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EFFECT OF GRAIN SIZE AND HEAT TREATMENT UPON IMPACT-TOUGHNESS AT LOW TEMPERATURES OF MEDIUM CARBON FORGING STEEL

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ABSTRACT

A study was made of the effect of grain size and heat treatment upon the impact-toughness of SAE 1050 steel, as judged by the temperature range wherein cold-brittleness occurred. There was no relation between grain size and impact-toughness in the hot-rolled steels. Normalizing improved this property, and in this condition the fine-grained steels proved superior to the coarse-grained steels. The toughness of the steels, either as hot-rolled or as normalized, was relatively low, but was markedly increased by hardening and tempering. Normalizing prior to heat treatment had no effect upon the impact properties. When heat-treated, there was no relation between grain size and impact-toughness. Each individual heat of steel appeared to have an inherent resistance to impact, dependent upon factors not at present recognized. Impact-toughness at room temperature was no criterion of impact-toughness at lower temperatures.

CONTENTS

I. INTRODUCTION

The purpose of this study was to determine the influence of grain size and heat treatment upon the impact properties at low temperatures of medium-carbon forging steels and to determine the temperature range in which brittleness of the steel occurs. This range is characterized by a marked decrease in the observed impact values accompanied by a change in the appearance of fracture from a fibrous one to a granular one. The study was made in cooperation with the Bureau of Aeronautics, Navy Department.

The technical literature contains numerous references on the impact-toughness of steel. Most data presented appear to substantiate the conclusion that fine-grained steel is superior in toughness to coarse-grained steel [1 to 6],[1] although a contrary opinion has been expressed [7].

II. MATERIALS AND METHODS OF TEST

Six heats of SAE 1050 steel, furnished by the Bethlehem Steel Corporation in the form of hot-rolled 1-in. diameter rods, were used in this study. The chemical compositions of these steels, as deter-

[1] Figures in brackets refer to the literature references at the end of this paper.

mined at this Bureau, are given in table 1. The microstructures and grain sizes of the steels in the as-received condition are shown in figure 1.

Steels *A*, *B*, and *C* were submitted by the manufacturer as having a coarse McQuaid-Ehn grain size and steels *D*, *E*, and *F* a fine grain size. However, tests made by carburizing at 1,700° F for 18 hours (the usual procedure for McQuaid-Ehn tests) showed that steel *C* was a medium fine-grained steel. The grain sizes developed in the McQuaid-Ehn tests are shown in figure 2 and table 2.

Each steel was tested in eight conditions of heat treatment, and the hardness for each was determined (table 3).

TABLE 1.—*Chemical composition of the steels* [1]

Steel	Constituent									
	C	Mn	P	S	Si	O_2	N_2	H_2	Al	Al_2O_3
	%	%	%	%	%	%	%	%	%	%
A	0.49	0.79	0.023	0.023	0.22	0.005 .004	0.004 .005	0.0003 .0001	0.002	0.001
B	.45	.80	.019	.023	.19	.006 .006	.004 .004	.0001 .0001	.002	.001
C	.52	.85	.021	.031	.29	.004 .005	.005 ND [2]	.0002 ND [2]	.002	.005
D	.49	.80	.022	.028	.21	.003 .003	.003 .004	ND [2] .0003	.016	.007
E	.46	.55	.040	.039	.20	.005 .003	.006 .005	.0003 .0003	.019	.004
F	.45	.59	.021	.028	.24	.002 .003	.003 .004	.0002 .0002	.013	.004

[1] Chemical analyses were made by W. H. Jukkola, gas analyses by V. C. F. Holm, both of the National Bureau of Standards.
[2] ND=not detected.

TABLE 2.—*Austenitic grain size of the steels*

Steel	At 1,475° F		At 1,600 F		As hot-rolled		As carburized (McQuaid-Ehn)	
	Grains per sq in. at ×100	ASTM grain size No.	Grains per sq in. at ×100	ASTM grain size No.	Grains per sq in. at ×100	ASTM grain size No.	Grains per sq in. at ×100	ASTM grain size No.
A	50	7	19	5	7	4	35	3
B	50	7	9	4	9	4	35	3
C	110	8	95	7	8	4	37	6
D	150	8	140	8	14	5	100	8
E	150	8	130	8	16	5	110	8
F	130	8	110	8	17	5	105	8

TABLE 3.—*Heat treatment and hardness of the steels*

Heat treatment [a]	Rockwell Hardness number for steels—					
	A	*B*	*C*	*D*	*E*	*F*
As received (hot-rolled)	B 95	B 91	B 97	B 94	B 88	B 89
As received, water-quenched from 1,475° F, tempered at 1,000° F	C 32	C 30	C 33	C 32	C 28	C 26
As received, water-quenched from 1,475° F, tempered at 1,150° F	C 23	C 21	C 24	C 22	C 19	C 19
As received, water-quenched from 1,475° F, tempered at 1,300° F	C 14	C 12	C 14	C 15	C 11	C 11
As normalized (air-cooled from 1,600° F)	B 97	B 93	B 96	B 93	B 89	B 88
Normalized, water-quenched from 1,475° F, tempered at 1,000° F	C 32	C 29	C 32	C 31	C 28	C 28
Normalized, water-quenched from 1,475° F, tempered at 1,150° F	C 22	C 20	C 23	C 22	C 20	C 18
Normalized, water-quenched from 1,475° F, tempered at 1,300° F	C 13	C 13	C 15	C 14	C 11	C 11

[a] All steels were held for 1 hour at normalizing and tempering temperatures and ½ hour at hardening temperatures. Bars were shaped to ½-in. square and cut to lengths of about 15 in. prior to heat treatment.

