EFFECT OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF 1 PER CENT CARBON STEEL

By H. J. French and W. George Johnson

ABSTRACT

The effects of varying time-temperature relations in heat treatment on tensile and impact properties, hardness, and structure of 1 per cent carbon steel have been studied, including (*a*) effect of temperature variations in hardening, (*b*) time at hardening temperatures both above A_{cm} and between the Ac_1 and A_{cm} transformations, (*c*) effects of tempering steel hardened in different ways and effects of "soaking" just under the lower critical range, (*d*) comparison of oil and water hardening for production of definite strengths.

CONTENTS

I. INTRODUCTION

During 1920 there was brought to the attention of one of the authors the lack of adequate information in the literature regarding the most suitable heat treatments for production of the best combinations of strength and ductility for 1 per cent carbon steel. While considerable data are available relating to tensile properties of high-carbon alloys, it was not possible to make satisfactory comparisons between the results reported by various investigators as to the effectiveness of different treatments for the purpose in view, due to differences in chemical composition, size of specimens treated, and other factors.

Because of the varied applications of slightly supersaturated carbon steels, including tools, dies, bearings, and springs, tests were made to correlate properties and structure and determine the magnitude of the effects observed with varying time-temperature relations in certain heat-treatment operations. At the same time treatments resulting in the best tensile and impact properties were sought.

II. PREVIOUS INVESTIGATIONS

Among the tests previously reported the following are considered of particular interest in the treatment of 1 per cent carbon steel or deal with variables studied by the authors.

1. ANNEALING

Sargent[1] found greatly increased strength with increase in annealing temperatures above the critical range and a maximum when cooled from 1025° C (1877° F), which was decreased about 38 per cent when the temperature was raised to 1150° C (2102° F). Maximum ductility was obtained in slow cooling from the upper end of the critical range, while temperatures even moderately above this reduced the elongation and reduction of area to very low values. The accompanying microstructural changes were marked, and it was found that after annealing at 915° C (1679° F) the cementite surrounding grains of pearlite had all left the boundaries and "gone toward binding groups of pearlite crystals into larger compound crystals."

Campbell[2] also studied the annealing of 1 per cent carbon steel and found that maximum strength was produced after slow cooling from 905° C (1661° F), while the highest ductility and lowest strength was obtained when using 760° C (1400° F), which is slightly above or at the end of the Ac_1 transformation. In general, the inflections in curves for strength and elastic limit

[1] George W. Sargent, "A study of the effect of heat treatment on crucible steel containing 1 per cent carbon," Trans. A. I. M. E., p. 303; 1901.

[2] William Campbell, "On the heat treatment of some high carbon steels," Proc. Amer. Soc. Test. Mats., p. 211; 1906.

were accompanied by the reverse inflections in curves for elongation and reduction of area, showing that an increase in one set was obtained at the expense of the other.

Both Sargent's and Campbell's results are shown graphically in Fig. 1, while in Table 1 are given results of tests included in the Sixth Report to the Alloys Research Committee[3] for steel con-

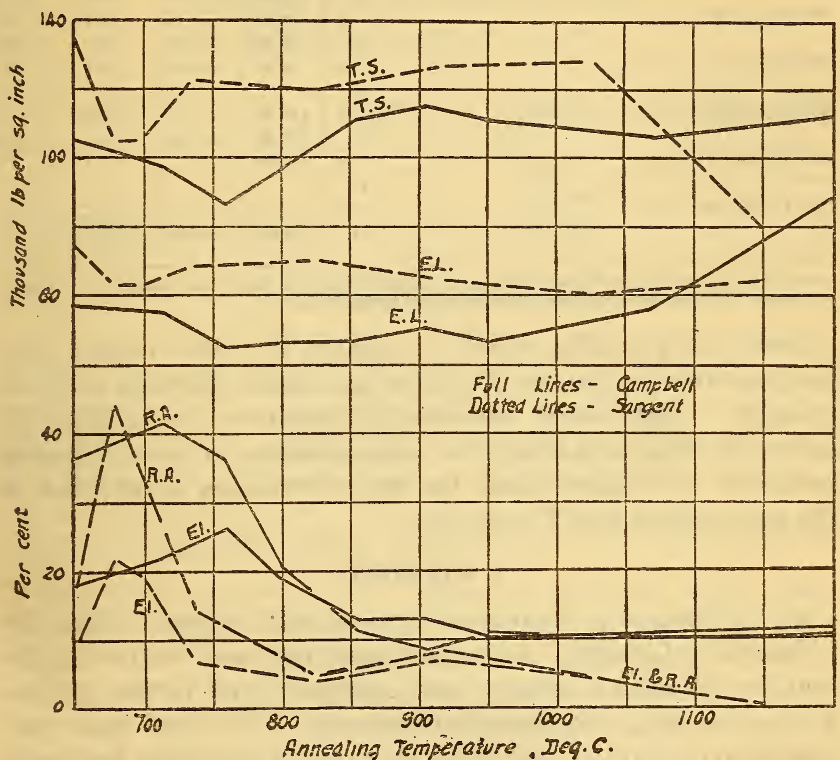

Fig. 1.—*Effect of different annealing temperatures on the tensile properties of 1 per cent carbon steel*

After Campbell and Sargent, as follows: W. Campbell, On the heat treatment of some high-carbon steels, Proc. A. S. T. M., p. 211; 1906. G. W. Sargent, A study of the effect of heat treatment on crucible steel containing one per cent carbon. Trans. A. I. M. E., p. 303; 1901.

taining 0.95 per cent carbon. Maximum strength was obtained in slow cooling from 900° C (1652° F), and the ductility gradually decreased with rise in temperature from 720° C (1328° F) to 1100° C (2012° F). Soaking decreased the strength and in general resulted in increase in elongation but decrease in reduction of area.

[3] Sir W. Roberts-Austen and W. Gowland, "Sixth Report to the Alloys Research Committee: On the heat treatment of steel," Proc. Inst. Mech. Eng., 1, p. 7; 1904.

TABLE 1.—Effect of Time and Temperature in Annealing on the Mechanical Properties of 0.95 Per Cent Carbon Steel [a]

Annealing temperature	Time at temperature	Breaking strength	Elastic limit	Elongation in 2 inches	Reduction area
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent
620° C (1148° F)	½	118 400	76 600	15.0	27.0
	12	101 800	51 800	18.5	27.1
720° C (1328° F)	½	88 000	....	22.0	45.0
	12	75 500	31 600	23.5	35.4
800° C (1472° F)	½	89 500	50 400	18.0	28.4
	12	....	....	....	....
900° C (1652° F)	½	114 500	....	10.0	15.4
	12	107 000	80 800	11.9	11.0
1100° C (2012° F)	½	111 300	....	7.5	9.1
	12	....	....	....	....
1200° C (2192° F)	½	....	....	....	....
	12	53 900	45 000	20.0	37.5

[a] From Sixth Report to the Alloys Research Committee, Proc. Inst. Mech. Eng., 1904, 1, p. 7. Pounds per square inch = tons per square inch given in original table, ×2240.

From the preceding results it appears that slow cooling from temperatures just above Ac_1 gives maximum ductility and low strength. With rise in annealing temperature the ductility decreases rapidly, and elongation and reduction of area in general remain at low values, while the strength reaches a maximum in the range about 900° C (1652° F).

2. HARDENING

(*a*) Quenching Temperature.—Brinell[4] showed that the "Hardening Capacity" of carbon steels increased up to 0.45 per cent carbon when it became nearly constant, with further increase to 0.90 per cent, and thereafter decreased. The steel under consideration is therefore just above the range of maximum hardening capacity, and, as is well known, is quite sensitive to thermal treatment, having slightly more carbon than required for saturation. After quenching in cold water from temperatures above the thermal transformations it is hard and brittle, while when more slowly cooled, as in oil, high strength and somewhat greater ductility results. In either case the properties are changed to a marked degree by the quenching temperature, whether subsequent tempering is at low or high temperatures or entirely omitted, as indicated by results reported by Roberts-Austen and Gowland[5] for an

[4] Axel Wahlberg, "Brinell's method of determining hardness and other properties of iron and steel," Jr. I. and S. Inst., 1, p. 243; 1901.

[5] See note 3.

alloy containing 0.95 per cent carbon, which are reproduced in Table 2. Based on their tests, the authors conclude that the oil-quenching temperature producing the best combination of strength, elastic limit, and elongation is in the neighborhood of 900° C (1652° F).

TABLE 2.—Effect of Various Methods of Quenching and Tempering on the Tensile Properties of 0.95 Per Cent Carbon Steel [a]

QUENCHED IN WATER AT 20° C (68° F)

Quenched from—	Tempered at—	Breaking strength	Yield point	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Per cent	Per cent
720° C (1328° F)		125 500		12.0	24.8
900° C (1652° F)		48 400		Nil.	Nil.
1200° C (2192° F)		9 400		Nil.	Nil.

QUENCHED IN OIL AT 80° C (176° F)

Quenched from—	Tempered at—	Breaking strength	Yield point	Elongation in 2 inches	Reduction of area
720° C (1328° F)		117 100	89 500	13.0	19.8
720° C (1328° F)	350° C (662° F)	122 500	81 700	12.0	18.6
870° C (1598° F)	350° C (662° F)	229 500	149 400	7.0	17.0
1000° C (1832° F)	350° C (662° F)	211 000	152 700	5.5	14.8
800° C (1472° F)	600° C (1112° F)	103 000	80 000	12.0	12.9
900° C (1652° F)	600° C (1112° F)	110 000	90 000	17.0	28.0

[a] From Sixth Report to the Alloys Research Committee, Proc. Inst. Mech. Eng., 1904, **1**, p. 7. Pounds per square inch=tons per square inch given in original table, ×2240.

Hanemann[6] reported direct decrease in strength as the water, hardening temperature increased from 750 to 1000° C (1382 to 1832° F) for 1 per cent carbon steel not subsequently tempered whereas for an alloy containing 1.33 per cent carbon the strength increased until the quenching temperature exceeded 900° C (1652° F).

(*b*) Time at Hardening Temperatures.—All that is generally deemed necessary in the treatment of steel as to time at hardening temperature is to maintain it for the minimum period required for uniform heating throughout. The time actually required to meet this condition is known to increase markedly with size, and it is also known that with increased mass the temperature at which the steel will first harden rises. Portevin[7] has shown that the effect of time of heating prior to quenching is marked, and that a change from 2 to 60 minutes resulted in increased strength and hardness as shown below.

[6] H. Hanemann, "Über die Wärmebehandlung der Stahle," Stahl und Eisen, **31**, p. 1365; 1911.

[7] A. Portevin, "Influence due temps de chauffage avant la trempe sur les résultats de cette operation," Rev. Met., **13**, p. 9; 1916.

TABLE 3.—Effect of Time of Heating Prior to Hardening on the Mechanical Properties of 1.08 Per Cent Carbon Steel [a]

Time of heating at 800° C	Maximum strength	Elastic limit	Elongation in 100 mm (3.94 inches)	Reduction of area	Brinell hardness number
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent	
2 minutes	91 500	78 300	10.5	17.2	600
20 minutes	121 000	121 000	10.5	17.2	571-652
60 minutes	125 000	122 000	10.5	17.2	875

[a] A. Portevin, "Influence du temps de chauffage avant le trempe sur les resultats de cette operation," Rev. Met. (1916), 13, p. 9. Pounds per square inch=kilograms per square millimeter given in original tables, $\times 1.422 \times 10^3$.

