, are (1) its chemical composition and (2) its grain size.

The far-reaching effect of austenitic grain size and its control has been discussed in a number of recent papers, notably those of the "Grain Size Symposium" of the American Society for Metals.[5]

In papers presented before the American Society for Steel Treating in 1929, both Shepherd and Luerssen discussed variations in the hardenability of tool steel. Shepherd [6] described a simple test for depth of hardness and Luerssen [7] pointed out the desirability, as well as the possibility, of controlling melting conditions to produce carbon tool steel with a predetermined hardness penetration and quenching temperature range. Such tool steels were shortly made available commercially.

Harrington [8] studied the effect of initial structure on the "body" (that is, the ability to withstand repeated heating and cooling cycles), the hardness, and the structure of hardened 1- percent-carbon tool steel. The body of the steel was influenced by the initial structure with quenching temperatures of 1,380 or 1,470° F, but was not affected when the quenching temperature was increased to 1,650° F.

Tests to determine the effect of various amounts of spheroidized cementite in the initial structure on the hardness of quenched specimens of a 0.9- percent-carbon steel have been reported by Lljynski.[9] Increasing the amount of spheroidized cementite in the initial structure resulted in a decrease in the hardness of the quenched steel.

In 1933 Engel and Engel [10] reported the results of their investigation on the effect of initial structure on the critical cooling rate of a 1-percent-carbon steel. Microscopical examination was made of specimens with different initial structures that were heated for varying lengths of time, quenched, and fractured. However, actual cooling rates and the austenite grain-size determinations, are not included in their published data.

Shepherd [11] recently called attention to the dependence of "penetration-fracture characteristics" of tool steel on the heat treatment and the microstructure of the steel prior to heating for hardening.

III. STEELS STUDIED

Plain carbon tool steels, of about 1-percent carbon representing widely used brands, were purchased through regular channels of supply from one foreign and five domestic manufacturers. Tests for the depth of hardening were made on initially spheroidized specimens by quenching ¾-inch rounds in brine from two temperatures,

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[4] E. C. Bain, Trans. Am. Soc. Steel Treating **20**, 385–428 (Nov. 1932).
[5] Trans. Am. Soc. for Metals **22** (Dec. 1934).
[6] B. F. Shepherd, Trans. Am. Soc. Steel Treating **17**, 90–110 (Jan. 1930).
[7] G. V. Luerssen, Trans. Am. Soc. Steel Treating **17**, 161–198 (Feb. 1930).
[8] R. H. Harrington, Trans. Am. Soc. Steel Treating **18**, 404–422 (1930).
[9] S. K. Lljynski, Proc. Second Congress of Scientific Promoters of Metallurgy in Leningrad, 161 (May 1924); Abs., Trans. Am. Soc. Steel Treating **9**, 492 (1926).
[10] W. Engel and N. Engel, Jernkontorets Ann. **117**, 409–418 (August 1933).
[11] B. F. Shepherd, Trans. Am. Soc. for Metals **22**, 979–1,016 (Dec. 1934).

1,425 and 1,550° F, and etching a section to show the hardness penetration. On the basis of these tests two steels were selected which had very similar depth of hardening on quenching from 1,425° F (within the usual hardening range), but very different depths of hardening on quenching from 1,550° F. The hardened and etched sections of these steels are shown in figure 1. Steel 65 obviously has markedly changed in its depth of hardening as a result of increasing the quenching temperature from 1,425 to 1,550° F, while steel 68 has changed very little. Steel 68 was, in fact, produced under conditions which resulted in control of austenitic grain size and was marketed with specific claims as to its uniformity in depth of hardening by quenching within and above the usual quenching temperature ranges. In this paper these two steels are occasionally indicated by the terms "shallow-hardening" or "controlled" for steel 68 and "deep-hardening" or "noncontrolled" for steel 65. As shown in table 1, the chemical compositions of the two steels differed chiefly in the aluminum and aluminum oxide contents. The controlled steel (68) contained appreciably greater proportions of both metallic aluminum (that portion soluble in acid) and aluminum oxide than the noncontrolled steel (65). The steels would be expected to have quite similar hardening characteristics if chemical composition were the only basis of comparison.

TABLE 1.—*Chemical composition of steels with different hardening characteristics*

Steel identification number	Chemical composition (percent by weight)														
	C	Mn	P	S	Si	Cr	Ni	W	Mo	V	Al_2O_3	Acid soluble Al	Total Al	H	O	N
65	1.05	0.28	0.019	0.013	0.22	0.08	0.13	(1)	<0.01	<0.01	0.006	0.001	0.004	0.0002	0.007	0.009
68	1.06	.26	.013	.011	.19	.09	.10	(1)	<.01	<.01	.010	.008	.013	.0003	.009	.007

(1) Not detected.

IV. COMPARISON OF DEEP-HARDENING AND SHALLOW-HARDENING STEELS

1. THERMAL ANALYSIS

Heating and cooling curves were made on specimens of steels 65 and 68, which were initially either normalized to produce a structure consisting essentially of lamellar pearlite or annealed to spheroidize the cementite. The curves were obtained on approximately ⅛- by ½- by ⅜-inch specimens heated and cooled in vacuum at a rate of 14 to 18° F per minute.

Typical inverse-rate and time-temperature curves for initially normalized samples are reproduced in figures 2 and 3, respectively. Differences were observed in the temperatures for the beginning of the transformation on slow heating and in the behavior of the two steels during this transformation. These effects are shown by the locations, lengths, and widths of the cusps of the heating curves in figure 2. The controlled steel (68) had a narrow transformation range on heating either the initially normalized or the annealed specimens as compared with the noncontrolled steel (65). The nor-

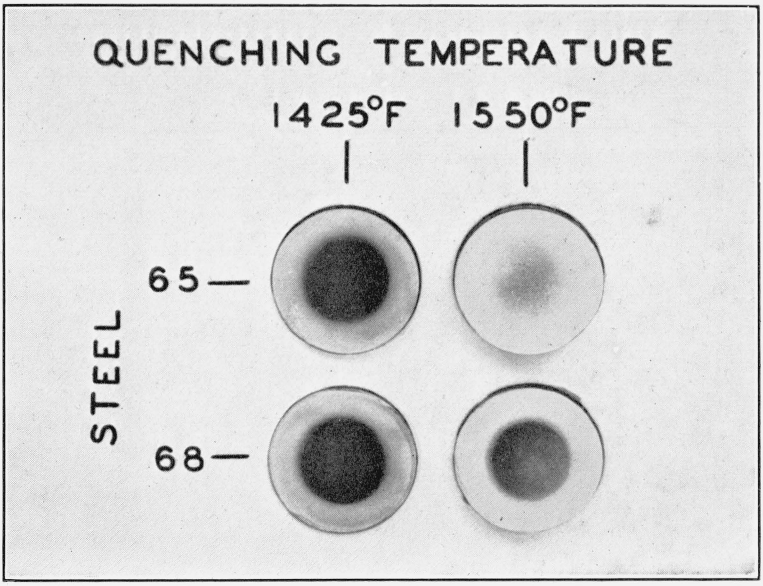

FIGURE 1.—*Relative depth of hardening of steels 65 and 68.*

Initially spheroidized, three-quarter-inch round specimens quenched from 1,425° or 1,550° F. in brine. Etched in 1 percent nitric acid in alcohol to darken the unhardened portions.