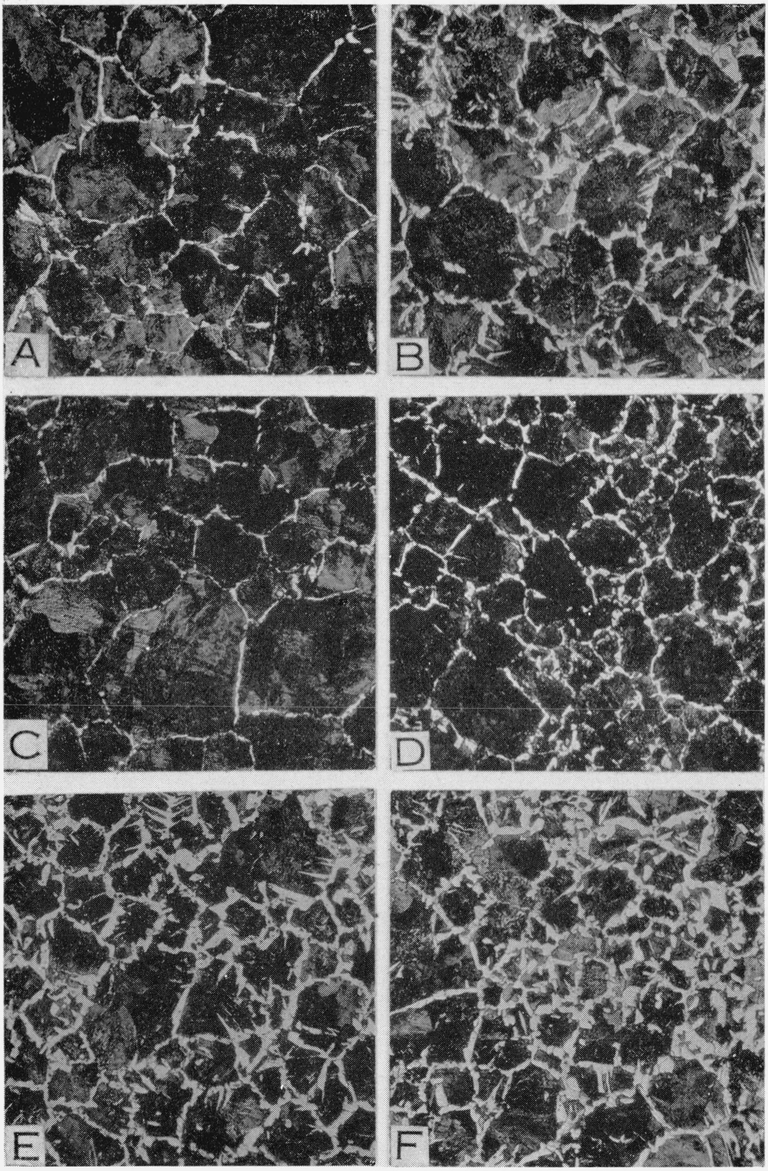

FIGURE 1.—*Microstructures of the steels as hot-rolled.*

Etched with 1-percent nital. ×100. The letters on the micrographs correspond with the designations used for the individual steels.