3. TEMPERING

(*a*) TEMPERING TEMPERATURE.—The effects of tempering on the tensile and impact properties of hardened 1 per cent carbon steel have been studied by a number of investigators, including Rudeloff,[8] Hanemann,[9] and Roberts-Austen, and Gowland.[10] More recently J. H. Nead[11] determined the tensile and impact properties of such steel quenched in oil from the recommended annealing temperature range of the American Society for Testing Materials[12] when followed by tempering at various temperatures, but the possibilities for production of high combinations of strength and ductility by varying hardening and tempering treatments have not been fully covered. It appears from Nead's results, reproduced in Table 4, that tempering has a relatively small effect in reducing the brittleness of the oil quenched steel, and that tempering temperatures in the neighborhood of 500° C (932° F) are required for a material increase in ductility or decrease in tensile strength. The cause of this is undoubtedly in incomplete hardening, as specimens one-half inch or more in diameter will not be martensitic throughout after quenching in oil.

[8] M. Rudeloff, "Untersuchungen Über den Einfluss des Ausglühens auf die physicalischen Eigenschaften von Eisen und Stahdrähten." Stahl und Eisen, 12, p. 63; 1892.

[9] See note 6.

[10] See note 3.

[11] J. H. Nead, "The effect of carbon on the physical properties of heat-treated carbon steel," Trans. Amer. Inst. Min. Eng. 53, p. 218; 1915. Charpy results as related to carbon content of steel, Tests of Metals, etc., p. 109; 1916.

[12] Year Book,. Amer. Soc. Test. Materials., p. 201; 1914.

TABLE 4.—Effect of Tempering on the Mechanical Properties of Hardened 1 Per Cent Carbon Steel [a]

[Samples quenched in oil from 790° C (1454° F)]

Tempered at—	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area	Brinell hardness number	Impact energy absorbed (Charpy)
	Lbs./in.²	Lbs./in.²	Per cent	Per cent		Ft.-lbs./in.²
....	192 500	127 000	10.5	34.0	387	....
375° C (707° F)	195 000	127 500	12.5	34.0	375	42
460° C (860° F)	201 500	111 000	12.5	40.3	402	41
560° C (1040° F)	168 500	104 500	14.5	30.7	321	54
650° C (1202° F)	134 000	86 000	20.0	40.3	277	57
As rolled	152 000	86 000	9.5	13.3	302	27

[a] J. H. Nead, "The effect of carbon on the physical properties of heat-treated carbon steel," Trans. A. I. M. E., 53 p. 218; 1915. Charpy results as related to carbon content of steel, Tests of Metals, etc., 1916; p. 109.

(b) TIME AT TEMPERING TEMPERATURE.—It is well recognized that a long time in tempering hardened steel at a given temperature is, within limits, equivalent to tempering for a short time at a higher temperature. Long-time tempering at a given temperature increases the ductility and lowers the strength and hardness, but the magnitude of these effects, especially at the lower tempering temperatures, depends upon the thoroughness of the hardening. The fact that Hayward and Raymond[13] found relatively small effects on the tensile properties of 0.45 per cent carbon steel with increased time of tempering was probably due in part to incomplete hardening, as pointed out in discussion of their results.

Matthews and Stagg[14] give detailed data relating to this subject, and their values are reproduced below. In part, they state

TABLE 5.—Effect of Time in Tempering Hardened Steel [a]

[Results are average of 4 check tests after each treatment, carried out on one-half-inch round tensile test bars.

Elastic limit	Maximum strength	Elongation	Reduction of area	Brinell hardness	Treatment
Lbs./in.²	Lbs./in.²	Per cent	Per cent		
228 750	260 137	2.5	....	425	843° C (1550° F) oil, 437° C (800° F), 8 minutes
201 125	214 562	11.6	45.4	390	843° C (1550° F) oil, 437° C (800° F), 20 minutes
175 000	183 187	12.0	49.35	340	843° C (1550° F) oil, 437° C (800° F), 40 minutes

[a] J. A. Matthews and H. J. Stagg, "Factors in hardening tool steel," Trans. A. S. M. E., p. 845; 1914.

"* * * time at the drawing temperature has a marked effect. The act of breaking down the martensite is progressive and not sharply defined. Both time and temperature have their effects."

[13] C. R. Hayward and S. S. Raymond, "Effect of time on reheating hardened carbon steel below the critical range," Trans. A. I. M. E., p. 517; 1916.

[14] J. A. Matthews and H. J. Stagg, "Factors in hardening tool steel," Trans. Amer. Soc. Mech. Eng., p. 845; 1914.

Similarly, other investigators have shown the importance of the time effect in tempering, notably Barus and Strouhal,[15] who used thermoelectric methods; Goerens,[16] who studied variations in tensile, magnetic, and other properties of low carbon steel; Portevin,[17] who carried out hardness tests and microscopic examination; and likewise Rudeloff[18] and Hanemann.[19]

III. MATERIALS AND METHODS OF TESTING

The steel tested was part of a lot of 1 by ½ inch hot-rolled bars of varying carbon contents supplied by the Carnegie Steel Co., Pittsburgh, Pa., and of the following chemical composition:

	Per cent
Carbon	1.04
Manganese	.17
Phosphorus	.017
Sulphur	.019
Silicon	.14

After cutting to the desired lengths for tensile and impact specimens the steel was normalized by heating to 815° C (1500° F) for 30 minutes and cooling in still air, thereafter showing the following tensile properties and hardness:

Tensile strength, pounds per square inch	129 900
Proportional limit, pounds per square inch	55 000
Per cent elongation in 2 inches	14.0
Per cent reduction of area	22.3
Brinell hardness	217
Shore hardness	32

Test samples were machined to slightly larger than the required size (approximately ½-inch round in reduced section), subjected to various heat treatments, and finally ground wet to the form and dimensions shown in Fig. 2. Tensile tests were made with a 50 000-pound testing machine, and a strain gage was used in determination of the limit of proportionality, while hardness was obtained by both the Shore and Brinell methods, by means of a recording scleroscope and an American Brinell hardness testing machine (the latter under standard conditions of 3000 kg load and 10 mm ball). Impact specimens of both Izod and Charpy types were

[15] Barus and Strouhal, "On the physical characteristics of iron carburets," Bull. 14, U. S. Geol. Survey; 1885.

[16] P. Goerens, "Influence du traitement thermique sur les proprietes de l'acier ecruit," Rev. Met. Memoires, **10**, p. 1337; 1913.

[17] A. Portevin, "Influence du temps de chauffage avant le trempe sur les resultats de cette operation," Rev. Met., **13**, p. 9; 1916.

[18] See note 8.

[19] See note 6.

tested in American made Izod and Charpy machines. Prior to subjecting the steel to heat-treatment the thermal transformations were determined in a manner already described by Scott and Freeman.[20] The heating and cooling curves so obtained are shown in Fig. 3.

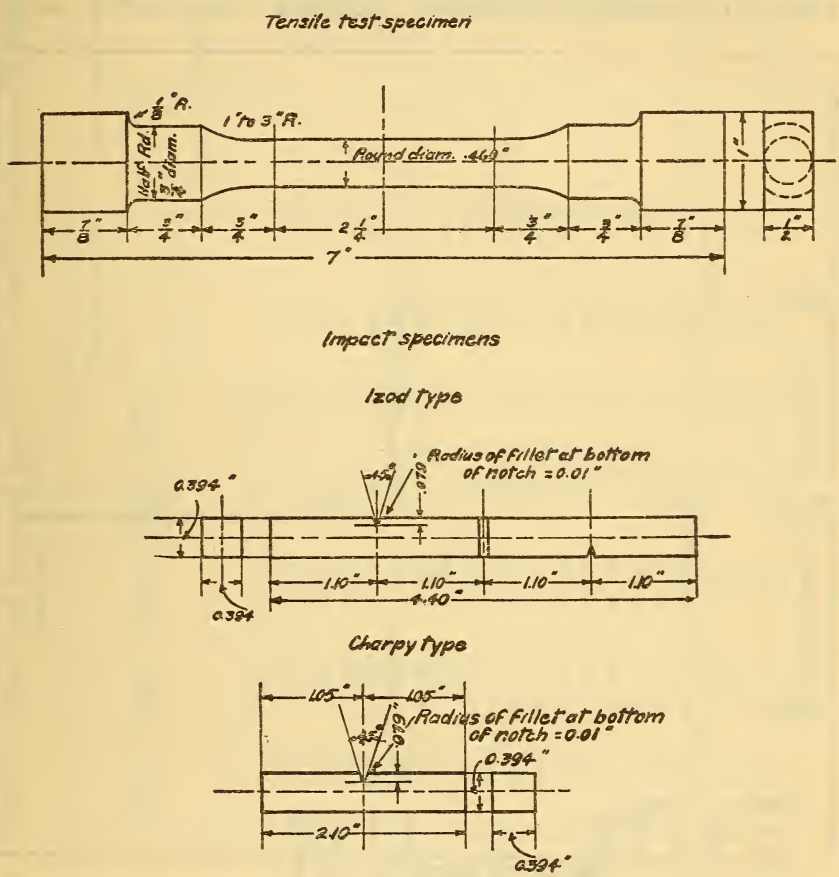

FIG. 2.—*Form and dimensions of test specimens used*

IV. EXPERIMENTAL RESULTS

1. HARDENING

(*a*) EFFECT OF QUENCHING IN DIFFERENT MEDIA.—In order to throw further light on the effect of several methods of hardening 1 per cent carbon steel when followed by high tempering, such as would possibly bring it into suitable condition for structural purposes, samples were quenched in water, oil, molten lead, and a hot

[20] H. Scott and J. R. Freemen, jr., Use of a Modified Rosenhain Furnace for Thermal Analysis, Bureau of Standards Scientific Paper No. 348, Oct. 24, 1919.

salt mixture consisting of 2 parts, by weight, of potassium nitrate and 3 parts sodium nitrate. The details of these treatments and test results are given in Table 6, and it is evident that the surface of the treated metal is an important and determining factor in the tensile properties obtained. Removal of surface irregularities resulting from scaling in treatment, including a large part or all of

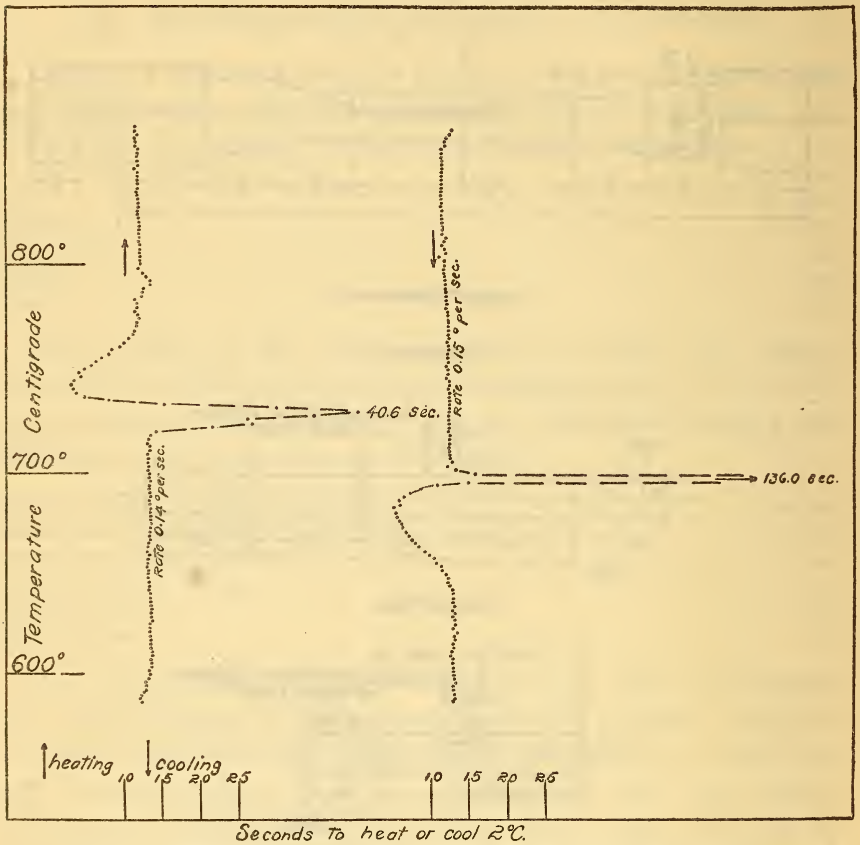

FIG. 3.—*Inverse rate heating and cooling curves of 1 per cent carbon steel*

Ac_1 (° C)			Ar_1 (° C)		
Beg.	Max.	End	Beg.	Max.	End
716	727	740	703	696	680

the decarburized surface, results in better combinations of strength and ductility, but the steel is very brittle, as shown by the low impact values, regardless of the quenching method employed. In general, the most marked effect of grinding after treatment is found in values of reduction of area, which greatly increase.