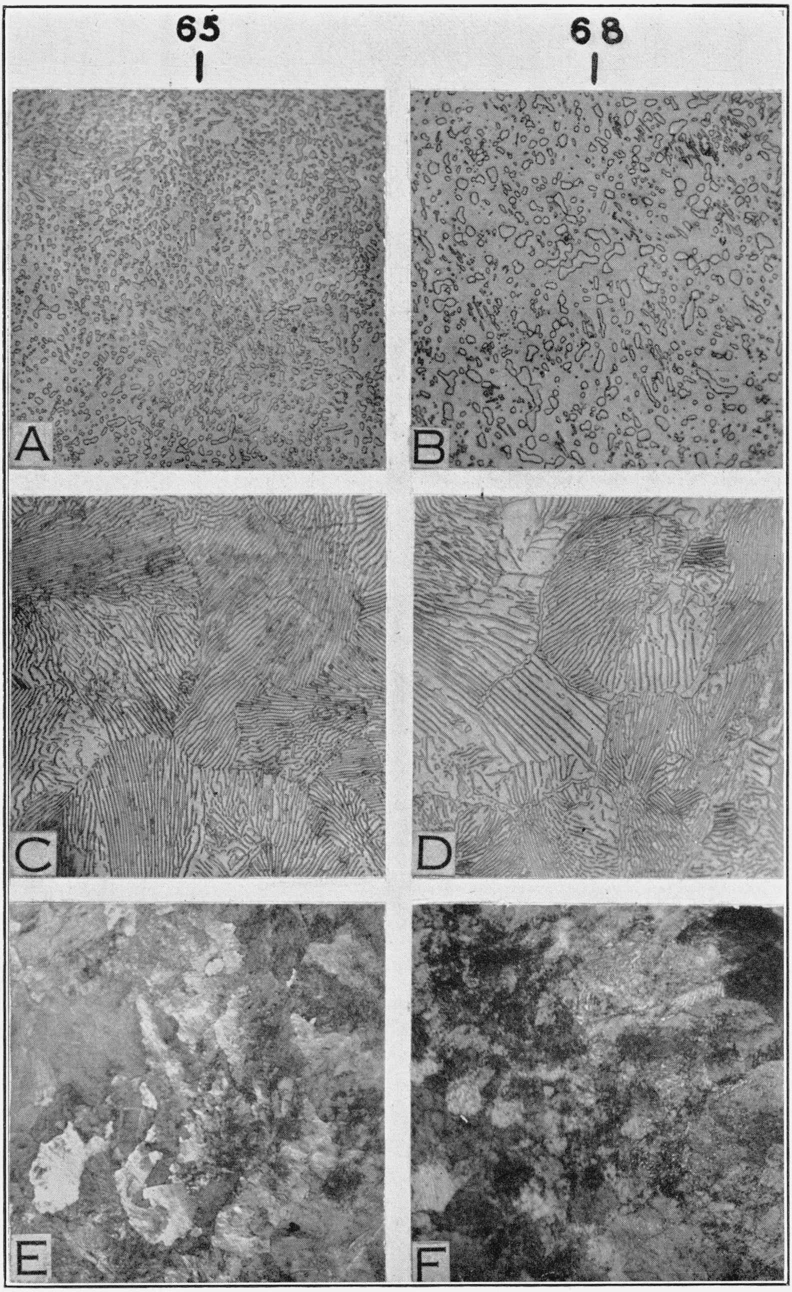

FIGURE 4.—*Initial structure of steels 65 and 68.*

A and *B*, Spheroidized cementite; *C* and *D*, coarse lamellar pearlite; *E* and *F*, sorbite. Etched with 1 percent nitric acid in alcohol, × 500.

malized specimens of steel 68 also had a greater undercooling effect after this transformation once started (fig. 3), than did similarly treated specimens of steel 65. Both steels had similar cooling characteristics on slow cooling from the austenitic condition (1,650 to 1,600° F) at the rate of 14 to 18° F per minute.

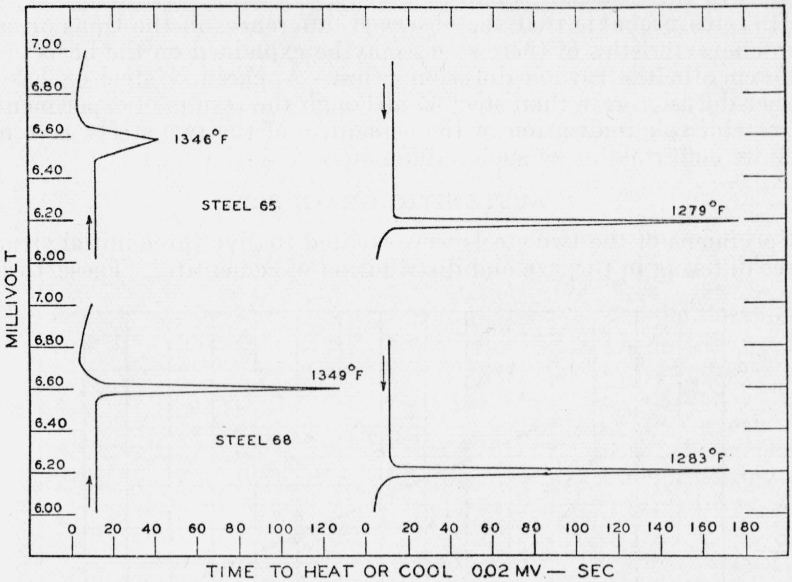

FIGURE 2.—*Inverse-rate heating and cooling curves for steels 65 and 68, with an initial structure of lamellar pearlite.*

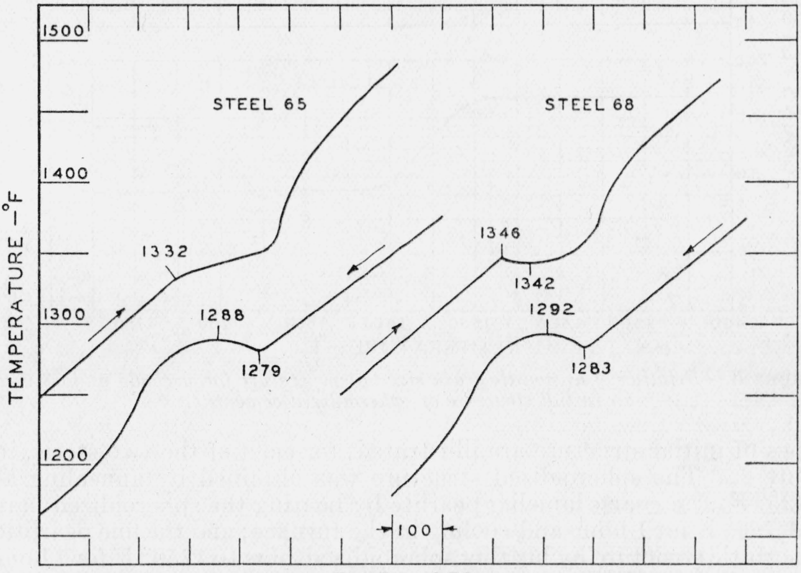

FIGURE 3.—*Time-temperature heating and cooling curves for steels 65 and 68 with an initial structure of lamellar pearlite.*

The initial structures investigated had no marked influence on the transformation characteristics on comparatively slow heating and cooling of these steels.

It seems probable that the observed differences in the transformation characteristics of these steels may be explained on the basis of a difference in the carbon diffusion rates. Apparently steel 68 has a higher diffusion rate than steel 65 although the results of experiments on rate of spheroidization of the cementite of the two steels gave no definite confirmation of such a difference.

2. AUSTENITIC GRAIN SIZE

Specimens of the two steels were treated to give three initial structures differing in the size and distribution of cementite. These three types of initial structure are illustrated, for each of the two steels, in figure 4. The spheroidized structure was obtained by annealing at 1,425° F; the coarse lamellar pearlite by heating the spheroidized bars at 1,750° F for 1 hour and cooling in the furnace; and the fine pearlitic or sorbitic structure by heating spheroidized bars to 1750° F for 1 hour and cooling in air.

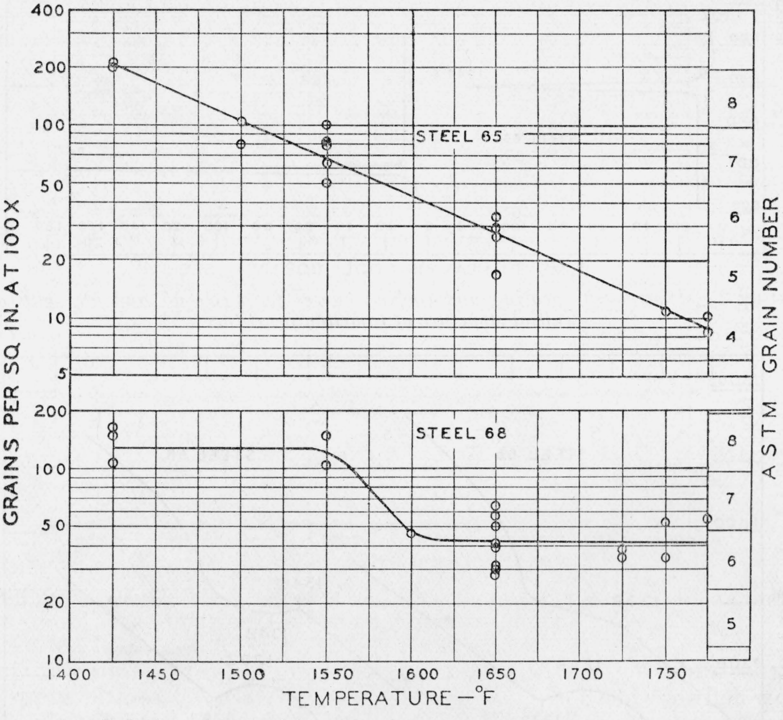

FIGURE 5.—*Relation of austenitic grain size to temperature for steels 65 and 68 with an initial structure of spheroidized cementite.*

For the determinations of the austenitic grain size and grain growth specimens ¼-inch square by 0.040-inch thick were cut from the ¾-inch rounds of both steels having each of the three initial structures. One wire of a 22-gage chromel-alumel thermocouple was spot-welded to the center of each of the two flat faces of each specimen. The specimens were heated in an atmosphere of dry nitrogen at a rapid rate, usually requiring 1 to 2 minutes to reach the temperature at which it was desired to determine the austenitic grain size, held at that temperature for 15 minutes and then cooled in a manner suitable for outlining the grains. If the temperature establishing the grain size was above the A_{cm} temperature, a cementite network outlining the austenite grains was produced by slowly cooling the specimen to about 1,400 to 1,375° F and holding it a short time in this temperature range before quenching. If the temperature establishing the grain size was between the A_{3-2-1} and A_{cm} temperatures, then the specimen was quenched under conditions (i. e., slightly slower than the critical cooling rate) which permitted the formation of just enough primary troostite to outline the austenitic grains. The grain counts were made by Jeffries' method [12]. The relations between austenitic grain size and temperature for each of the initial structures consisting of (a) spheroidized cementite, (b) coarse pearlite or (c) sorbite, are shown in figures 5, 6, and 7, respectively. The curves representing these relations for all three initial structural conditions are summarized in figure 8.