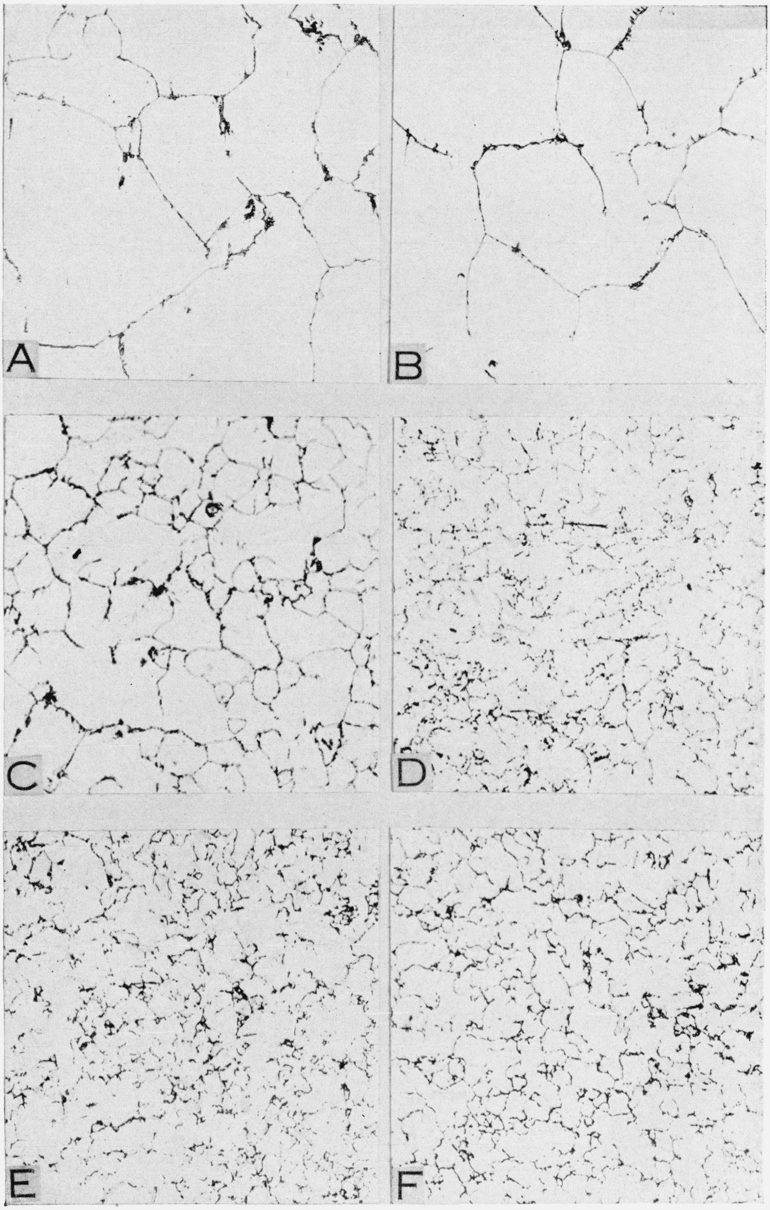

Figure 2.—*Grain size of the steels as developed by the McQuaid-Ehn test.*

Etched with boiling sodium picrate. ×100. The letters on the micrographs correspond with the designations used for the individual steels.

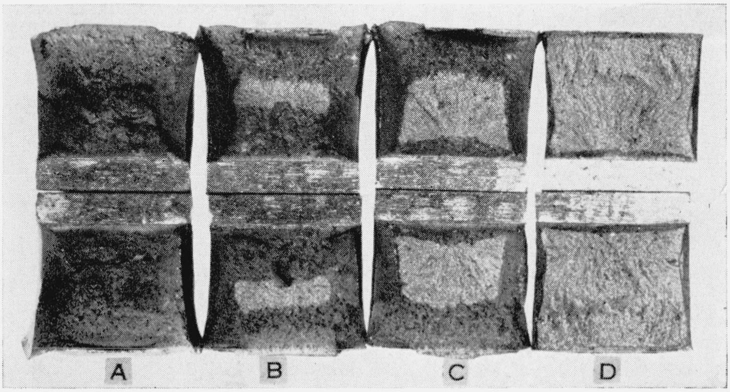

FIGURE 3.—*Appearance of typical Charpy impact fractures.* ×2.

A, Fibrous fracture obtained by testing specimen at a temperature above the cold-brittle range. Fracture was accompanied by considerable deformation and the energy absorbed was high.

B, Partly fibrous, partly granular fracture obtained by testing specimen at a temperature within the cold-brittle range.

C, Partly fibrous, partly granular fracture obtained by testing specimen at a temperature within the cold-brittle range.

D, Granular fracture obtained by testing specimen at a temperature below the cold-brittle range. Fracture was accompanied by but little deformation, and the energy absorbed was low.

The austenitic grain sizes (table 2) were determined on bars 3 in. long, after heating at 1,475° F and 1,600° F and quenching one end into water. To eliminate variables in grain size, the procedure (rate of heating, time at temperature, etc.) was approximately the same as that employed during the heat treatment of the steels.

The specimens used for impact tests were 10 mm square by 55 mm long with a 45° V-notch 2 mm deep having a root radius of 0.25 mm. Since the shape of the notch can influence the impact properties of a specimen, particular care was exercised in grinding the cutter used for this work. All impact tests were made in quadruplicate at test temperatures of +100° C, room temperature, 0°, −20°, −40°, and −78° C in a Charpy machine having a capacity of 224 foot pounds. The constants of this machine and details of test procedure have been given in a previous paper [8].

III. RESULTS OF THE TESTS AND GENERAL DISCUSSION

Before proceeding to a discussion of the results of the tests, it is advisable to consider the meaning of the results of impact tests, particularly as modified by test temperatures.

It should be pointed out that any impact test is only qualitative, despite the fact that results are given numerical values indicative of the energy absorbed during the deformation and fracture of test specimens. The primary objective of impact tests of steels is to ascertain the relative tendency of different steels to fail in a brittle fashion, and this cannot be accomplished by making a few impact tests under one set of conditions. Slight changes in the size and shape of the test specimen, in the depth or sharpness of the notch, in total energy or velocity of the hammer, or in temperature, may cause disproportionate changes in the results of impact tests. At least one of these factors must be varied in order to obtain a true picture of the impact-deformation characteristics of any steel. The effects of these various factors and the interpretation of the results of impact tests are discussed by McAdam and Clyne [9] and by Hoyt [10].