TABLE 6.—Mechanical Properties of 1 Per Cent Carbon Steel Quenched from 788° C or 843° C in Different Media and Subsequently Tempered at 538° C

Treatment	Sample No.[a]	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed, foot-pounds			
						Brinell	Shore	Charpy		Izod	
								Values	Average	Values	Average
		Lbs./in.²	Lbs./in.²	Per cent	Per cent						
788° C (1450° F), 30 minutes, water quench; tempered 15 to 20 minutes, 538° C (1000° F)	51B	165 500	143 000	11.0	27.7	340	56	2.5, 3.1, 3.2	2.9	2.2, 2.2, 2.0	2.2
	52B	156 200	132 000	12.5	34.6	340	53				
	49A	114 400	98 900	14.0	23.1	262	42				
	50A	116 200	101 400	15.0	26.1	255	43				
843° C (1550° F), 30 minutes, water quench; tempered 15 to 20 minutes, 538° C (1000° F)	49B	171 650	130 000	9.5	31.4	340	51	...	...	...	...
	50B	160 800	125 000	10.5	31.0	340	45	...	...	...	...
	51A	143 200	82 000	6.5	11.5	294	46	...	...	...	...
	52A	138 500	92 000	7.5	8.2	286	46	...	...	...	...
788° C (1450° F), 30 minutes, oil quench; tempered 15 to 20 minutes, 538° C (1000° F)	3B	188 250	110 500	...	...	340	48	3.0, 3.5, 2.3	2.9	2.0, 2.0, 3.0	2.3
	4B	169 000	113 000	13.0	39.3	318	48				
	13A	157 500	92 500	11.0	16.5	321	48				
	14A	156 100	90 000	10.5	16.1	321	48				
788° C (1450° F), 30 minutes, quench salt at 538° C (1000° F), holding 15 minutes before cooling in oil	43B	133 700	90 500	14.5	35.0	294	42	3.9, 3.6, 3.4	3.8	4.2, 3.4, 3.8	3.8
	44B	147 000	80 500	14.5	36.0	289	40				
	7A	143 000	81 500	8.5	22.5	278	39				
	8A	142 900	77 500	8.5	17.0	294	42				
788° C (1450° F), 30 minutes, quench lead at 538° C (1000° F), holding 15 minutes before cooling in oil	47B	151 800	84 000	15.0	37.4	255	37	3.2, 3.5, 3.0	3.2	3.1, 3.0, 3.3	3.1
	48B	148 200	81 000	14.5	36.3	278	37				
	9A	130 800	71 000	10.0	12.6	238	38				
	10A	131 200	68 500	9.5	12.4	228	31				
843° C (1550° F), 1 hour, quench lead at 538° C (1000° F), holding 30 minutes before cooling in oil	25A	136 700	70 000	12.0	23.2	248	33	...	...	...	...
	26A	139 200	72 500	10.0	15.2	278	36	...	...	...	...

[a] Samples marked B were ground wet after treatment and before testing; those marked A were tested without grinding after heat treatment.

It appears that the highest strength and ductility are obtained by cooling in oil, but a much higher elastic ratio results from water quenching. It does not necessarily follow, however, that the results reported for any quenching method are the best which

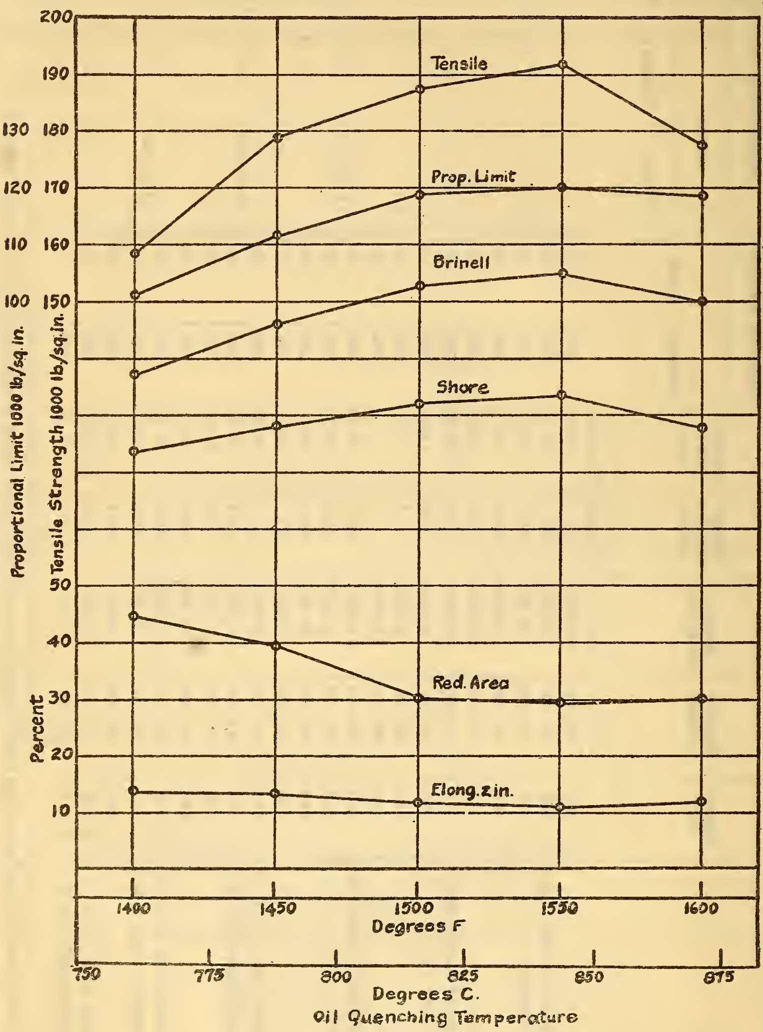

FIG. 4.—*Effect of varying oil quenching temperatures on mechanical properties of 1 per cent carbon steel subsequently tempered at 538° C*

may be produced, for it is possible that better combinations of strength and ductility may be obtained when using higher quenching temperatures than 788° C (1450° F), as is true when cooling in molten lead (Table 6).

The structures of this steel after application of these different treatments are shown in Fig. 10, and after quenching in water or oil, followed by tempering at 538° C (1000° F), the steel is sorbitic. When quenched in molten lead or salt, the steel consists of sorbitic pearlite, but the transformation appears to have progressed somewhat further to pearlite in the case of the lead quenching.

(*b*) Effect of Various Oil-Quenching Temperatures.—The effect of different oil-quenching temperatures on the properties and structures of steel subsequently tempered at 538° C (1000° F) is marked, as shown in Table 7 and Figs. 4 and 11. With rise in temperature to 843° C (1550° F) strength and limit of proportionality increase and elongation and reduction of area decrease. With further rise in quenching temperature the strength factors decrease with practically no change in ductility but in all cases the resistance to impact is low.

TABLE 7.—Effect of Varying Oil-Quenching Temperatures on the Mechanical Properties of 1 Per Cent Carbon Steel, Subsequently Tempered at 538° C

Specimen No.	Heated to temperatures noted, held 30 minutes, and quenched in oil [a]	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
		Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
1B	760° C (1400° F)	158 000	101 000	13.5	44.3	288	43	2.2; 2.5; 3.0	2.3; 2.2; 2.5
60B		....	....	....	....	......	......	....	....
Av.	....	....	....	....	....	......	......	2.6	2.3
3B	788° C (1450° F)	188 250	110 500	....	....	340	48	3.0; 3.5; 2.3	2.0; 2.0; 3.0
4B		169 000	113 000	13.0	39.3	318	48	3.0; 3.5; 2.3	2.0; 2.0; 3.0
Av.	....	178 600	111 750	13.0	39.3	329	48	2.9	2.3
5B	816° C (1500° F)	193 600	122 000	10.0	29.2	364	54	3.1; 3.3; 3.6	....
6B		181 600	116 000	12.5	31.0	364	50	....	....
Av.	....	187 600	119 000	11.2	30.1	364	52	3.3	....
7B	843° C (1550° F)	199 000	121 000	10.5	29.5	364	53	3.1; 3.3; 3.1	3.1; 3.2; 3.1
8B		185 000	119 000	11.5	29.5	387	54	....	....
Av.	....	192 000	120 000	11.0	29.5	376	54	3.2	3.1
9B	871° C (1600° F)	177 900	118 000	11.5	30.3	345	46	3.2; 3.9; 3.9	3.1; 2.8; 3.1
10B		177 100	119 000	12.5	29.8	356	50	....	....
Av.	....	177 500	118 500	12.0	30.0	350	48	3.7	3.0

[a] All samples subsequently tempered at 538° C (1000° F) for 20 minutes and cooled in oil.

Benedicks[21] has shown that an increase in temperature results in more rapid cooling for steel of constant mass, and that the metal passes more rapidly through the transformations. His results for an alloy containing 1 per cent carbon are reproduced in part below.

TABLE 8.—Influence of Temperature on Time of Cooling in Quenching 1 Per Cent Carbon Steel[a]

Weight of specimen in grams	Quenching temperature	Cooling time to 100° C
	° C	Seconds
12.5	950	3.07
12.3	845	4.43
12.4	750	4.11
12.3	703	5.73
12.2	695	6.20

[a] C. Benedicks, "Experimental researches on the cooling power of liquids, on quenching velocities, and on the constituents of troostite and austenite," Jr. I. and S. Inst. 2, p. 153; 1908.

It is quite evident, therefore, that a hardening of the matrix of the steel under investigation should result with rise in quenching temperatures and more carbide should be held in solution. In this case, however, there is an added factor contributing to the increased hardness and strength shown in Fig. 4 in the retention of the excess cementite when quenching from above its solution temperature range. The rate of cooling in oil when the steel is heated to 843° C (1550° F) is not sufficiently rapid to retain all this carbide in solution, but an increase to 871° C (1600° F) increases the cooling rate through the transformations enough to cause retention of the few remaining globules found after the first-mentioned treatment. These structures, as well as those obtained on using lower quenching temperatures, are shown in Fig. 11, and because of the tempering at 538° C (1000° F) the groundmass is sorbitic. There is free cementite present in good proportion until quenching temperatures above 816° C (1500° F) are used, while the condition of maximum strength obtained in the sample quenched from slightly above the A_{cm} transformation is coincident with the minimum proportion of free carbide. Undoubtedly the cementite is first wholly retained in quenching from a temperature somewhat below 871° C (1600° F), where the first disappearance has been noted, and possibly this condition

[21] C. Benedicks, "Experimental researches on the cooling power of liquids, on quenching velocities, and on the constituents of troostite and austenite," Jr. I. and S. Inst., 2, p. 153; 1908.

would be coincident with higher strength than shown in Fig. 4. However, it is acknowledged that each increase in temperature is accompanied by increased grain size. This effect opposes whatever beneficial results might be obtained by total retention of the cementite and will finally induce greater brittleness and lowered tensile strength, and that this has happened in the range under consideration is shown by the sharp decrease in strength between samples quenched from 843 and 871° C (1550 and 1600° F).