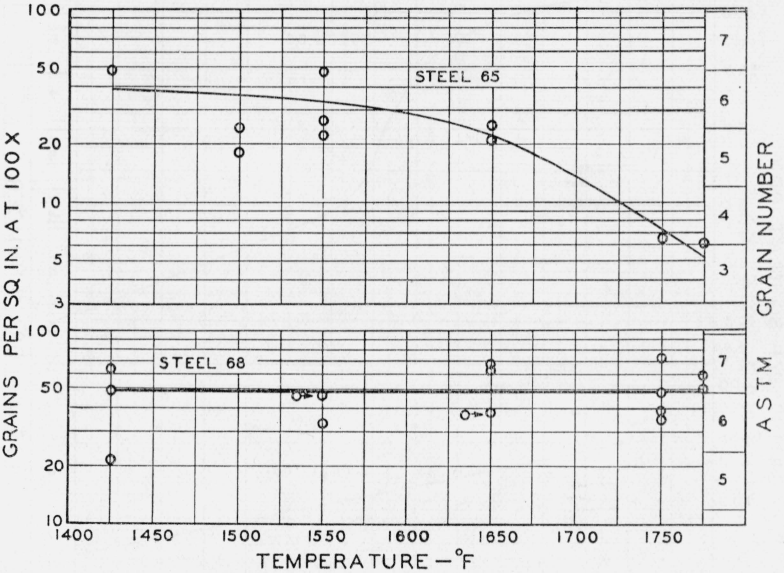

FIGURE 6.—*Relation of austenitic grain size to temperature for steels 65 and 68 with an initial structure of coarse lamellar pearlite.*

At the highest temperatures at which measurements were made, namely, 1,750 to 1,775° F, each steel developed a rather characteristic grain size which was independent of the initial structural condition. In this temperature range, the controlled steel had a grain-size number of 6 to 7 and the noncontrolled steel of 3 to 4. The grain size versus temperature curves separate into two characteristic groups only at temperatures above 1,600° F, that is, above the

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[12] Zay Jefferies, Am. Soc., Testing Materials, Stds. pt. 1, 902 (note 2) (1933).

temperature of the A_{cm} line and in the range in which all cementite is presumably in solution in the austenite. At temperatures from 1,425 to 1,600° F, the range in which the structure consists of austenite and cementite, the grain size is noticeably dependent on the initial structure as well as on the temperature. The noncontrolled steel 65, which is characteristically coarse grained at 1,750° F, had a very fine grain at 1,425° F, if its initial structure prior to heating was either spheroidized or sorbitic. Each steel, with an initially spheroidized or sorbitic structure, had a smaller grain size at 1,425° F than did the same steel with an initial coarse pearlitic structure. The two steels possessed austenitic grain sizes of the same order of magnitude at 1,425° F if they had similar initial structures. In two cases sharp inflections occurred in the grain-size-temperature curves, in the temperature range 1,550 to 1,600° F. These inflections evidently indicated the completion of the solution of the separate carbide phase.

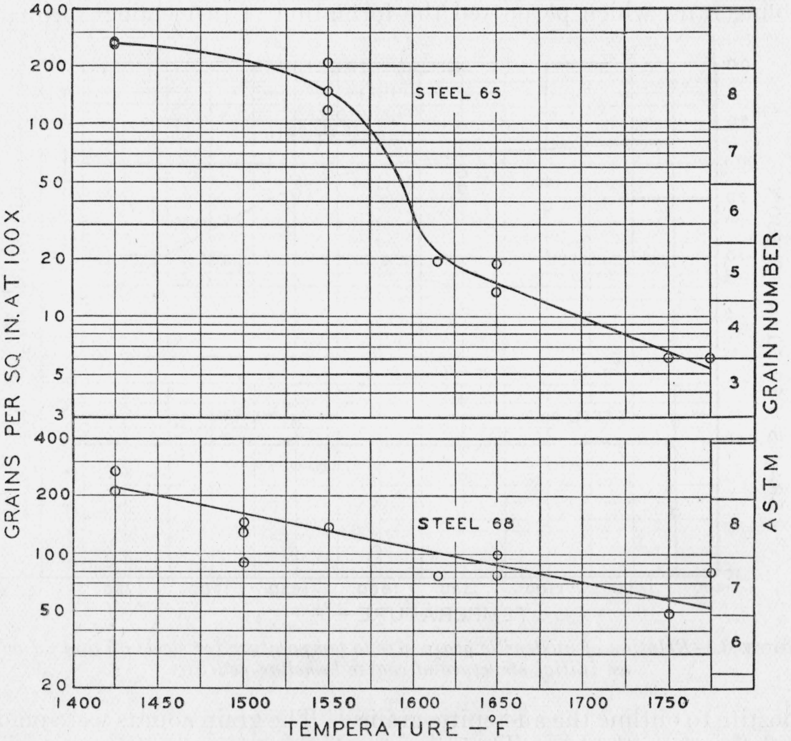

FIGURE 7.—*Relation of austenitic grain size to temperature for steels 65 and 68 with an initial structure of sorbite.*

These results are consistent with the hypothesis that the greater the degree of subdivision of cementite the smaller the austenitic grain size on heating into the temperature range just above the eutectoid temperature. At 1,425° F in both steels the smallest grain was obtained from the initial sorbitic structure, a slightly larger grain from the spheroidized structure and a relatively coarse grain from the coarse lamellar pearlitic structure. Because each steel ultimately reached a definite characteristic grain size at the maximum temperature, as is shown in figure 8, it follows that, for a given steel, the initial (prehardening) structure which results in the smallest austenitic grain size (e. g., at 1,425° F) also undergoes the greatest grain growth at the higher temperatures. Whether this subsequent growth takes place steadily and progressively with increasing temperatures or occurs as a more rapid growth over a restricted range of temperature does not appear to be determined by the initial structure. Thus, in the noncontrolled steel (65) rapid growth over a restricted temperature range occurred only in the specimens where initial structure was sorbitic. A similar rapid growth over a small range of temperature occurred only in the spheroidized samples of the controlled steel (68).

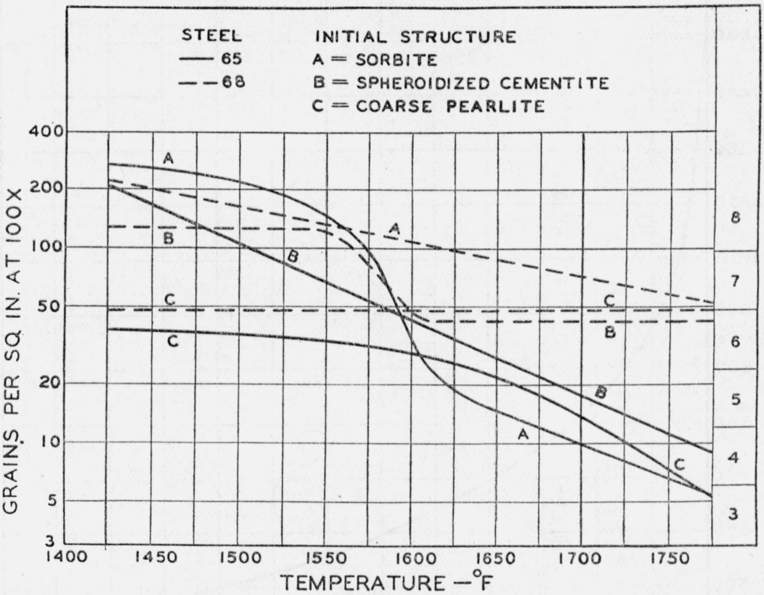

FIGURE 8.—*Relation of austenitic grain size to temperature for steels 65 and 68 with different initial structures.*

3. CRITICAL COOLING RATES

The critical cooling rates were determined for specimens representing the entire range of austenitic grain sizes developed in each steel from each of the three initial structures. The critical cooling rate was taken as the average cooling rate between 1,110 and 930° F when the structure of the quenched specimen was martensite containing nodular troostite in proportions estimated to be between 1 and 3 percent. The specimens for the determinations of the critical cooling rates were of the same shape and size as those used for the determination of the grain size and were heated in the same manner, held for the same time at the temperature establishing the austenitic grain size, and were then quenched directly from that temperature into a suitable quenching medium contained in a bath which sealed the bottom end of the vertical tube of the heating furnace. A photographic time-temperature curve was obtained during the quench in the manner previously described by French and Klopsch.[13] Examination of the microstructure of the quenched specimens was made on a cross-section of the 0.040-inch-thick sheet near the point of contact of the thermocouple wires. A typical time-temperature cooling curve plotted from the data obtained from a photographic record is shown in figure 9.

The relations between the time required to cool from 1,110 to 930° F and the quenching temperature (which was also the temperature establishing the austenitic grain size) for the initially spheroidized specimens of steels 65 and 68 are shown in figures 10 and 11, respectively, for the initially coarse pearlitic specimens in figures 12 and 13, respectively, and for the initially sorbitic specimens in figures 14 and 15, respectively. The estimated amounts of nodular troostite formed with the various quenching rates are also shown on the charts and the curves represent the relation of the critical cooling time to the quenching temperature values.