The location of the temperature range wherein impact values are markedly decreased and the type of fracture changes from fibrous to granular (the cold-brittle range) is not a definite temperature range for any special steel. It may be moved to higher or lower temperatures merely by changing any one of numerous test variables. The *relative* tendency of a steel toward cold brittleness may, however, be established by studying the effect of test temperature upon the results of impact tests made under a certain set of test conditions. The temperature range in which cold brittleness occurs is an indication of the impact-toughness of the steel being tested. Under comparable conditions of test, the lower the temperature at which this transition occurs, the more dependable is that steel for engineering service. This statement is true despite the fact that a steel may absorb greater energy in impact at a temperature above and at one below the cold-brittle range than does another steel.

The appearance of the impact fractures obtained over a range of test temperatures, with all other factors constant, is an excellent guide to the impact-toughness of the steel under study. Typical fractures, shown in figure 3, are of three types. That shown in figure

3 (*A*), the fibrous or tough type, is accompanied by appreciable deformation and high energy absorption, and occurs at temperatures above the cold-brittle range. That shown in figure 3 (*D*) is of the granular or brittle type, is accompanied by little or no deformation and low energy absorption, and occurs below the cold-brittle range. Those shown in figure 3 (*B* and *C*) are typical of breaks which occur within the cold-brittle range. The relative areas of fibrous and granular appearance may vary widely, with concomitant variations in the

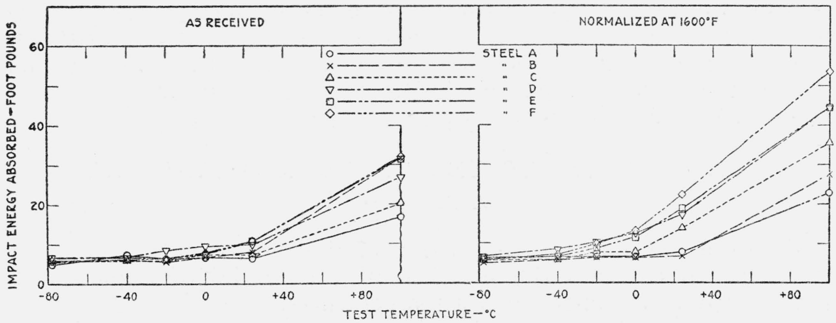

FIGURE 4.—*Effect of test temperature upon the impact-toughness of the steels as hot-rolled and as normalized.*

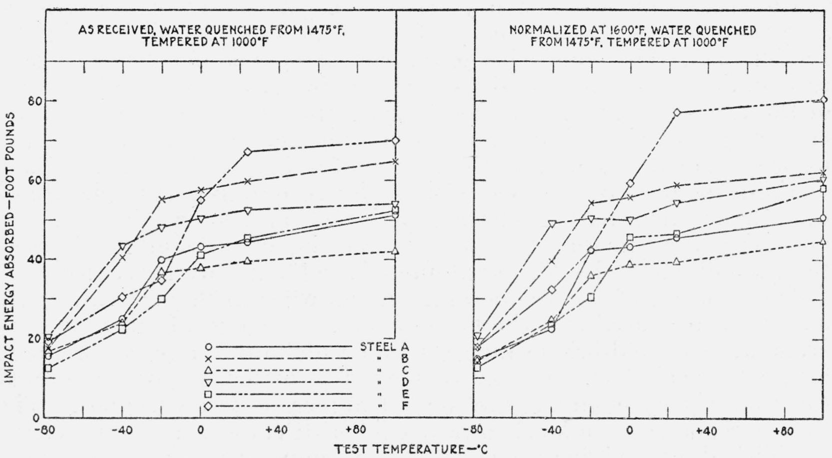

FIGURE 5.—*Effect of test temperature upon the impact-toughness of the steels as hardened and tempered at 1,000° F.*

impact-energy absorbed. The theory underlying the discontinuity of the transition from fibrous to granular fracture has been discussed by McAdam and Clyne [9].

The values obtained in impact tests at various temperatures are presented in several ways to show a comparison:

1. Between steels in the as-received condition and after normalizing at 1,600° F (fig. 4).

2. Of the effect of tempering at 1,000°, 1,150°, and 1,300° F on steels quenched from 1,475° F in both as-received and normalized conditions (figs. 5 to 7).