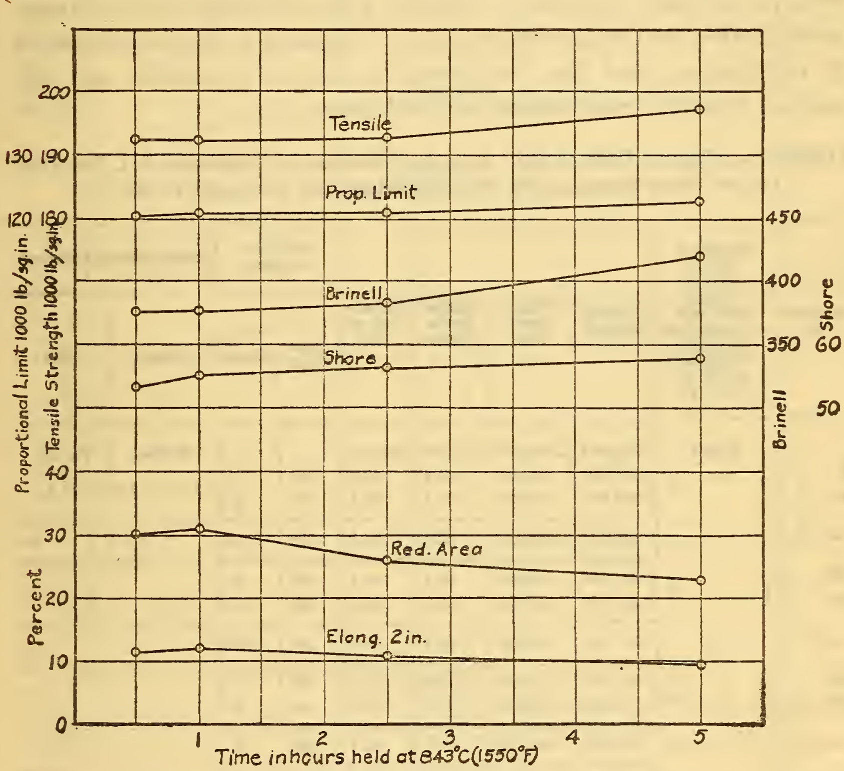

FIG. 5.—*Effect of time at 843° C on the mechanical properties of 1 per cent carbon steel subsequently oil quenched and tempered at 538° C*

(c) TIME OF HEATING PRIOR TO OIL QUENCHING.—In order to further investigate the magnitude of the effects of "soaking" at various hardening temperatures, samples were held for different intervals at 760° C (1400° F) and 843° C (1550° F) prior to quenching in oil and tempering. The first temperature is just above or at the end of Ac_1, while the latter is slightly above the temperature range at which the excess carbide goes into solution.

Time at Temperature Above A_{cm}.—The time (over 30 minutes) for which the steel is held at 843° C (1550° F) when subsequently oil quenched and tempered at 538° C (1000° F) has a relatively small effect on the tensile and impact properties, as shown in Fig. 5 and Table 9. A change from 30 minutes' heating to 1 hour does not alter the strength appreciably, but results in slightly increased ductility, whereas with increase in time of "soaking" from 1 to 5 hours the hardness, tensile strength, and proportional limit gradually increase with accompanying decrease in elongation and reduction of area. The steel is very brittle after all treatments, and the variations in impact resistance are not such as to allow conclusions to be drawn.

TABLE 9.—Effect of Time at 843° C on the Mechanical Properties of 1 Per Cent Carbon Steel Subsequently Oil Quenched and Tempered at 538° C

Specimen No.	Heated to 843° C (1550° F) for time noted and oil quenched; tempered 20 minutes at 538° C (1000° F)	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
7B	½	199 000	121 000	10.5	29.5	364	53	3.1, 3.3, 3.1	3.1, 3.2, 3.1
8B		185 000	119 000	11.5	29.5	387	53		
Av.	....	192 000	120 000	11.0	29.5	376	53	3.2	3.1
27B	1	202 100	128 000	10.5	27.7	387	56	....	....
28B		181 800	113 000	12.5	34.4	364	54	....	....
Av.	....	191 950	120 500	11.5	31.0	376	55	....	....
65B	2½	192 350	121 000	11.0	26.3	376	55	....	....
29B		193 400	120 500	9.5	26.6	387	57	....	....
Av.	....	192 875	120 750	10.2	26.4	382	56	....	....
31B	5	207 900	129 500	8.5	19.5	477	56	3.2, 3.2, 4.0	3.1, 3.1, 3.0
32B		187 000	116 000	10.5	27.0	364	59		
Av.	....	197 450	122 750	9.5	23.2	421	58	3.5	3.1

The hardening temperature chosen is only slightly above the solution temperature of the excess carbide which, according to recent determination by Ishiwara,[22] takes place at about 835° C (1535° F), and that this reaction proceeds slowly is at once evident from examination of the structures shown in Fig. 12. Solution is

[22] Torajuro Ishiwara, "On the magnetic determinations of A_0, A_1, A_2, and A_3 points in steels containing up to 4.8 per cent carbon," Science Reports of the Tohoku Imperial Univ., **9**, No. 5, p. 401.

incomplete at 30 to 45 minutes, whereas in 2½ hours this change has progressed nearly to completion, coincident with a marked decrease in reduction of area in tensile test. In the sample heated

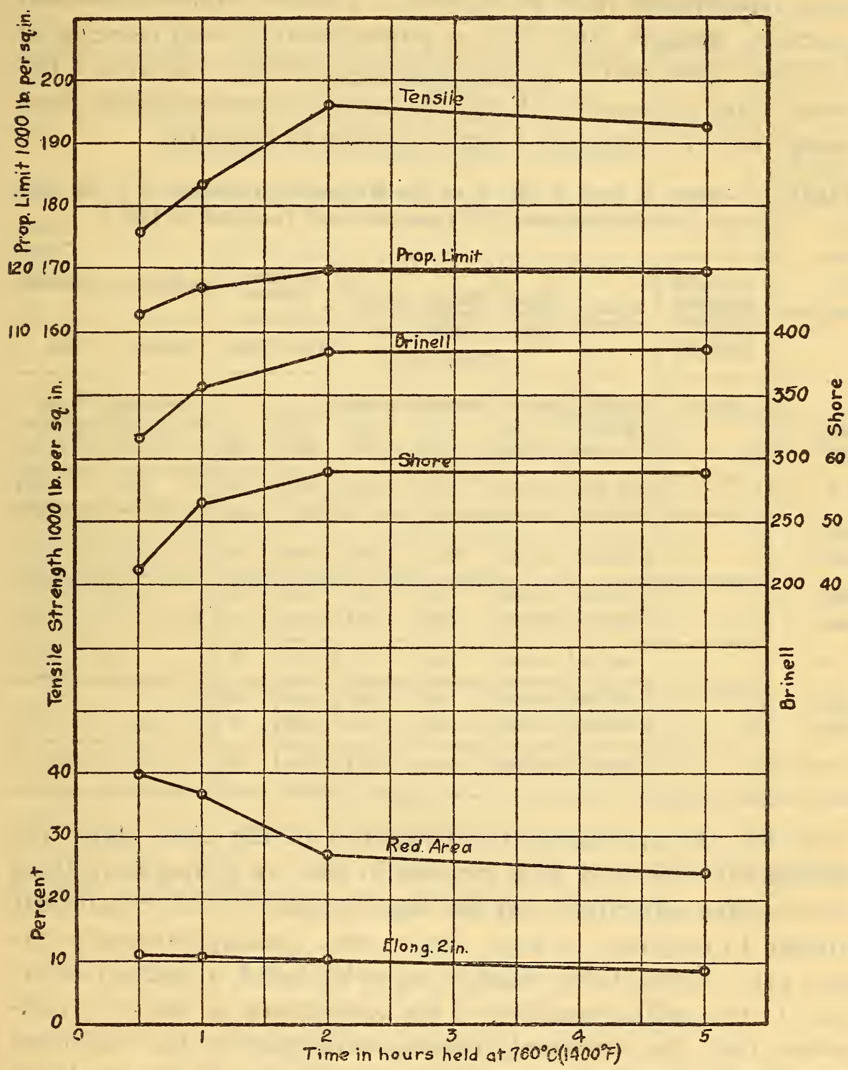

Fig. 6.—*Effect of time at 760° C on the mechanical properties of 1 per cent carbon steel subsequently oil quenched and tempered at 538° C*

for five hours the excess carbide is wholly in solution, which partly accounts for the increased hardness obtained.

Time at Temperature Between Ac_1 *and* A_{cm}.—When this steel is "soaked" at 760° C (1400° F), which is slightly above the end of the Ac_1 transformation, oil quenched and subsequently tempered, as in the preceding samples, marked changes in properties result, as illustrated in Fig. 6 and Table 10. An increase in time at hardening temperature from 30 minutes to 2 hours results in increased hardness, strength, and limit of proportionality with decrease in ductility, particularly as measured by reduction of area. Between 2 and 5 hours the changes in properties are negligible, there being evident principally a small decrease in strength.

TABLE 10.—Effect of Time at 760° C on the Mechanical Properties of 1 Per Cent Carbon Steel Subsequently Oil Quenched and Tempered at 538° C

Specimen No.	Time at oil quenching temperature of 760° C (1400° F)	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
25B	½	186 800	117 500	11.0	38.1	321	45	3.1; 2.9; 3.0	2.8; 2.7; 3.0
26B		170 000	108 000	11.5	41.6	304	40		
Av.		175 400	112 750	11.2	39.8	313	43	3.0	2.8
37B	1								
38B		183 250	117 000	10.5	36.8	358	53		
39B	2	192 800	119 000	9.5	25.2	382	56		
40B		198 700	120 000	10.5	29.3	387	60		
Av.		195 750	119 500	10.0	27.2	385	58		
41B	5	192 500	118 500	8.0	20.9	376	58		
42B		192 000	120 000	8.5	24.0	398	58		
Av.		192 250	119 250	8.2	22.4	387	58		

In Fig. 13 are shown the structures of the steel under the treatments used, and with increase in time at temperature there is more free cementite, and the small globules of this constituent appear to combine to form larger ones (microphotographs 13*e* and 13*f*). While these changes are to be noted, a marked difference in the etching qualities of the groundmass is observed, indicating that the structural changes accompanying the variations in tensile properties are partly due to changes in the condition of the matrix. Specimens heated for various intervals and oil quenched without subsequent tempering were examined under the microscope and found to consist of troosto-sorbite, and it appeared that the proportion of troostite was greater the longer the "soaking."

When supplemented by Brinell hardness tests, the results of which are given in Table 11, it is evident that the effect of increasing the duration of heating for hardening results in a noticeable increase in hardness as does an increase in temperature.

TABLE 11.—Effect of Time at 760° C Prior to Oil Quenching on the Hardness of 1 Per Cent Carbon Steel

Heated at 760° C (1400° F) for time specified and oil quenched	Brinell hardness number
½ hour	340
1 hour	351
5 hours	364

2. TEMPERING

(*a*) Effect of Tempering Steel Hardened in Different Ways.—To supplement available information and correlate the tensile and impact properties of one heat of steel tempered at different temperatures after hardening in different ways, samples were tempered between 316 and 704° C (600 and 1300° F) after quenching in oil or in water from just above or at the end of Ac_1 and in oil from a temperature slightly above the A_{cm} transformation.

The results obtained in tests of steel quenched in water from 788° C (1450° F), followed by tempering between 538 and 704° C (1000 and 1300° F), are given in Fig. 7 and Table 12, and it is noted that the most rapid decrease in strength occurs when the tempering temperature is raised from about 538 to 649° C (1000 to 1200° F), while at the same time the elongation is almost doubled and reduction of area materially increased.