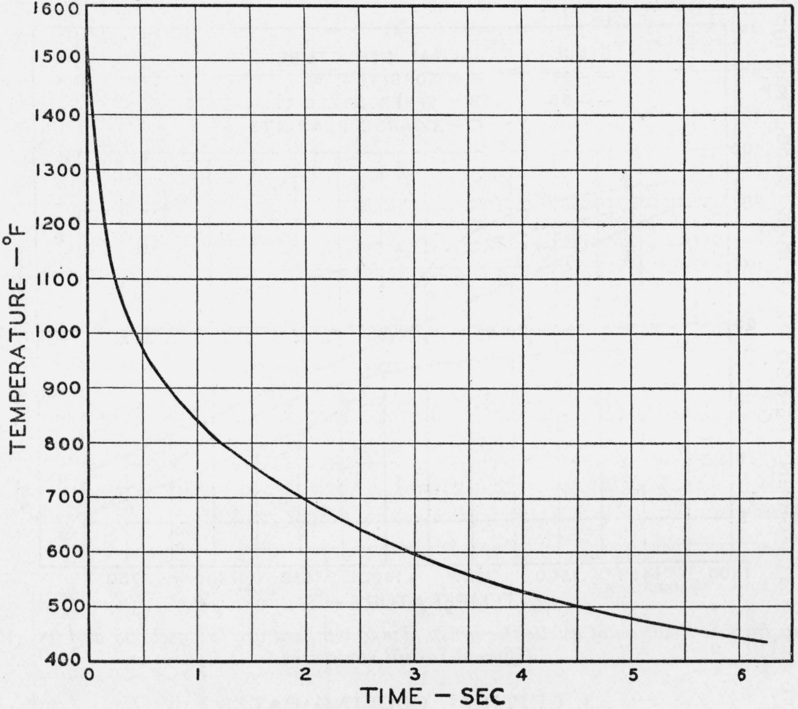

FIGURE 9.—*Time-temperature cooling curve for a ¼-inch square by 0.040-inch thick specimen quenched from 1,550° F.*

Data derived from a photographic record of the string galvanometer.

For the purpose of convenient comparison, the critical cooling rate versus quenching temperature curves for all three initial structural conditions of each steel are summarized in figure 16.

When quenched from 1,425° F, the critical cooling rates for the two steels were approximately the same whether the initial structures were sorbitic or spheroidized, that is, the steels hardened with equal

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[13] H. J. French and O. Z. Klopsch, Trans. Am. Soc. Steel Treating **6,** 251–294 (1924).

facility. The critical cooling rates for the two steels were also the same when the initial structure was coarse pearlite, but this rate was much lower than that of the initially sorbitic or spheroidized steels. With quenching temperatures in the lower range—1,425 to about 1,600° F—the critical cooling rate for either steel is clearly influenced by the initial structure. Above 1,600° F the curves separate into two

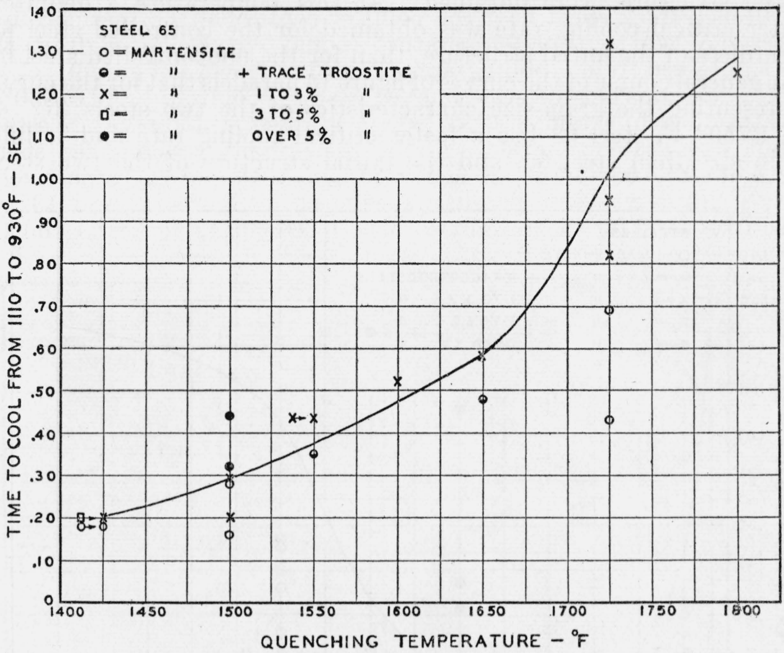

FIGURE 10.—*Time required for steel 65, with an initial structure of spheroidized cementite, to cool from 1,110 to 930° F, when quenched from different temperatures.*

The specimens were ¼ inch square by 0.040 inch thick.

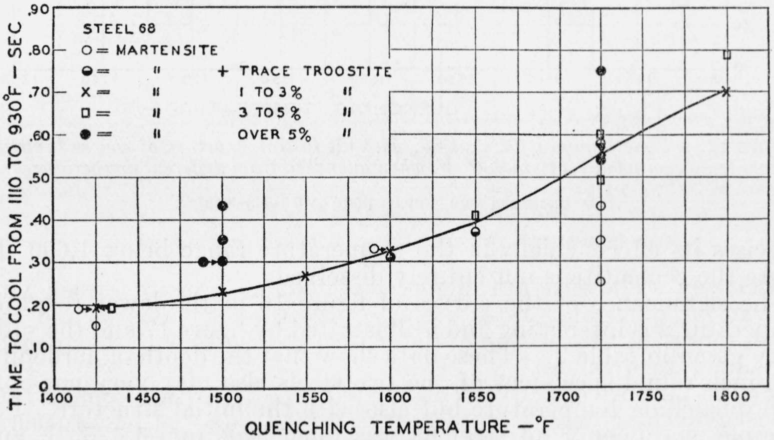

FIGURE 11.—*Time required for steel 68, with an initial structure of spheroidized cementite, to cool from 1,110 to 930° F, when quenched from different temperatures.*

The specimens were ¼ inch square by 0.040 inch thick.

groups (one for each steel). At 1,725 to 1,750° F, critical cooling rates, which appear to be characteristic of the steels irrespective of their initial structure, were obtained. At this temperature a definitely faster critical cooling rate was obtained for the controlled steel 68, regardless of the initial structure, than for the noncontrolled steel 65. The general course of the curves of figure 16 parallels that for the curves representing the grain-size characteristics of the two steels (fig. 8). At 1,750° F, steel 68 has a faster critical cooling rate and a finer grain size than steel 65, and the initial structure of the two steels exercises its effects chiefly in the temperature range below 1,600° F, where the cementite is not entirely dissolved.

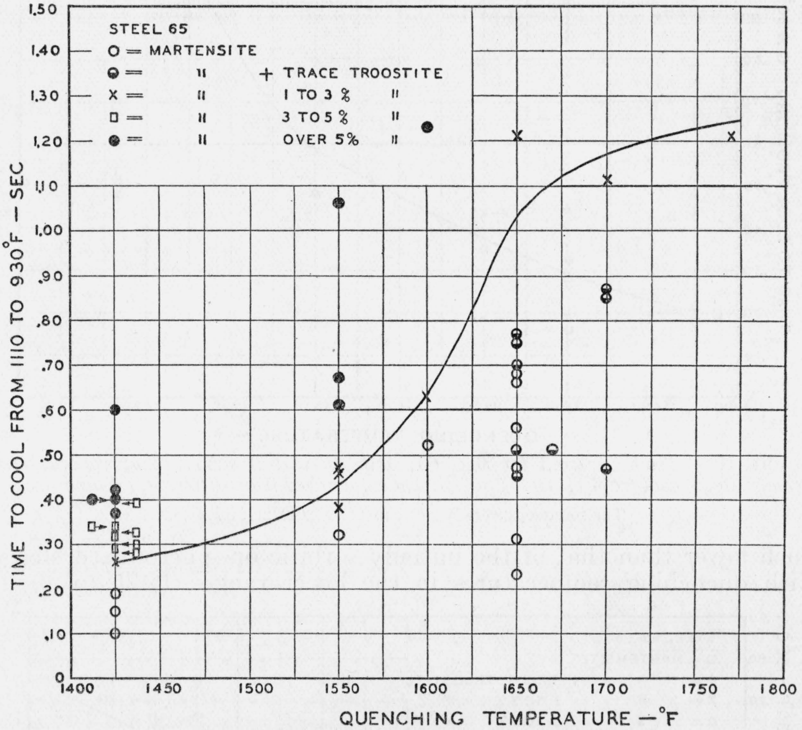

Figure 12.—*Time required for steel 65, with an initial structure of coarse lamellar pearlite, to cool from 1,110 to 930° F, when quenched from different temperatures.*

The specimens were ¼ inch square by 0.040 inch thick.

The significance of the curves of figure 16 in the lower range of temperatures is interesting and is illustrated by figure 17 and the summary given in table 2. These data show that the depth of hardening of ¾-inch round specimens of the two steels also may vary not only with quenching temperature but also with the initial structure. For example, specimen E of steel 65 was quenched from 1,425° F and specimen F of the same steel was quenched from 1,500° F. A higher quenching temperature normally results in deeper hardening, especially in a noncontrolled steel such as steel 65. It is obvious from figure 17, however, that specimen F has hardened less deeply than specimen E. This difference is due to the different initial structure of the specimens, E having initially a coarse pearlitic structure, and F a sorbitic structure. Figure 16 shows that a critical cooling rate of 900° F per second is obtained for specimen F quenched from 1,500° F, while a critical rate of approximately 700° F per second is obtained for specimen E quenched from 1,425° F. Obviously, there is a correlation between depths of hardening of specimens of similar size and shape and critical cooling rates, the lower rates corresponding to the deeper-hardening, and the curves of figure 16 may be used as an index of the relative depths of hardening. As shown in table 2 and figure 17, a relatively slow critical cooling rate (less than 500° F/sec) was required to harden completely the ¾-inch round specimens. Furthermore, the depth of hardening was not materially influenced by variations in initial structures consisting essentially of lamellar pearlite, or spheroidized cementite, or martensite and troostite.