3. Of the effect of the various heat treatments on each steel individually (figs. 8 to 13).

Figure 4 shows that there was no significant difference between the impact resistance of the as-received and normalized steels at room temperature or below. The impact resistance was low, the fractures

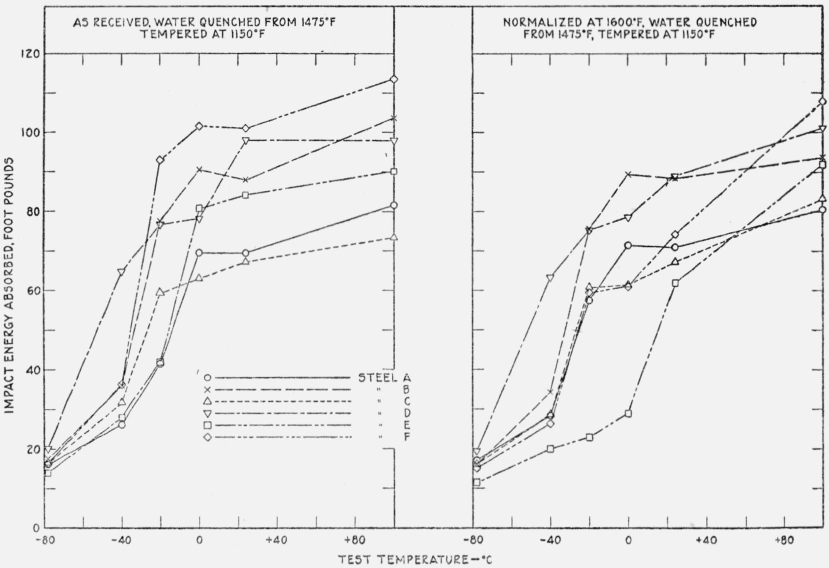

FIGURE 6.—*Effect of test temperature upon the impact-toughness of the steels as hardened and tempered at 1,150° F.*

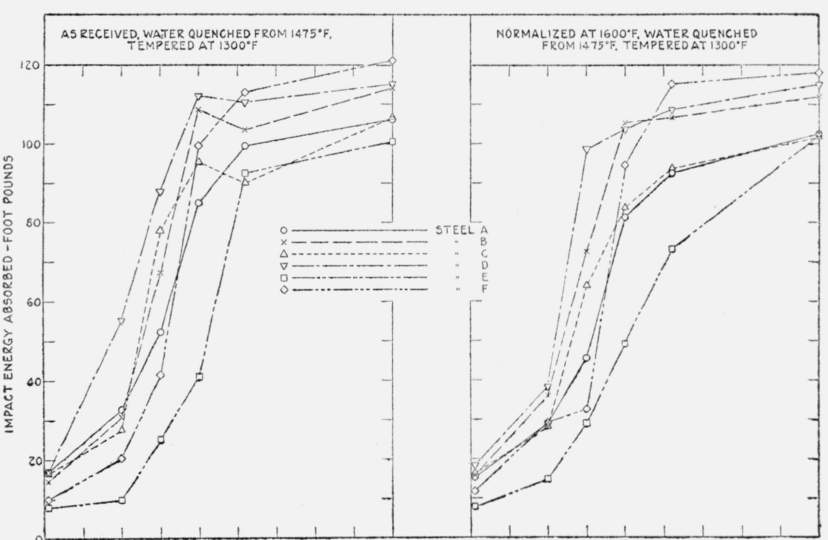

FIGURE 7.—*Effect of test temperature upon the impact-toughness of the steels as hardened and tempered at 1,300° F.*

were granular, and the cold-brittle range, as determined under the specific conditions of test, occurred above room temperature.

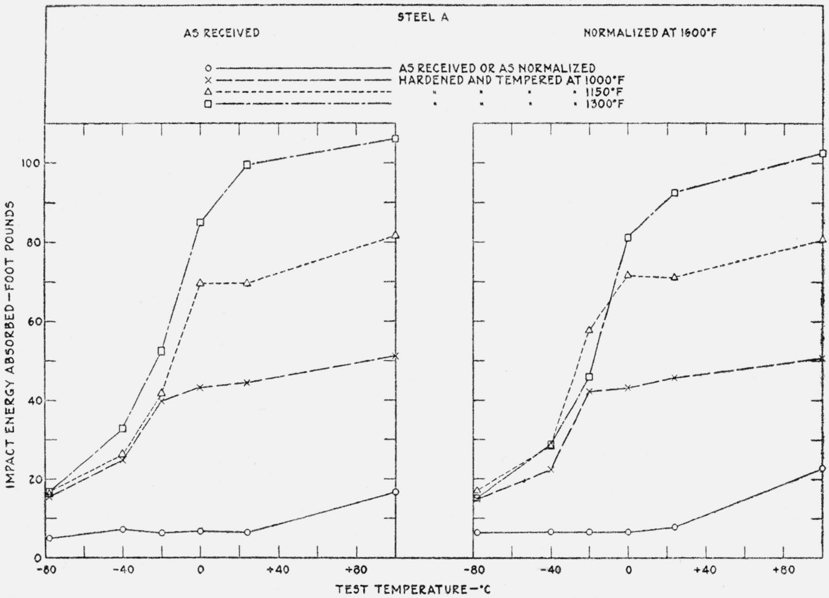

FIGURE 8.—*Comparison of the effect of different heat treatments upon the impact-toughness of steel A at different temperatures.*