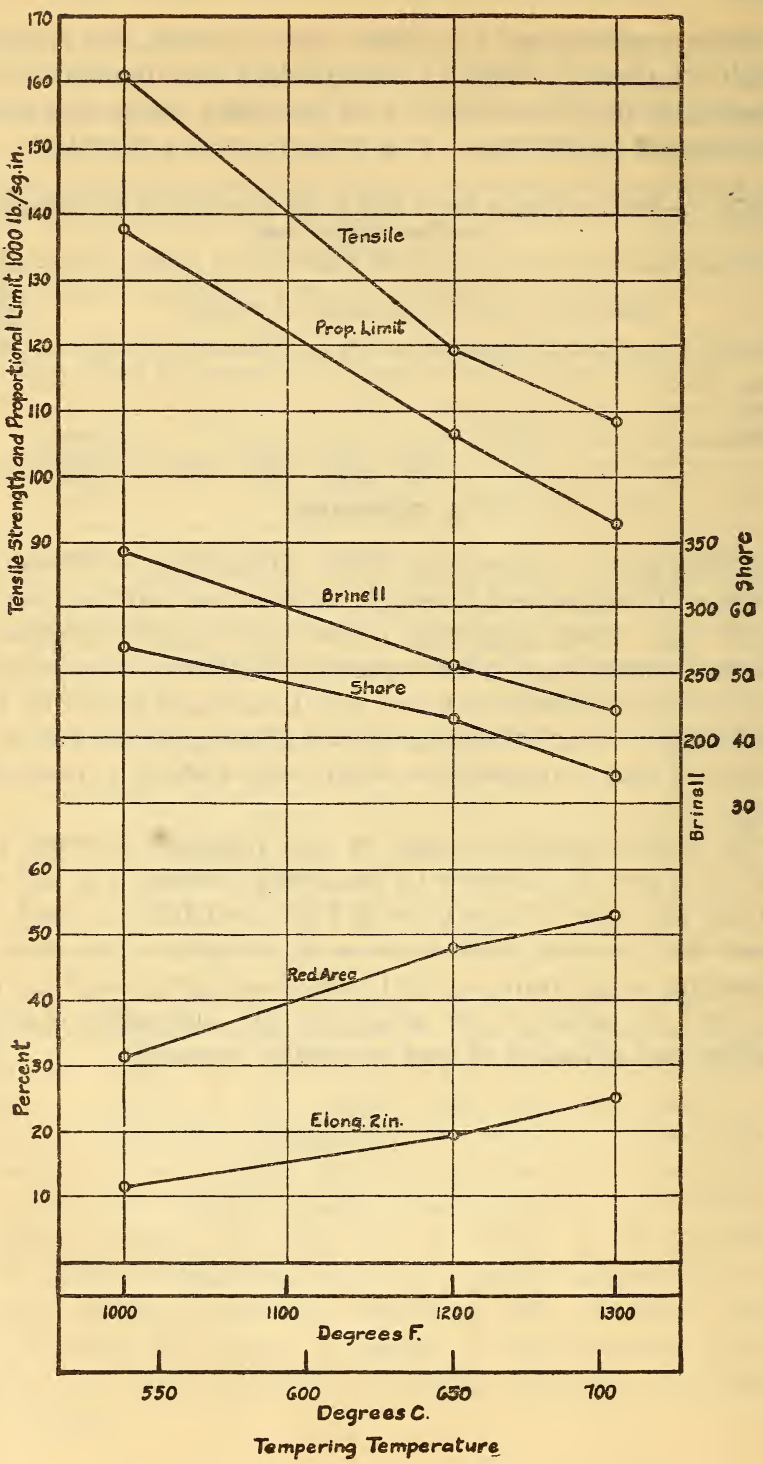

FIG. 7.—*Effect of tempering on the mechanical properties of 1 per cent carbon steel first quenched in water from 788° C*

TABLE 12.—Effect of Tempering on the Mechanical Properties of 1 Per Cent Carbon Steel First Quenched in Water from 788° C

Specimen No.	Held 20 minutes at tempering temperature indicated and air cooled	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
		Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
51B	538° C (1000° F)	165 500	143 000	11.0	27.7	340	56	2.5, 3.1, 3.2	2.2, 2.2, 2.0
52B		156 200	132 000	12.5	34.6	340	53	....	....
Av.	....	160 850	137 500	11.8	31.2	340	54	2.9	2.1
53B	649° C (1200° F)	....	106 509	17.0	47.4	255	43	....	....
54B		118 800	106 000	22.0	48.6	255	43	3.2, 2.6	2.3, 2.0, 2.1
Av.	....	....	106 250	19.5	48.0	255	43	2.9	2.1
55B	704° C (1300° F)	108 400	91 000	....	....	223	34	5.7, 10.7, 8.5	11.0, 5.5, 7.7
56B		108 700	95 000	25.0	52.9	220	34	3.0, 2.9, 2.8	2.0, 2.4, 2.3
Av.	....	108 650	93 000	....	....	222	34	5.6	5.2
67B	760° C (1400° F)	124 400	68 000	16.5	37.0	255	34	3.2, 2.3, 2.7	2.6, 2.4, 2.2
68B		115 800	67 500	18.5	44.6	269	39	....	....
Av.	....	120 100	67 750	17.5	40.8	262	36	2.7	2.4

The mechanical properties-tempering temperature curves shown in Fig. 8 are based on results given in Table 13 for steel quenched in oil from 788 or 843° C (1450 or 1550° F) and are of the same general type. Samples quenched at the highest temperature show the highest strength with lowest elongation and reduction of area throughout than those quenched from 788° C (1450° F), or, in other words, a higher tempering temperature is required when using the highest quenching temperature to produce a given strength.

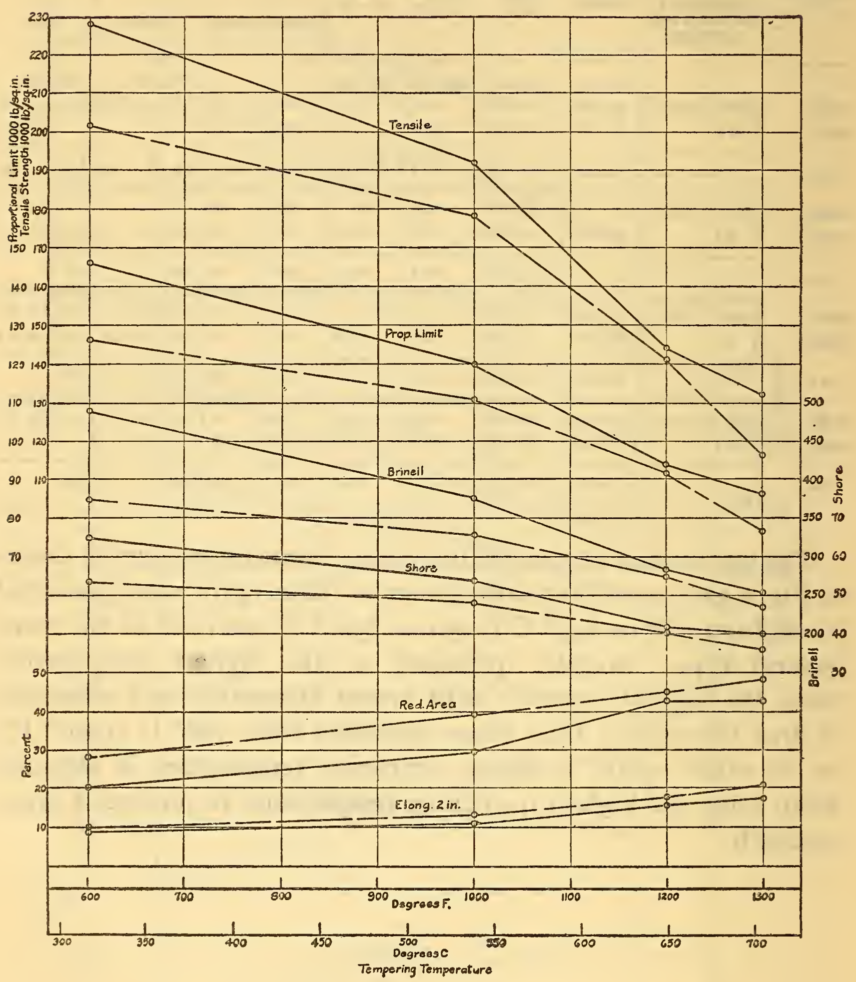

FIG. 8.—*Effect of tempering on the mechanical properties of 1 per cent carbon steel, first oil quenched from either 788 or 843° C*

Dotted lines represent samples quenched from 788° C

TABLE 13.—Effect of Tempering on the Mechanical Properties of 1 Per Cent Carbon Steel, First Oil Quenched from 788° C or 843° C

STEEL HEATED FOR 30 MINUTES AT 788° C (1450° F) AND OIL QUENCHED

Specimen No.	Held 30 minutes at tempering temperature indicated and oil quenched	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
		Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
11B.....	316° C (600° F)	197 000	122 000	8.0	24.8	364	52	2.2, 3.1, 3.3	2.7, 2.1, 3.3
12B.....		206 000	130 000	9.5	32.0	386	56	4.8, 7.5, 4.8	....
Av....	....	201 500	126 000	8.8	28.4	375	54	4.3	2.7
3B......	538° C (1000° F)	188 250	110 500	....	....	340	48	3.0, 3.5, 2.3	2.0, 2.0, 3.0
4B......		169 000	113 000	13.0	39.3	318	48	3.9, 3.9, 4.8	....
Av....	....	178 600	111 750	....	....	329	48	3.5	2.3
13B.....	649° C (1200° F)	140 700	93 000	18.0	45.3	278	41	3.0, 3.1, 3.0	2.3, 2.0, 2.4
14B.....		141 800	91 500	....	....	277	41	3.9, 4.4, 3.9	....
Av....	....	141 250	92 250	....	....	278	41	3.5	2.2
59B.....	704° C (1300° F)	115 800	72 500	20.0	49.8	235	36	2.8, 2.1, 2.2	3.5, 3.7, 4.0
16B.....		117 800	82 000	21.0	47.6	241	36	4.8	2.6, 2.1, 2.1
Av....	....	116 800	77 250	20.5	48.7	238	36	3.0	3.0
17B.....	760° C (1400° F)	171 700	108 000	12.0	40.4	302	42	....	....
18B.....		171 600	110 000	11.5	42.3	286	40	....	....
Av....	....	171 650	109 000	11.7	41.3	294	41	....	....
STEEL HEATED FOR 30 MINUTES AT 843° C (1550° F) AND OIL QUENCHED									
61B.....	316° C (600° F)	228 000	145 000	8.0	20.3	512	66	3.1, 3.2, 3.0	4.0, 2.7, 3.8
62B.....		228 200	147 000	8.0	20.3	470	64	8.0, 2.2	....
Av....	....	228 100	146 000	8.0	20.3	491	65	3.9	3.5
7B......	538° C (1000° F)	199 000	121 000	10.5	29.5	364	53	3.1, 3.3, 3.1	3.1, 3.2, 3.1
8B......		185 000	119 000	11.5	29.5	387	54	....	....
Av....	....	192 000	120 000	11.0	29.5	376	54	3.2	3.1
22B.....	649° C (1200° F)	....	90 500	17.5	45.6	277	42	3.9, 4.8, 4.8	3.5, 3.5, 3.5
63B.....		144 700	98 500	15.0	41.0	290	42	....	....
Av....	....	144 700	94 500	16.2	43.3	284	42	4.5	3.5
23B.....	704° C (1300° F)	125 200	86 000	18.8	46.7	260	40	3.3, 3.0	3.0, 2.8, 3.0
24B.....		140 200	....	17.0	40.2	248	40	9.6, 6.6, 4.8	4.5, 5.5, 6.0
Av....	....	132 700	86 000	17.9	43.4	254	40	5.5	4.1
25B.....	760° C (1400° F)	186 800	117 500	11.0	38.1	319	45	3.1, 2.9, 3.0	2.8, 2.7, 3.0
26B.....		170 000	108 000	11.5	41.6	332	40	....	....
Av....	....	178 400	112 750	11.2	39.8	326	43	3.0	2.8

By interpolation of the graphs giving variations in tensile properties of the tempered steel hardened in different ways it is possible to compare the various treatments applied in order to produce a given strength, and the results obtained from this approximation are given in Table 14.