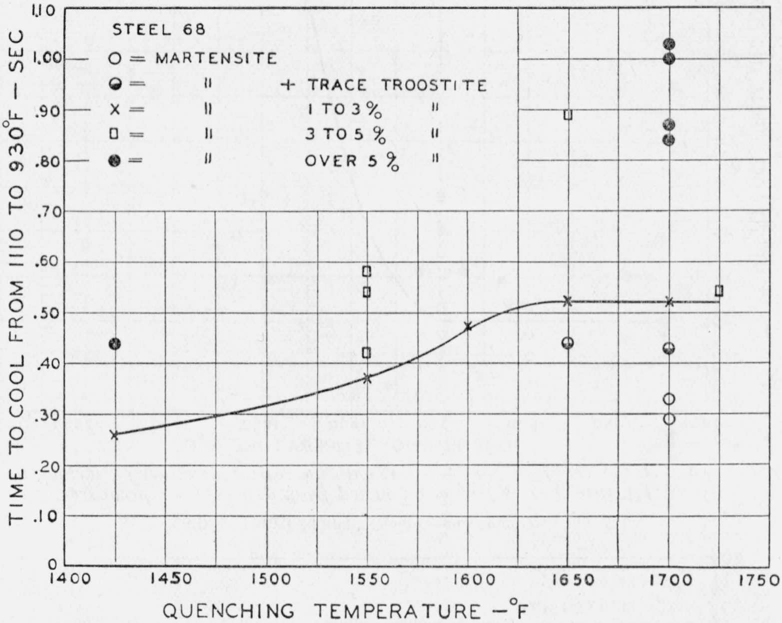

FIGURE 13.—*Time required for steel 68, with an initial structure of coarse lamellar pearlite, to cool from 1,110 to 930° F, when quenched from different temperatures.*

The specimens were ¼ inch square by 0.040 inch thick.

The curves of figure 16 for the spheroidized initial structure of the two steels simply reflect the basis upon which the two steels were selected, namely, that with this initial structure the steels have the same depth of hardening on quenching from 1,425° F, but very different depths of hardening on quenching from 1,550° F, steel 65 being the deeper-hardening steel. With this in mind, the significance of initial structure is well illustrated by the fact that steel 68 with an

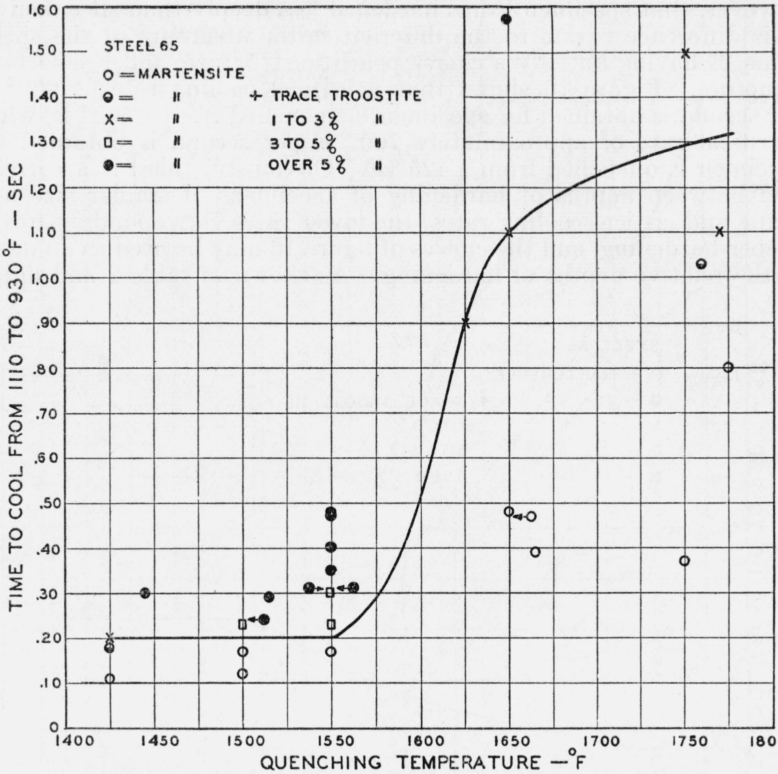

FIGURE 14.—*Time required for steel 65, with an initial structure of sorbite, to cool from 1,110 to 930° F, when quenched from different temperatures.*

The specimens were ¼ inch square by 0.040 inch thick.

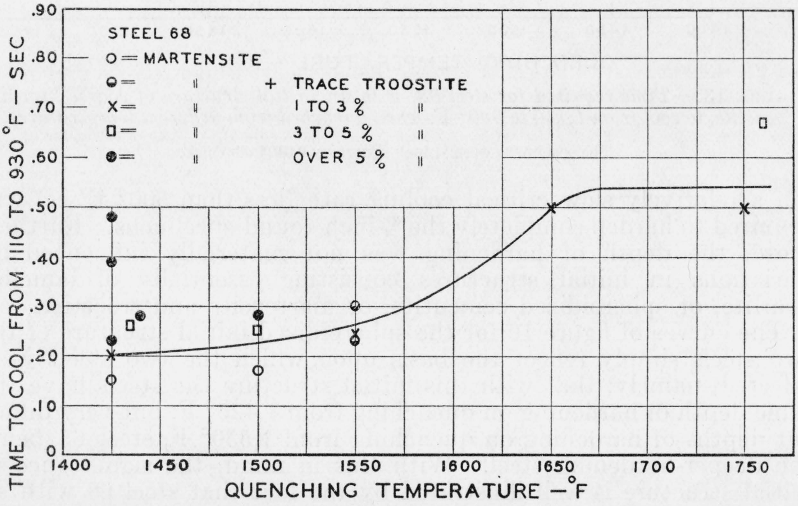

FIGURE 15.—*Time required for steel 68, with an initial structure of sorbite, to cool from 1,110 to 930° F, when quenched from different temperatures.*

The specimens were ¼ inch square by 0.040 inch thick.

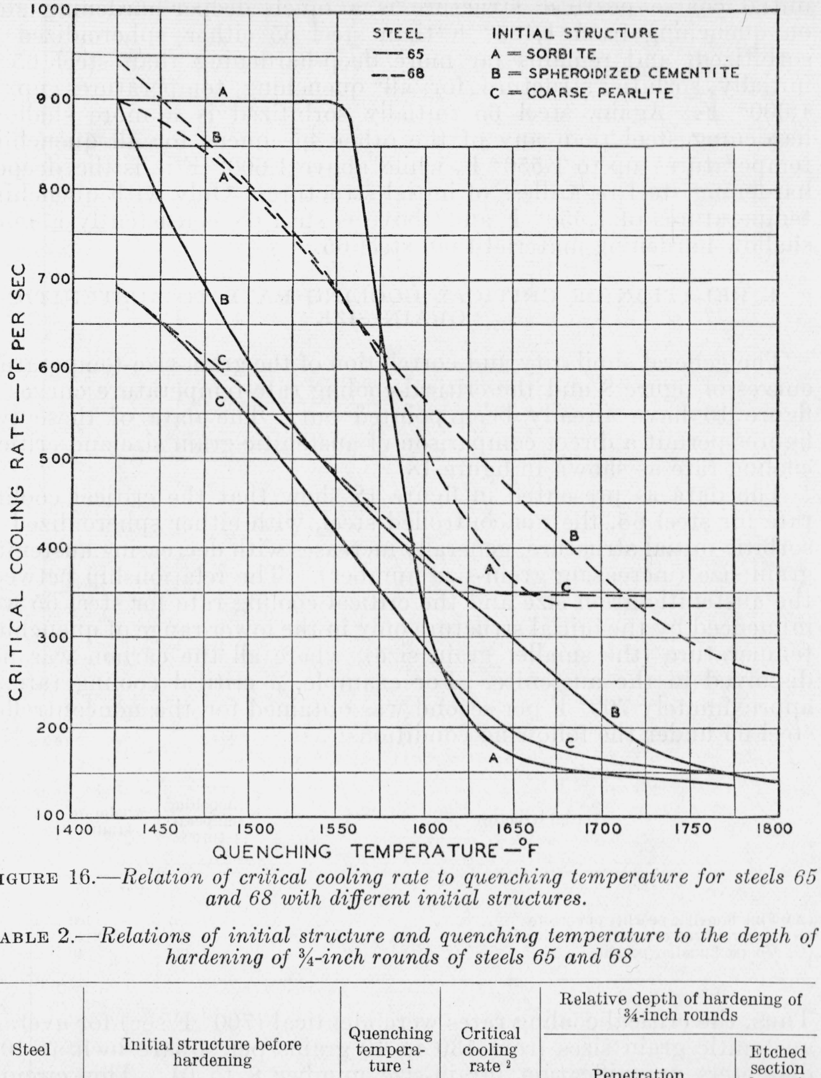

FIGURE 16.—*Relation of critical cooling rate to quenching temperature for steels 65 and 68 with different initial structures.*

TABLE 2.—*Relations of initial structure and quenching temperature to the depth of hardening of ¾-inch rounds of steels 65 and 68*

Steel	Initial structure before hardening	Quenching temperature[1]	Critical cooling rate[2]	Relative depth of hardening of ¾-inch rounds	
				Penetration	Etched section shown in fig. 17
		°F	°F/sec		
65	Spheroidized cementite	1,425	900	Shallow	A
65	do	1,550	480	Deep	B
65	Lamellar pearlite	1,425	(3)	Shallow	C
65	do	1,550	(3)	Deep	D
65	Coarse lamellar pearlite	1,425	700	Intermediate	E
65	Sorbite	1,500	900	Shallow	F
65	Martensite and troostite	1,550	(3)	Deep	G
68	do	1,550	(3)	Shallow	H
68	Spheroidized cementite	1,425	950	do	I
68	do	1,550	700	Intermediate	J
68	Lamellar pearlite	1,425	(3)	Shallow	K
68	do	1,550	(3)	Intermediate	L
68	Coarse lamellar pearlite	1,425	700	Shallow	M
68	do	1,550	480	Deep	N
68	Sorbite	1,425	900	Shallow	O
68	do	1,550	700	Intermediate	P

[1] Heated for 35 minutes, quenched in brine. [2] Data from fig. 16. [3] Not determined.

initial coarse pearlitic structure is a much deeper-hardening steel on quenching from 1,425° F than steel 65 either spheroidized or sorbitized, and remains far more deep-hardening than steel 65 of initially sorbitic structure for all quenching temperatures up to 1,600° F. Again, steel 65 initially sorbitized is a more shallow-hardening steel than any of the other specimens for all quenching temperatures up to 1,550° F, while above 1,600° F it is the deeper-hardening steel regardless of initial structure. Only with quenching temperatures of 1,650° F and above is steel 68 consistently a more shallow-hardening material than steel 65.