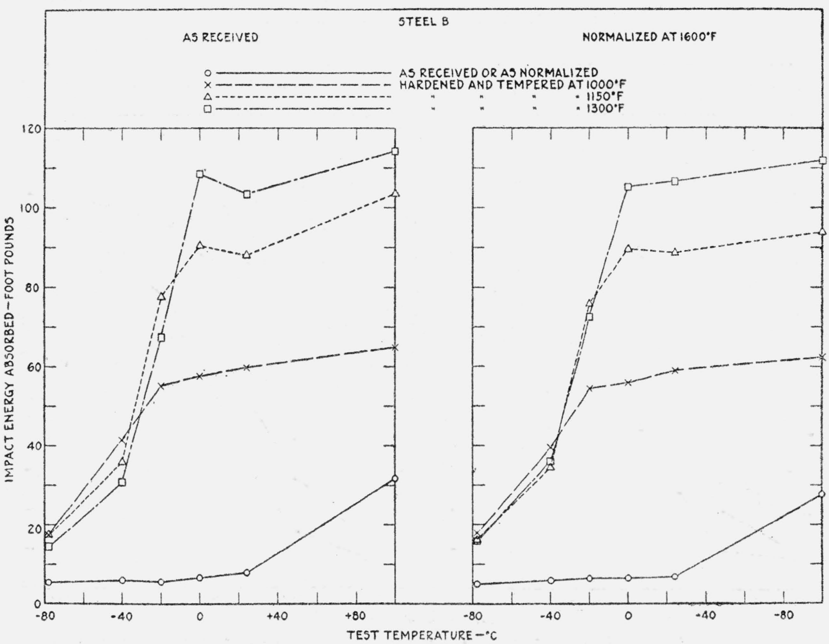

FIGURE 9.—*Comparison of the effect of different heat treatments upon the impact-toughness of steel B at different temperatures.*

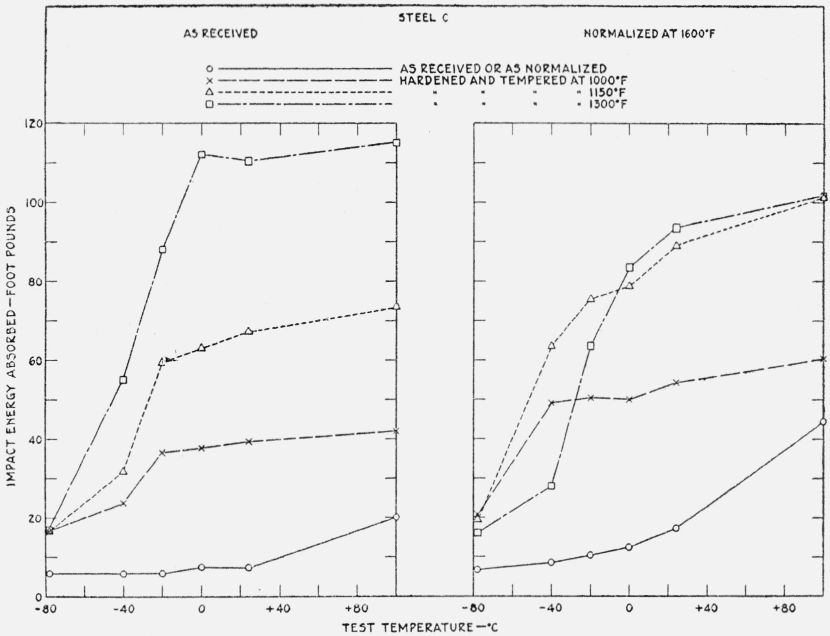

FIGURE 10.—*Comparison of the effect of the different heat treatments upon the impact-toughness of steel C at different temperatures.*

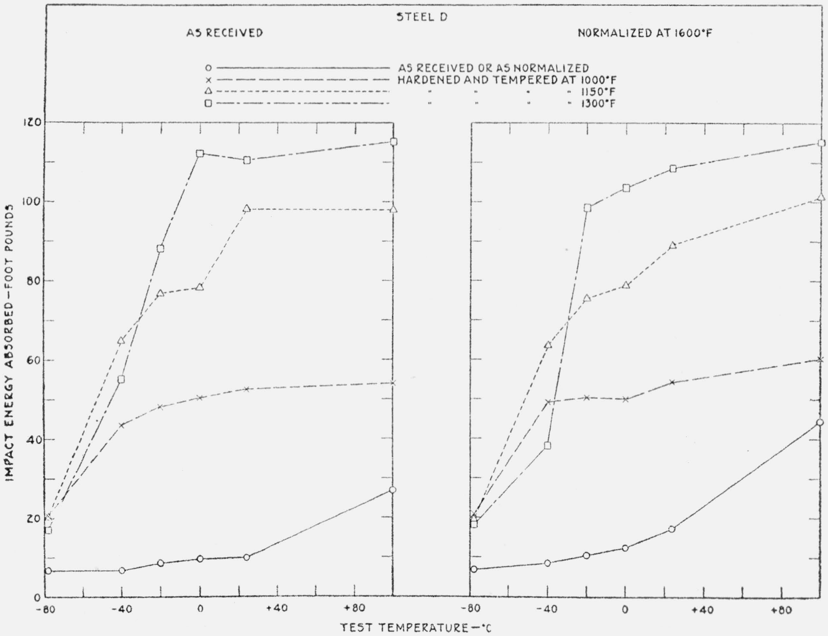

FIGURE 11.—*Comparison of the effect of different heat treatments upon the impact-toughness of steel D at different temperatures.*

In the as-received condition all of the steels exhibited granular, or mostly granular fractures, at +100° C. In this condition, therefore, the cold-brittle range of all the steels occurred above +100° C.