TABLE 14.—Comparison of Oil and Water Hardening of 1 Per Cent Carbon Steel for Production of Definite Strengths

[Approximate values by interpolation]

Strength chosen in pounds per square inch	Method of hardening	Tempering required	Proportional limit	Elastic ratio	Elongation in 2 inches	Reduction of area	Hardness number	
							Brinell	Shore
			Lbs./in.²	Per cent	Per cent	Per cent		
200 000	843° C oil	489° C (912° F)	125 000	62.5	10.5	27.5	400	56
	788° C oil	331° C (628° F)	125 000	62.5	10.0	29.0	370	53
160 000	843° C oil	611° C (1132° F)	102 500	64.0	14.0	38.5	312	46
	788° C oil	591° C (1096° F)	101 500	63.5	15.5	42.2	302	44
	788° C water	540° C (1004° F)	136 500	85.3	12.0	32.0	342	54
135 000	843° C oil	690° C (1274° F)	88 000	65.1	19.5	48.0	260	41
	788° C oil	661° C (1222° F)	87 500	64.8	18.5	45.5	265	39
	788° C water	608° C (1126° F)	118 000	87.3	17.0	42.0	290	47
120 000	788° C oil	696° C (1284° F)	78 000	65.0	20.0	48.0	240	37
	788° C water	648° C (1198° F)	107 000	89.0	19.0	48.0	260	43

For the production of given strength by heat treatment a slightly higher tempering temperature is required after oil quenching from just above the Ac_1 transformation than when the steel is water quenched from the same temperature.

Likewise a higher temperature is required when oil quenching from above the A_{cm} transformation than when similarly cooled from just above Ac_1 in order to produce the same strength. In general, this difference is less as the temperatures at which the steel is tempered increases.

Water-quenched steel subsequently tempered to show the same strength as that quenched in oil and tempered has a very much higher proportional limit than the latter and also greater hardness as measured by the Brinell and Shore methods. As the tempering temperature approaches the lower critical range these differences at first decrease and then slightly increase. While the difference between the hardness of water and oil quenched steels is well known, it is interesting to note the magnitude of this difference for the steel under consideration and the fact that it is maintained over a wide range of tempering.

In view of the slight differences in tensile properties between the steel quenched in oil from 788° C (1450° F) and that from 843° C (1550° F) the lower temperature is recommended. If the excess carbide exists in plate form, due to a previous high heating, it may readily be refined by normalizing. A preliminary quench from above A_{cm}, however, appears preferable. Water hardening is the best method for the production of strengths in the neighborhood of 120 000 lbs./in.^{2} requiring a tempering of about 649 to 710° C (1200 to 1300° F), providing always that the size and shape of the material is such as to allow the use of a drastic quenching medium.

The structures of samples subjected to the various tempering treatments are shown in Figs. 14 and 15 and are of the usual type. After short-time tempering at 316° C (600° F) the steel is troosto-sorbitic, and as the tempering temperature increases there is a gradual transition of the groundmass to its more stable form. The water-quenched steel, however, has the finest structure regardless of the tempering temperature used.

(*b*) Effect of Time in Tempering at a Temperature Slightly Below Ac_1.—The effect of "soaking" at 704° C (1300° F) when followed by quenching in oil on the properties of oil-hardened steel is shown in Fig. 9 and Table 15. A change from one-half hour to five hours has reduced the hardness considerably, the strength by about one-third, and markedly increased the ductility. As shown in Fig. 16, there is very little change in the character of the excess carbide with increased heating time, so that the change in properties is a result of a distinct softening of the matrix. Comparison of the tensile properties shown in Fig. 9 with results obtained on normalized steel at once shows the effectiveness of temperatures just under the lower transformation for softening this alloy.

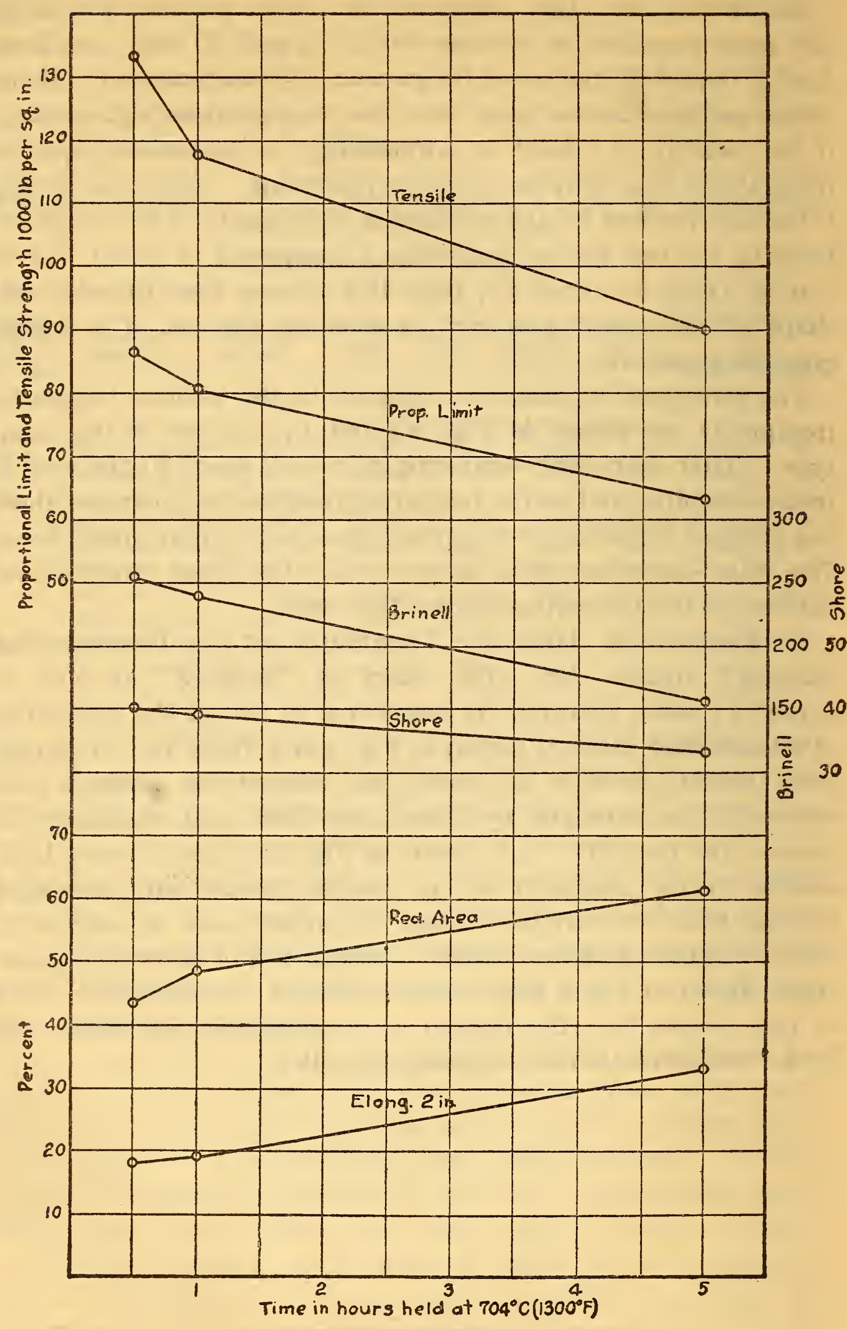

FIG. 9.—*Effect of time at a temperature slightly below* Ac_1 *on the mechanical properties of 1 per cent carbon steel previously oil quenched from 843° C*

Samples were oil quenched from the tempering temperature

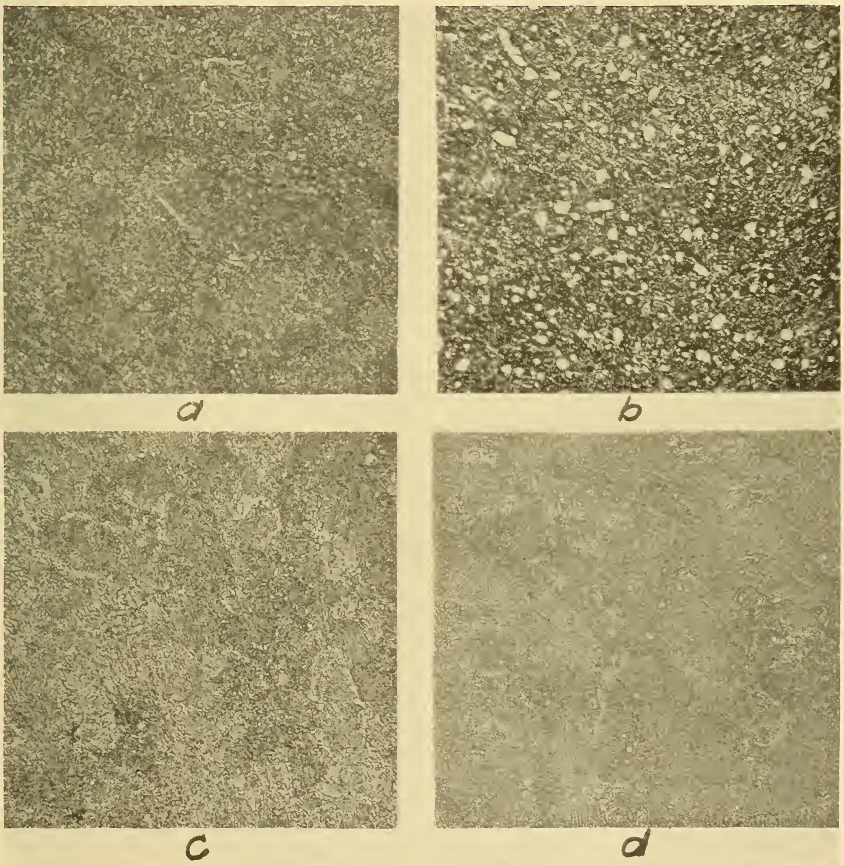

FIG. 10.—*Microstructure of 1 per cent carbon steel quenched from 788° C in different media and tempered at 538° C.* ×500

(a) Quenched in water
(b) Quenched in oil
(c) Quenched in molten lead at 538° C
(d) Quenched in molten sodium and potassium nitrates at 538° C