4. RELATION OF CRITICAL COOLING RATE TO AUSTENITIC GRAIN SIZE

The general similarity and correlation of the grain-size-temperature curves of figure 8 and the critical-cooling rate-temperature curves of figure 16 have already been pointed out. The data of these two figures permit a direct comparison of austenitic grain size and critical cooling rate as shown in figure 18.

The data as presented in figure 18 show that the critical cooling rate for steel 65, the noncontrolled steel, with either spheroidized or sorbitic initial structure, generally increases with decreasing austenitic grain size (increasing grain-size number). The relationship between the austenitic grain size and the critical cooling rate for steel 65 was influenced by the initial structure only in the lower range of quenching temperature (the smaller grain size), where all the carbon was not dissolved in the austenite. For example, a critical cooling rate of approximately 700° F per second was obtained for the noncontrolled steel 65 under the following conditions:

Initial structure	Quenching temperature	Austenite grains	ASTM grain no.
	°F	Per sq in. at×100	
(A) Fine lamellar pearlite or sorbite	1, 570	100	8
(B) Spheroidized cementite	1, 475	130	8
(C) Coarse lamellar pearlite	1, 425	40	6

Thus, the critical cooling rates were identical (700° F/sec) for average austenitic grain sizes from 130 to 40 grains per square inch at 100-diameters magnification (grain-size number 8 to 6). This circumstance is probably attributable to differences in the amount and distribution of carbon in the austenite. Considering the recognized effect of grain size alone, a lower critical cooling rate might be anticipated for the specimen containing 40 austenitic grains per square inch at 100-diameters magnification than for specimens of the same steel having 100 or 130 grains per square inch at 100-diameters magnification. When the specimen of initially coarse pearlitic structure is heated to 1,425° F it is a relatively short distance above the eutectoid temperature; a limited proportion of the cementite goes into solution; a considerable number of free cementite particles remain within the austenite grains and a network of cementite outlines the grains (fig. 19, C). Both the relatively low carbon content of the austenite and

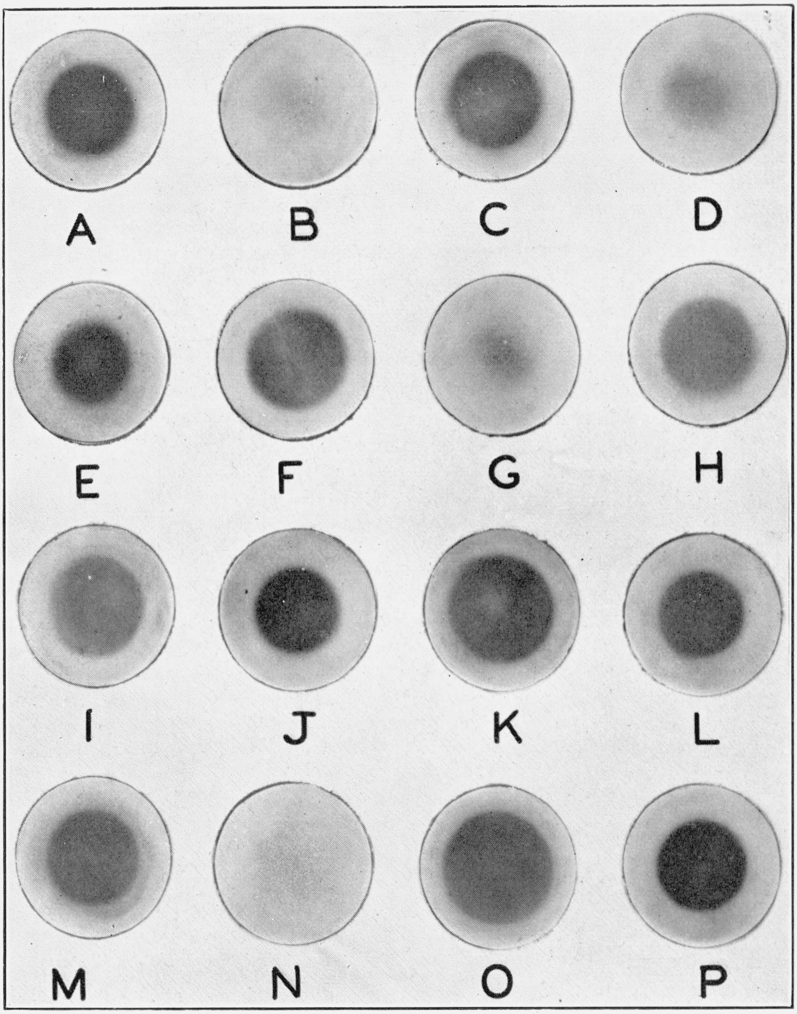

FIGURE 17.—*Relative depth of hardening of three-quarter-inch rounds of steels 65 and 68, with different initial structures, quenched from different temperatures.*

Refer to table 2 for the initial structures (before hardening) and quenching temperatures used. The prepared cross sections were etched in 1 percent nitric acid in alcohol to darken the unhardened portions.

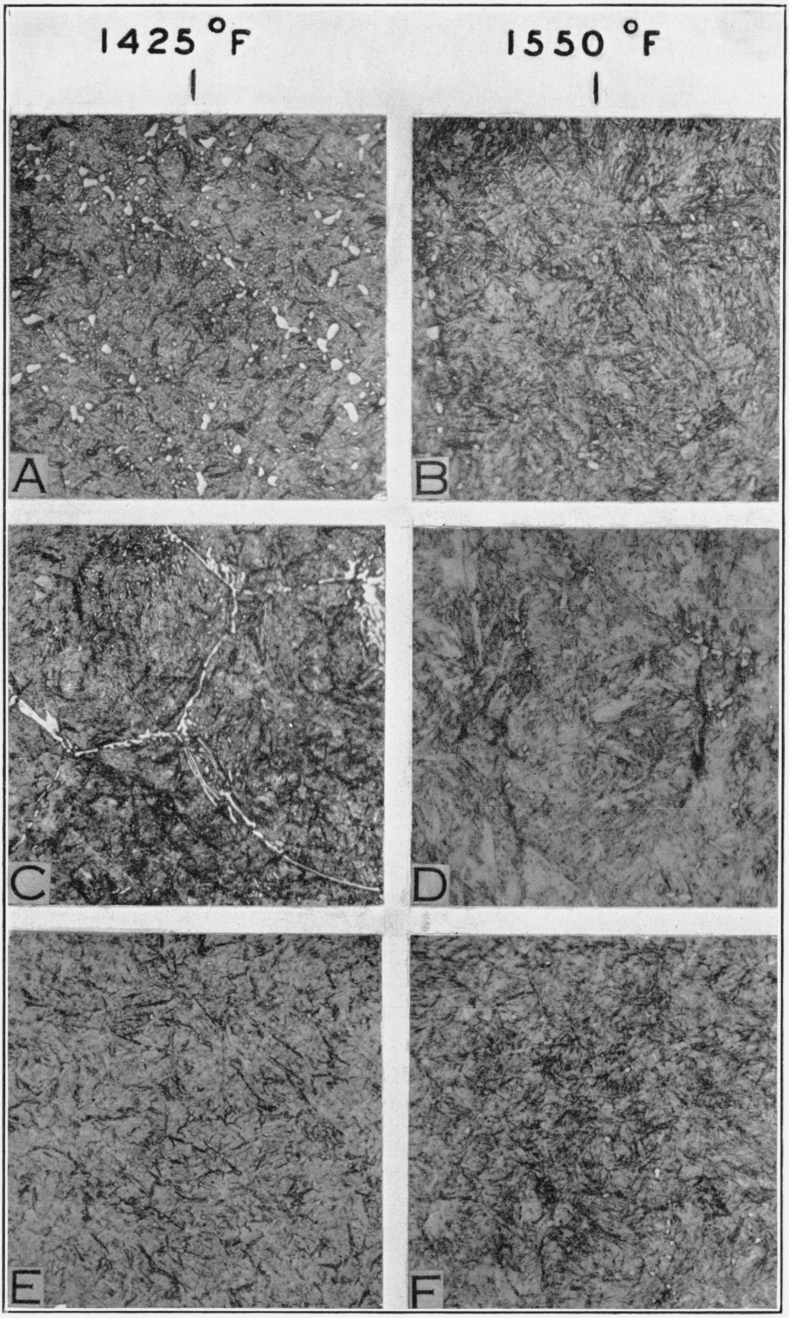

Figure 19.—*Effects produced by the initial structure on the free carbides remaining in specimens of steel 65 quenched from 1,425° or 1,550°F.*

A and *B*, Initial structure of spheroidized cementite; *C* and *D*, initial structure of coarse lamellar pearlite *E* and *F*, initial structure of sorbite. Etched with 1 per cent nitric acid in alcohol, × 500.

the presence of a considerable number of free cementite particles within the grain, which supply nuclei for austenite decomposition in the Ar′ temperature range, act to increase the critical cooling rate and oppose the effect of the relatively large grain, which decreases the critical cooling rate. The resultant rate thus becomes the same as that of the much finer-grained specimen heated from an initial sorbitic structure to 1,570° F, where the carbon content of the austenite is higher than in the coarse pearlitic specimen just described and where less free cementite remains (fig. 19, F).