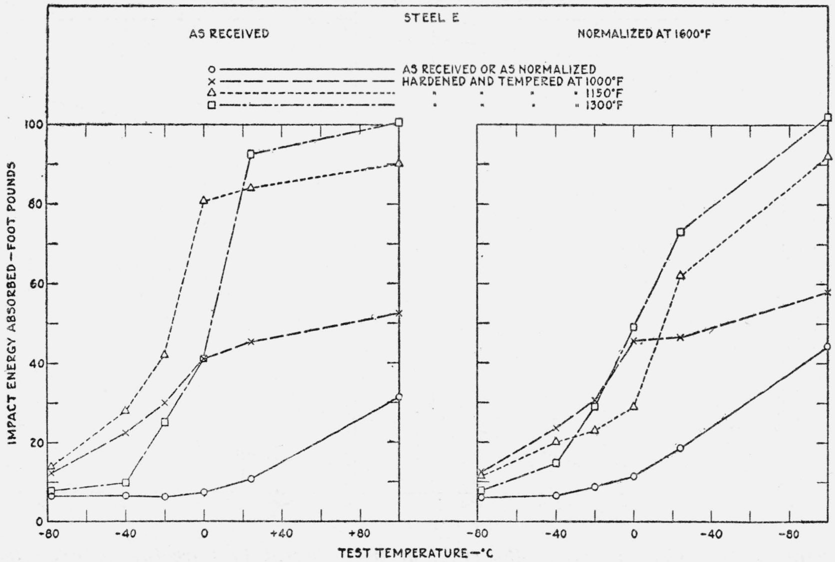

Figure 12.—*Comparison of the effect of different heat treatments upon the impact-toughness of steel E at different temperatures.*

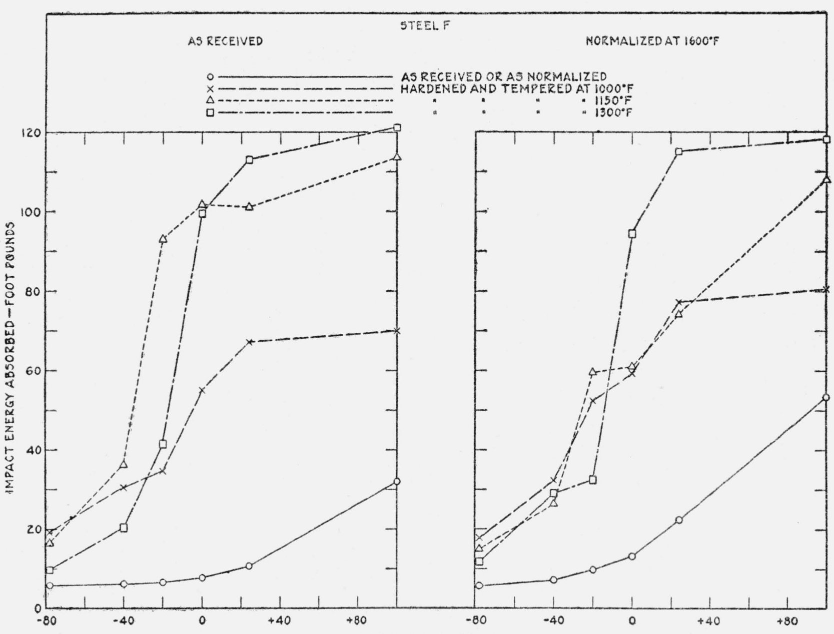

Figure 13.—*Comparison of the effect of different heat treatments upon the impact-toughness of steel F at different temperatures.*

In the normalized condition, steels *D*, *E*, and *F*, at +100° C, had fibrous fractures, high impact values, and the cold-brittle range, therefore, occurred between room temperature and +100° C. These steels had fine McQuaid-Ehn grain sizes (No. 8), as well as fine grain sizes at the normalizing temperature (also No. 8). Steel *C*, as normalized, had somewhat lower impact resistance at +100° C, the fractures were partly fibrous and partly granular, and the cold-brittle range occurred in the neighborhood of +100° C. This steel had a medium-fine McQuaid-Ehn grain size (No. 6), and at the normalizing temperature its grain size was No. 7. Steels *A* and *B*, both of which had coarse McQuaid-Ehn grain sizes (No. 3), exhibited granular fractures at +100° C, and the cold-brittle range, therefore, must be located at some temperature above +100° C. At the normalizing temperature, steels *A* and *B* had grain sizes of No. 5 and No. 4, respectively.