All samples etched with 2 per cent nitric acid in alcohol

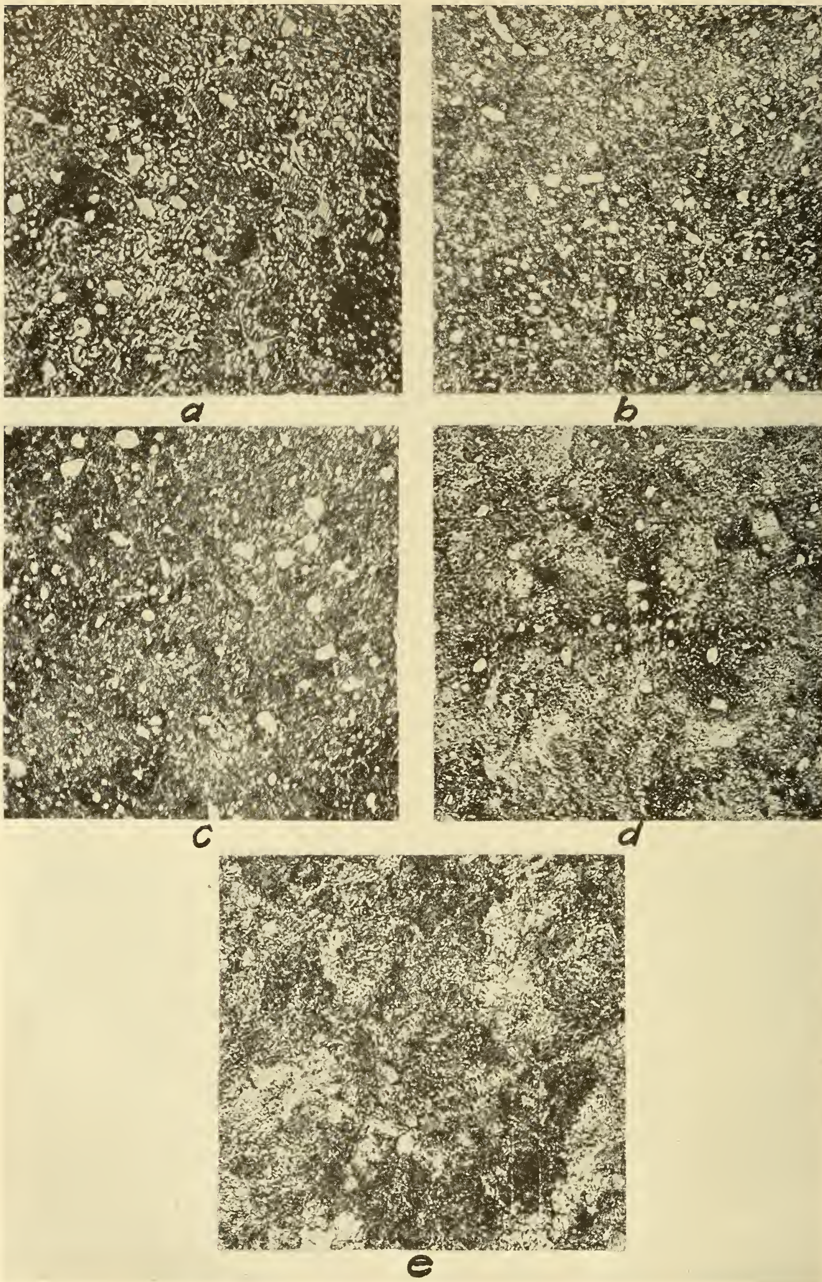

FIG. 11.—*Microstructure of 1 per cent carbon steel oil quenched from various temperatures and subsequently tempered at 538° C. ×500*

(*a*) 760° C (1400° F)
(*b*) 788° C (1450° F)
(*c*) 616° C (1500° F)
(*d*) 843° C (1550° F)
(*e*) 871° C (1600° F)

Samples etched with 2 per cent nitric acid in alcohol

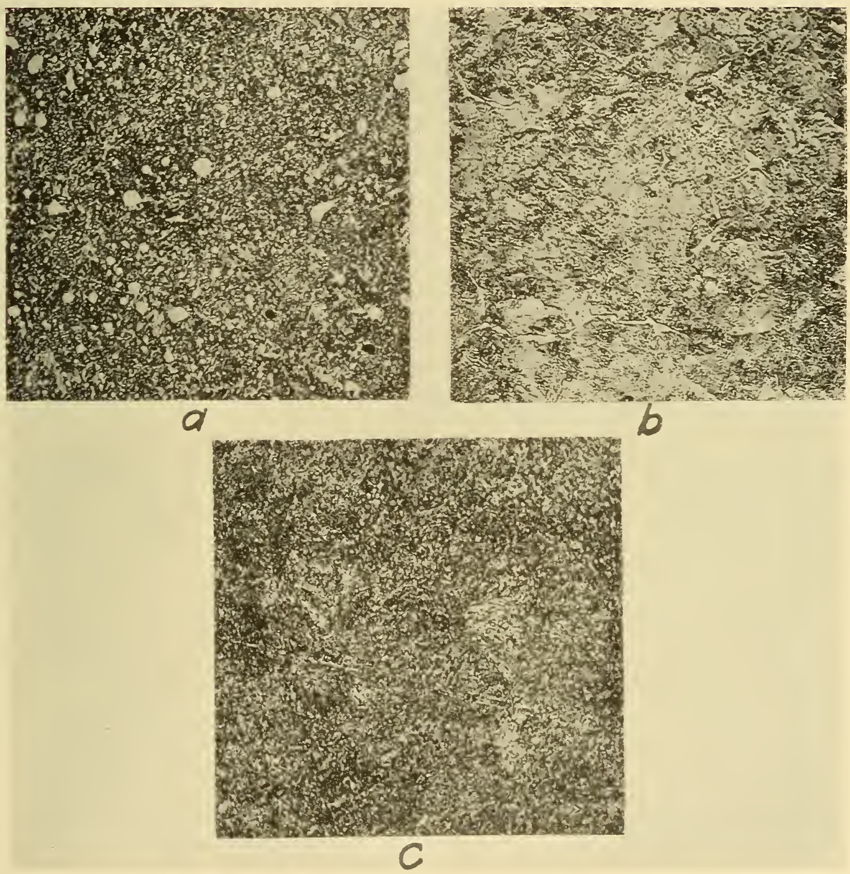

FIG. 12.—*Microstructure of 1 per cent carbon steel held at 843° C for various times and subsequently oil quenched and tempered at 538° C.* ×500

(*a*) 45 minutes (*b*) 2½ hours (*c*) 5 hours

Samples etched with 2 per cent nitric acid in alcohol

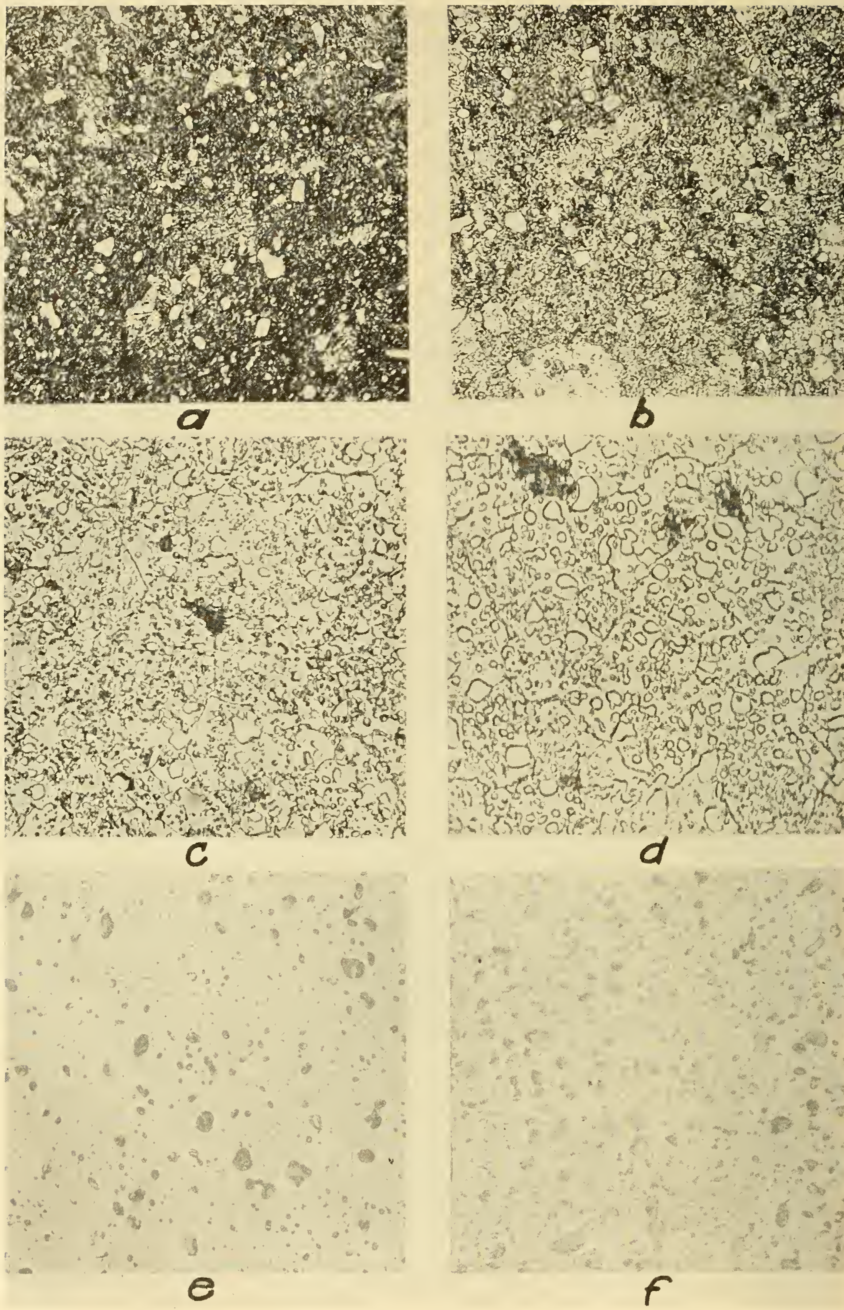

FIG. 13.—*Microstructure of 1 per cent carbon steel held at 760° C for various times and subsequently oil quenched and tempered at 538° C.* ×500

(*a*) ½ hour (*b*) 1 hour (*c*) 2 hours (*d*) 5 hours (*e*) ½ hour (*f*) 5 hours
Samples (*e*) and (*f*) etched with boiling sodium picrate. Other samples etched with 2 per cent nitric acid in alcohol

TABLE 15.—Effect of Time Slightly Below Ac_1 on the Mechanical Properties of 1 Per Cent Carbon Steel, Previously Oil Quenched from 843° C

Specimen No.	Heated at 704° C (1300° F) for time specified and then oil quenched	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
23B	½	126 200	86 000	18.8	46.7	260	40	3.3, 3.0	3.0, 2.8, 3.0
24B		140 200	....	17.0	40.2	248	40	....	4.5, 5.5, 6.0
Av.	....	133 200	86 000	17.9	43.4	254	40	3.2	4.1
34B	1	121 500	79 000	....	....	241	39	....	....
64B		113 200	81 500	19.0	48.4	235	39	....	....
Av.	....	117 350	80 250	....	....	238	39	....	....
35B	5	86 100	54 500	33.0	61.3	156	32	2.8, 8.4, 2.5	2.6, 2.3, 3.9
36B		93 900	72 000	....	....	207	34	....	....
Av.	....	90 000	63 250	....	....	182	33	4.6	2.9

V. DISCUSSION

As far as the tensile and impact properties of heat-treated 1 per cent carbon steel are concerned certain facts deserve emphasis in connection with the tests previously described. The steel remains extremely brittle, even though good combinations of tensile strength and ductility are obtained by suitable treatment. Such low resistance to impact makes the surface condition of the metal of great importance, so that moderately sharp corners and even scratches may greatly effect the behavior of the steel in service.

It is extremely sensitive to heat treatment. Small changes in the hardening temperature produce large differences in tensile properties, though after quenching in a given medium as in oil such differences may be largely removed by varying the tempering temperature.

To retain all excess cementite in solution when quenching in oil requires a relatively high temperature. The lowest temperature at which this may be brought about is, among other factors, dependent upon the time of heating prior to hardening and is lower the longer the "soaking," but must be at or above the range of solution of this carbide. Between Ac_1 and A_{cm} the excess cementite spheroidizes and coalesces to form larger globules, which are retained in the free state in the oil-quenched steel.

At temperatures slightly below Ac_1 long-time heating when followed by cooling in oil produces no change in the condition of the cementite which may be readily observed under the microscope.

In this connection attention is directed to a recent study of the formation of spheroidal cementite by Honda and Saitô.[23] The authors conclude that spheroidization of granular pearlite takes place below Ac_1 if held at temperature for a sufficiently long time, but that spheroidization of lamellar pearlite can not proceed until Ac_1 has been reached or exceeded. If the maximum temperature in heating exceeds a certain limit above this formation, the cementite appears as a lamellar pearlite on cooling, and therefore no spheroidization will take place.

The tests carried out in this investigation further indicate the importance of time at temperatures between Ac_1 and A_{cm} (Fig. 6). The sensitivity of 1 per cent carbon steel in this temperature range (within which it is ordinarily heated for hardening) to varying time-temperature relations is great, and the data obtained show why widely different results may so readily be obtained in the application of the heat-treated product.