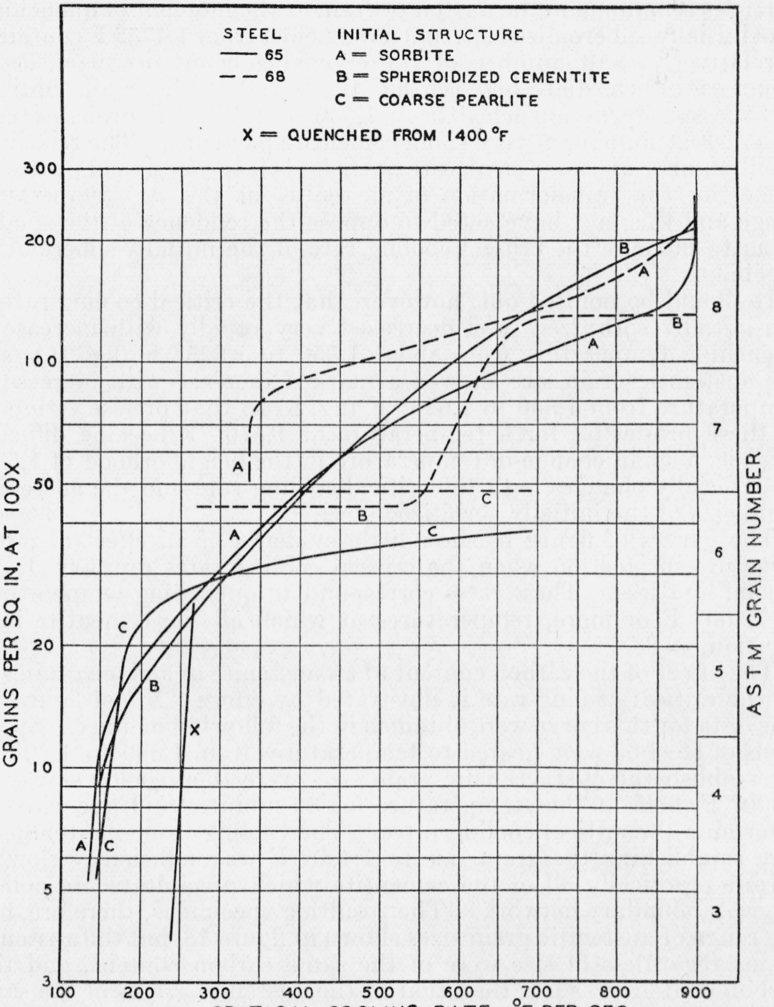

FIGURE 18.—*Relation of austenitic grain size to critical cooling rate for steels 65 and 68 with different initial structures.*

The initially spheroidized specimen of steel 65 has a grain size at 1,475° F slightly smaller than the initially sorbitic specimen at

1,570° F, and would be expected to give a relatively higher critical cooling rate. This specimen also should have an austenite of somewhat lower carbon content, tending to increase further the critical cooling rate. Yet actually the observed rate was again 700° F per second. The factor which probably offsets any such tendency to increase the critical rate is a difference in the number of free cementite particles remaining in the austenite grain at the moment of quenching. The initially spheroidized specimen quenched from 1,475° F contained a relatively small number of rather coarse cementite particles (a structure intermediate between fig. 19, A and 19, B), while initially sorbitic specimens quenched from 1,550 to 1,570 ° F probably contain a great number of very small cementite particles. The relatively small number of coarse cementite particles is less effective in providing nuclei for the transformation of austenite, in the Ar′ temperature range and this may have acted to oppose the tendency of the smaller grain to increase the critical cooling rate of the initially spheroidized specimen.

It should be pointed out, however, that the critical cooling rate of the initially sorbitized steel decreased very rapidly with increase in quenching temperature from about 1,550 to 1,625° F (fig. 16), and the austenitic grain size showed a marked increase with increase in temperature from 1,550 to 1,625° F (fig. 8) so that precise estimates of these properties for a temperature of 1,570° F became difficult. That is, a small change in temperature in the neighborhood of 1,570° F materially changes both the critical cooling rate and the austenitic grain size of the initially sorbitized steel.

The curves of figure 18 show little evidence of an effect of initial structure in steel 65 when the critical cooling rates are 300° F per second and less. These rates correspond to quenching temperatures of 1,600° F or more, temperatures at which all the cementite is in solution.

The effect of the carbon content of an austenite of a given grain size on the critical cooling rate is illustrated by curve "X" of figure 18. The data for this curve were obtained in the following manner: Specimens of steel 65 were heated to temperatures from 1,600 to 1,800° F to establish the characteristic grain size, were then cooled slowly to 1,400° F, held at that temperature for 30 minutes and quenched to determine the critical cooling rates. The cooling from the temperature establishing the grain size to 1,400° F was sufficiently slow to permit practically all of the cementite which precipitated to collect as grain boundary network. The resulting specimens, therefore, had the range of austenitic grain sizes shown in figure 18, but the austenite grains regardless of size were of the same carbon content, and this carbon content was less than that of the austenite grains of the same size quenched directly from the grain coarsening temperatures. The increase of the critical cooling rate for a given size of austenite grain caused by a lower carbon content of the austenite is very marked.

As has already been shown in figures 8 and 16, both austenitic grain sizes and critical cooling rates for temperatures between 1,425 and 1,775° F cover appreciably narrower ranges for the controlled steel 68 than for the noncontrolled steel 65. Steel 68 with an initial structure of coarse pearlite covers a range of critical cooling rates from 700 to 350° F/sec with no change in austenitic grain size. This holds true not only for the range of quenching temperatures below the A_{cm} temperature, where differences in the amount and uniformity of distribution of carbon dissolved in the austenite may effect changes in critical cooling rates, but also is true for quenching temperatures considerably above the A_{cm} temperature, where such effects of carbon from cementite should be absent. In this higher range of quenching temperature, if the grain size is constant and the effect of the amount and distribution of carbon from cementite is absent, changes in critical cooling rates must be dependent on some other factor, probably the nucleation effects of the oxides or carbides which are commonly considered to be the influencing elements in controlling austenitic grain sizes.

Similarly, the specimens of steel 68 with an initial structure of spheroidized cementite show pronounced changes in critical cooling rates with no change in austenitic grain size for ranges of quenching temperatures both above and below the A_{cm} temperature (quenching temperatures corresponding to low and high critical cooling rates, respectively). In the lower range of quenching temperatures the grain size is uniformly small; in the higher range, uniformly large. Between these two temperature ranges, however, the critical cooling rate does change with grain size. The wide range of cooling rates for the specimens with an initial sorbitic structure, in spite of the relatively slight change in grain size, may be tentatively explained in a similar manner.

Since the grain size is constant and no effect is to be expected from carbon content, the continued change of critical cooling rates above the A_{cm} temperature may be an indication that oxide and carbide constituents which control grain size themselves undergo modification as the quenching temperature is increased. Such modifications are in the direction of decreasing the effectiveness of such particles as nucleation centers for austenite decomposition, as evidenced by the fact that the critical cooling rates become progressively lower.

5. RATE OF HEATING TO HARDENING TEMPERATURES

Initially spheroidized, ¾-inch round specimens of steels 65 and 68 were heated at different rates to 1,425 and 1,550° F, held at temperature for 35 minutes, and subsequently quenched in brine. Depth of hardening was determined by etching a section of the quenched specimen to show the hardness penetration.

The time required for the center of ¾-inch round specimens of 1-percent-carbon tool steel to reach the desired temperatures with the different methods of heating was as follows:

Heating medium	Approximate time required for center of ¾-inch round to reach 1,425 or 1,550° F.
	Minutes
Lead bath	1 to 1½
Salt bath	3 to 4
Electric furnace	10 to 13

The rates of heating used had no significant influence on the depth of hardening of the two steels. Both steels again had similar depths of hardening on quenching from 1,425° F in brine (fig. 1), but quite different hardness penetration on quenching from 1,550° F.

6. RATE OF SPHEROIDIZATION OF CEMENTITE

Specimens of steels 65 and 68, with initial structures consisting essentially of lamellar pearlite, were pack-annealed at 1,300° F for ¼, ¾, 1, 1½, 3, 5, 17, 24, and 48 hours, respectively. Similar specimens were also pack-annealed at 1,340° F for ¾ and 5 hours, respectively. As judged from a microscopical examination of the annealed specimens, there was no marked difference in the rate of spheroidization of the two steels.

7. STRUCTURAL NORMALITY OR ABNORMALITY

Initially spheroidized specimens of steels 65 and 68 were packed in a commercial carburizing mixture and heated with the furnace to 1,725° F, held at that temperature for 8 hours and furnace-cooled. Similar specimens were also packed in sand containing a small amount of charcoal and heated in the furnace together with the above specimens.