It is apparent that (1) normalizing caused an improvement in the impact-toughness of fine-grained SAE 1050 steel as compared with the same steel as hot-rolled, and (2) the impact-toughness of the normalized steels was related to both the McQuaid-Ehn and the austenitic grain size—the finer the grain size the greater the toughness. No relation between grain size and impact-toughness was apparent in the hot-rolled steels under the specific conditions of test. This type of steel (SAE 1050) does not, however, have appreciable impact-toughness in either the as-rolled or as-normalized conditions. This deficiency can be remedied by suitable heat treatment.

The effect of quenching from the proper temperature and tempering at relatively high temperatures was to lower markedly the temperature range within which cold-brittleness occurred (figs. 5, 6, and 7). None of the steels was cold-brittle at room temperature. In a few instances, cold-brittleness was manifested between room temperature and 0° C; but usually it did not occur above 0° C, and in many cases was observed only at temperatures lower than −40° C.

From figures 5, 6, and 7, it is obvious that the cold-brittle range of steel *D*, in all conditions of heat treatment, occurred at lower temperatures than in any of the other steels. This steel may therefore be considered to have the best impact-toughness, even though other steels sometimes had higher impact values at temperatures above the cold-brittle range. Steel *D* had a fine McQuaid-Ehn grain size and a fine austenitic grain size at the heat-treating temperature (1,475° F.). Steel *E*, however, with the same grain size as steel *D*, consistently exhibited the minimum impact-toughness, as measured by the location of the cold-brittle range, in all conditions of heat treatment.

Steel *B*, which generally showed the second-best impact-toughness, had a coarse McQuaid-Ehn grain size and a fine austenitic grain size (on the low side of No. 7) at the hardening temperature. Steel *A*, with the same grain sizes as steel *B*, however, had decidedly lower impact-toughness than steel *B* in the various conditions of heat treatment.

From the foregoing discussion it may be concluded that when heat-treated (1) there was no significant relation between grain size and impact toughness in SAE 1050 steel, and (2) each heat of SAE 1050 steel had its own characteristic resistance to impact. Another point to be emphasized is that high impact-toughness at room temperature

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was no assurance of superior impact-toughness at lower temperatures. This is particularly well illustrated by the curves in figure 5, which show that steel *F* had higher numerical values for impact resistance when tested at room temperature than any of the other steels. When the impact-temperature curve is examined, however, it may be seen that cold-brittleness was manifested at higher temperatures in steel *F* than in steels *B* and *D*.

The curves in figures 8 to 13 illustrate the effect of heat treatment upon the impact-toughness of the individual steels at the various test temperatures. Normalizing prior to heat treatment had no beneficial effect upon the impact-toughness of any of the steels. At room temperature, maximum resistance to impact was obtained with specimens tempered at 1,300° F and minimum resistance with specimens tempered at 1,000° F. This condition did not always exist at lower test temperatures. The tempering temperature for maximum impact toughness, as judged by the impact-temperature curves, varied in the different steels. In general, the tempering temperature of 1,150° F seemed to impart maximum impact-toughness.

IV. SUMMARY AND CONCLUSIONS

A study was made of the effect of McQuaid-Ehn and austenitic grain sizes at heat-treating temperatures and of different heat treatments upon the low-temperature impact-toughness of six heats of SAE 1050 steel. Charpy impact tests, of standard Charpy V-notch specimens, were made at temperatures ranging from +100° C to −78° C. Under the specific conditions of test described, the following conclusions appear justified:

1. SAE 1050 steel, either as hot-rolled or as normalized, has low impact-toughness. In the hot-rolled condition this type of steel is cold-brittle at room temperature and the transition range to cold-brittleness occurs at temperatures above +100° C. Normalizing the hot-rolled steel improves the impact-toughness at room temperature and above, and the range of temperature at which cold-brittleness occurs is lowered, in some cases, to below +100° C.
2. Differences in grain size in the normalized steels appear to exert an influence on the impact toughness; the finer the McQuaid-Ehn or the normalized grain size, the lower is the temperature at which cold-brittleness is manifested. This trend was not observed, however, with the hot-rolled steels.
3. Impact-toughness is markedly improved by hardening and tempering, but normalizing prior to heat treatment has no effect upon this property.
4. Impact-toughness at room temperature is no criterion of impact-toughness at lower temperatures.
5. Fine grain size, either McQuaid-Ehn or austenitic, is no assurance of impact-toughness superior to that of coarser-grained steel similarly heat-treated (quenched and tempered), particularly as regards the occurrence of cold-brittleness.
6. SAE 1050 steel, in various conditions of heat treatment, does not have a characteristic resistance to impact in the same sense, for instance, as it has a characteristic tensile strength. Each individual heat, when heat-treated, apparently has an inherent resistance to impact between certain limits, and this is dependent upon factors not at present recognized.

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