VI. SUMMARY AND CONCLUSIONS

Based on the tests made under conditions previously described, the following conclusions are drawn:

1. The most suitable oil or water quenching temperature for steel which is subsequently to be tempered at relatively high temperatures is slightly above the end of the Ac_1 transformation.

2. With increase in oil-quenching temperature for steel subsequently tempered at 538° C (1000° F) hardness, strength, and limit of proportionality increase and maximum values are obtained after quenching from 843° C (1550° F) which is coincident with retention of all but a small portion of the excess cementite. A higher quenching temperature results in decreased strength.

3. When this steel is subsequently to be tempered to produce tensile strength in the neighborhood of 120 000 lbs./in² water quenching is to be preferred on account of the higher elastic ratio produced, always assuming that the size and shape of material is such as to allow drastic treatment. If higher strength is desired (which condition requires lower tempering), oil quenching from

[23] K. Honda and S. Saito, "On the formation of spheroidal cementite," Jr. I. and S. Inst., 2, p. 261; 1920.

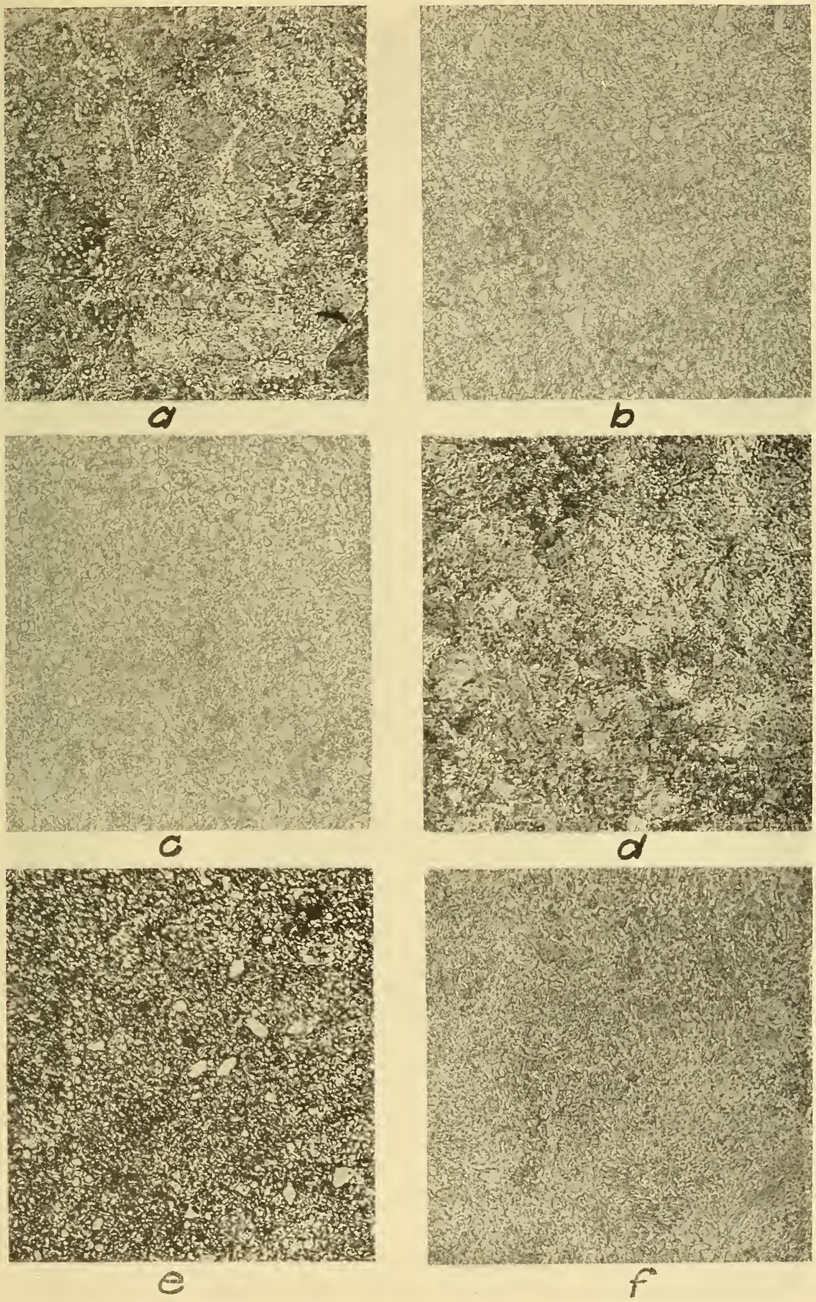

FIG. 14.—*Microstructure of 1 per cent carbon steel oil quenched from 788° C or 843° C and subsequently tempered at different temperatures.* ×500

(*a*) Quenched from 788° C and tempered at 316° C (600° F)
(*b*) Quenched from 788° C and tempered at 649° C (1200° F)
(*c*) Quenched from 788° C and tempered at 704° C (1300° F)
(*d*) Quenched from 843° C and tempered at 316° C (600° F)
(*e*) Quenched from 843° C and tempered at 649° C (1200° F)
(*f*) Quenched from 843° C and tempered at 704° C (1300° F)
All samples etched with 2 per cent nitric acid in alcohol

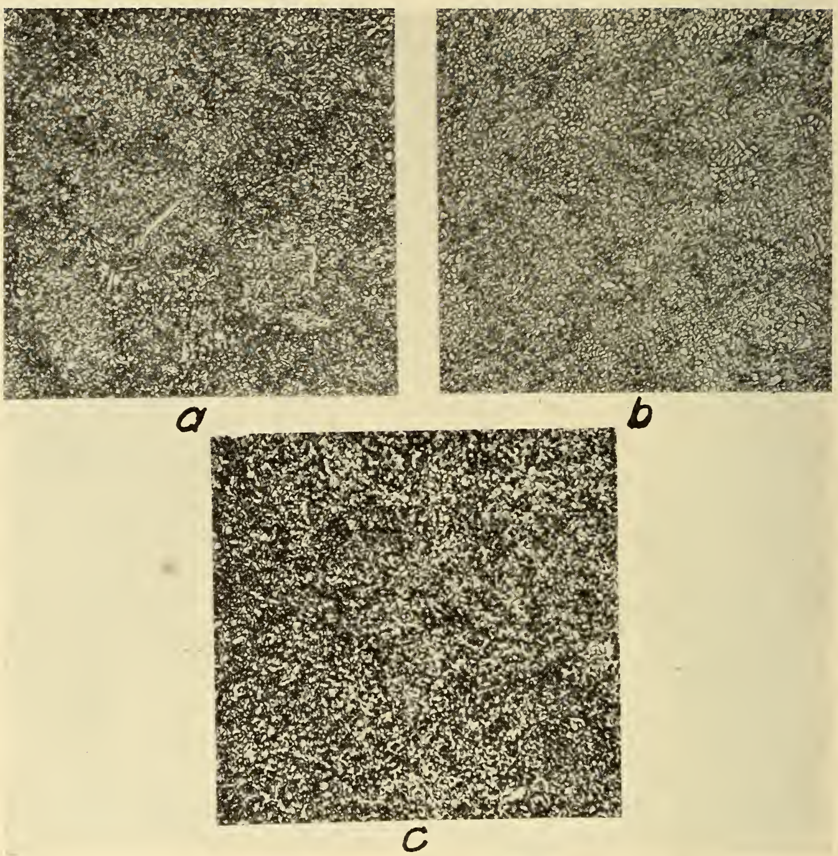

Fig. 15.—*Microstructure of 1 per cent carbon steel water quenched from 788° C and subsequently tempered at different temperatures.* ×500

(*a*) 538° C (1000° F) (*b*) 649° C (1200° F) (*c*) 704° C (1300° F)

Samples etched with 2 per cent nitric acid in alcohol

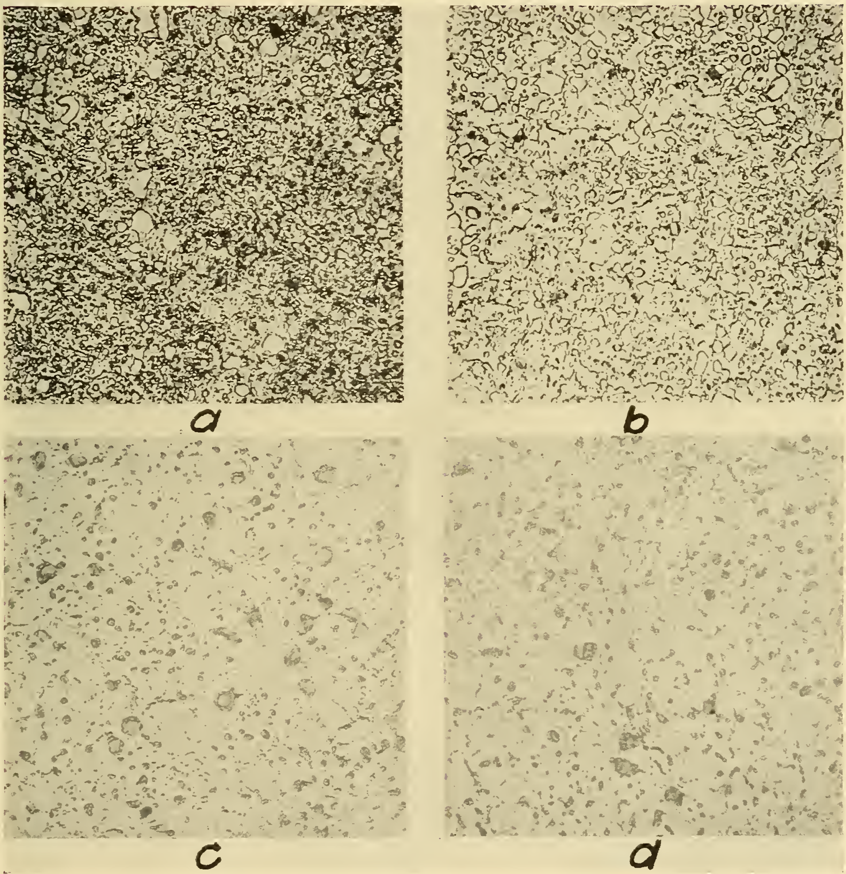

FIG. 16.—*Microstructure of 1 per cent carbon steel oil quenched from 843° C and subsequently tempered for various times at a temperature slightly below Ac_1.* ×500

(*a*) 1 hour (*b*) 5 hours (*c*) 1 hour (*d*) 5 hours

(*a*) and (*b*) etched with 2 per cent nitric acid in alcohol; (*c*) and (*d*) etched with boiling sodium picrate

just above the Ac_1 transformation will give slightly better combinations of strength and ductility but with lower elastic ratio than are obtained by water hardening.

4. A lower tempering temperature is required after water hardening than when cooling in oil from the same temperature in order to produce the same strength. This difference in temperature in general increases the higher the strength required (the lower the tempering temperatures).

5. When samples are quenched in water and others quenched in oil and all so tempered as to produce the same strength, the water-quenched steel will have the highest hardness as determined by the Brinell and Shore methods.

6. While good combinations of tensile strength and ductility may be obtained by tempering at the higher tempering temperatures, the steel is brittle and has low resistance to impact. This is shown by the much higher combinations of strength and ductility obtained in tensile tests when the steel is ground to size after heat treatment and by the low Charpy and Izod values obtained in all cases.

7. Increased time at hardening temperatures results in increased hardness, strength, and limit of proportionality, and decreased ductility, as does rise in temperature.

8. Long-time heating just under the lower critical range results in a material softening of the steel, equivalent to a decrease of 40 per cent in Brinell hardness and 20 per cent in Shore hardness when the time at temperature is increased from 30 minutes to 5 hours. Short-time heating in this temperature range results in a softer steel than that air cooled from above the transformations.

9. The changes in physical properties which have been described are in all cases coincident with well-defined structural changes.

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