Steel 65 had a normal structure after each treatment as evidenced by the continuity of the pearlite grains bounded by a thin layer of cementite, while steel 68 was probably more abnormal than normal, as shown by a lack of perfection of the crystallization of the pearlite.

8. PERFORMANCE AS LATHE TOOLS

Lathe tests were made with ¼- by ½-inch tools of steels 65 and 68 which were quenched in brine from different temperatures, namely, 1,425 and 1,550° F, and tempered at 300° F. The lathe tests were made under heavy duty or roughing conditions on a 3½-percent-nickel-steel forging.

TABLE 3.—*Summary of heat treatment of tools and lathe tests made with steels 65 and 68* [a]

Steel	Quenching [b] temperature	Cutting speed	Tool life (minutes)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Average
	°F	Ft/min							
68	1,425	11	12.6	30.2	14.0	[c] (48)	[c] (48)	35.5	31.4
65	1,425	11	10.8	8.0	8.4	18.5	[c] (48)	[c] (48)	23.6
68	1,550	11	9.7	[c] (48)	7.7	[c] (48)	6.0	5.8	20.9
65	1,550	11	[c] (48)	27.2	7.1	5.1	[c] (48)	14.0	24.9
68	1,425	12	6.3	11.2	32.1	26.6	14.4	1.8	15.5
65	1,425	12	5.9	5.2	10.3	4.7	3.7	5.0	5.8
68	1,550	12	5.4	13.6	5.7	6.6	10.0	5.2	7.8
65	1,550	12	4.6	3.8	.8	6.8	23.2	3.3	7.1

[a] The lathe tests were made "dry" with a feed of 0.028 inch/rev and 3/16-inch depth of cut on annealed 3½-percent nickel (SAE 2340) steel with a tensile strength of approximately 88,000 lb/in^2. The tools were ¼ by ½ inch, with 6° front and side clearance, 8° back slope, 14° side slope and ⅛-inch nose radius.

[b] Initially annealed to produce spheroidized cementite. Quenched in brine; tempered 1 hour at 300° F, air-cooled.

[c] Test stopped after 48 minutes, tool did not fail.

The heat treatments of tools and details of the lathe tests are summarized in table 3. The results show that the tools of steel 68 ("shallow-hardening") quenched from the usual range of hardening temperature had a somewhat greater average life than those of similarly treated tools of steel 65 ("deep-hardening"). However, the average life of the tools of both steels quenched from 1,550° F was of the same order of magnitude. Furthermore, the variations used in the hardening treatments did not influence the performance of steel 65. No significant differences were, therefore, observed in the lathe tool performance of the two steels initially spheroidized, quenched and tempered, and tested under roughing conditions.

9. CHARPY IMPACT

Charpy impact tests were made on specimens of steels 65 and 68 which were subjected to different heat treatments. All of the specimens were prepared from ¾-inch round bars after a normalizing or annealing treatment and were notched and ground to a standard size before the hardening and tempering treatments.

The heat treatments used, and the Charpy impact values, are summarized in table 4. In the annealed or spheroidized condition (fig. 4, A and B) the impact strength of steel 65 was greater than that of steel 68, but in the normalized or lamellar pearlitic condition the strength of steel 68 was greater than that of steel 65. However, these differences were small as were the differences observed in the strengths of the two steels after similar hardening and tempering treatments.

TABLE 4.—*Summary of Charpy impact tests made on steels 65 and 68*

Steel	Heat treatment				Charpy impact
	Annealing temp [1]	Normalizing temp [2]	Quenching temp [3]	Tempering temp [4]	
	°F	°F	°F	°F	Ft-lb
65	1,425	None	None	None	4.5
68	1,425	do	do	do	3.0
65	None	1,575	do	do	2.3
68	Mill annealed [5]	1,575	do	do	3.0
65	1,425	None	1,425	do	0.6
65	1,425	do	1,425	350	0.9
65	1,425	do	1,425	680	2.6
65	1,425	do	1,550	None	0.5
65	1,425	do	1,550	350	0.5
65	1,425	do	1,550	680	0.5
68	Mill annealed [5]	do	1,425	None	0.7
68	do	do	1,425	350	1.2
68	do	do	1,425	680	3.6
68	do	do	1,550	None	0.6
68	do	do	1,550	350	0.7
68	do	do	1,550	680	1.5

[1] At temperature 2 hours.
[2] At temperature 1 hour.
[3] Heated in salt bath at temperatures as indicated for 20 minutes, quenched in brine.
[4] Heated in oil or nitrate bath at the temperatures as indicated for 1¼ hours, air-cooled.
[5] Spheroidized structure.

10. ROCKWELL HARDNESS AND SUSCEPTIBILITY TO GRINDING CRACKS

Initially spheroidized specimens approximately ½ inch square by 3 inches long of steels 65 and 68 were quenched from 1,425° F in brine and a similar series in water. The quenched specimens were used for the determination of Rockwell hardness and for grinding and etching tests.

The Rockwell hardness, grinding, and etching tests are summarized in table 5. When quenched from 1,425° F. in brine both steels had the same average surface hardness; namely, Rockwell C 67.5, and no soft spots were observed on the surfaces of the specimens. When quenched in water, the average value of the surface hardness of steel 65 was about a point higher than of steel 68 (Rockwell C 66.5 and 65.5, respectively) and the latter steel also had the higher index for soft spots. The steels as treated showed no difference in susceptibility to hardening or grinding cracks.

TABLE 5.—*Summary of Rockwell hardness, grinding, and etching tests made on steels 65 and 68*

Steel	Quenched [1] from 1,425°F into—	Rockwell hardness C [2]		Index for soft spots [5]	Grinding cracks [6]	Appearance after etching [7]
		Average [3]	Normal [4]			
65	Water	66.5	67.0	2	None	Slightly mottled area on 2 surfaces.
65	Brine	67.5	67.5	0	do	Clear.
68	Water	65.5	66.5	7	do	Small mottled area on 4 surfaces.
68	Brine	67.5	67.5	0	do	Clear.

[1] Specimens were first annealed, then machined and ground to approximately .515 by .520 by 3.0 inches. Heated in salt bath for 35 minutes for hardening.

[2] Rockwell hardness determinations were made on the four 0.5 -by 3-inch surfaces of each specimen after hardening and without grinding. Ten readings regularly spaced, were made on each of these surfaces.

[3] Average of all 40 readings.

[4] Average of readings of 60 or more.

[5] Rockwell readings below 60 were taken as an indication of softness and were given the following weights: 60 to 55=1; 55 to 50=2; 50 to 45=3; below 45=4.

[6] Ground dry with cuts 0.001 inch deep; 4 cuts made.

[7] Etched, after grinding, in hot aqueous HCl (1:1; 160° F), for 20 minutes.

V. SUMMARY

Two commercial 1-percent-carbon tool steels were selected, on the basis of widely different hardening characteristics, for a detailed study of the relation of the initial structure, prior to heating for hardening, on the austenitic grain size and grain growth. Comparisons of the steels were also made with respect to their behavior in the transformation temperature range during thermal analysis, relative rates of spheroidization of the cementite, Charpy impact strengths, relative susceptibility to grinding cracks, Rockwell hardness values on quenching at different rates, structural normality, performance as lathe tools, and the effect of rate of heating to the hardening temperatures on the depth of hardening.

Measurements of austenitic grain size were made and critical cooling rates were determined for the temperature range from 1,425 to 1,775° F. The data thus secured permitted the derivation of grain size critical cooling rate relations throughout this range of temperature.

For quenching temperatures below that at which all the carbon is completely dissolved in the austenite, both the austenitic grain size and critical cooling rates are influenced to a large degree by the initial structure of the steels. Above this temperature, each steel approached both a grain size and a critical cooling rate which was characteristic of the steel regardless of its initial structure. At the highest temperature, namely, 1,775° F, the characteristic grain size was smaller and the characteristic critical cooling rate was higher for the steel known to have been made under conditions producing so-called "controlled steel." The effect of grain size on the critical cooling rates was marked in the "noncontrolled" steel throughout the entire range of quenching temperatures. The influence of the initial structure was also evident at the lower quenching temperatures. The critical cooling rate of the controlled steel, however, may change very appreciably with little or no change in austenitic grain size. At the lower quenching temperatures, differences in carbon content and carbon distribution in the austenite may be the controlling factor, but at higher temperatures oxides or carbides introduced for grain control are probably the effective factors in changing the critical cooling rate.

The initial structure of the controlled steel exerts an influence on the grain size-critical cooling rate relations at both low and high quenching temperatures.

A few determinations made on a noncontrolled steel indicated that the critical cooling rate of this steel with austenitic grains containing carbon above eutectoid composition is lower than that for the same steel with grains of the same size containing about eutectoid proportions of carbon.

The differences observed in the transformation of the two steels on slowly heating to the temperature range of austenite are believed to be caused by a variation in the rates of carbon diffusion, the controlled steel having a higher rate than the noncontrolled steel.

The controlled steel was more abnormal in structure than the noncontrolled steel on slowly cooling from the austenite temperature range.

Variations in rates of heating to the hardening temperatures did not influence the depth of hardening of the two steels.

No marked differences were observed in the behavior of the two steels with respect to their tool performance in la the cutting, Charpy impact values, and Rockwell hardness values, and susceptibility to grinding cracks.

WASHINGTON, August 27, 1935.