Mechanical Properties and Microstructure of Plain Low-Carbon Steels after Quenching

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Abstract

The mean austenite grain size of two plain low-carbon steels were investigated using International Standard (ISO 643) with determination of grain size by comparing to the standard charts and application to the index G equation. The grain size of austenite was evaluated after heating at 1000-1200°C for 1-6 h and water quenching. The grain size in many samples are similarly, because the heating temperatures were too high, and had been retarded recrystallization and grain growth by the aluminium single alloying. During overheating, a coarse grain structure is obtained, such a coarse-grained structure will have poor mechanical properties. It was found that the Vickers hardness estimated had good correlation to grain size.

1. Introduction

By far the largest fraction of plain low-carbon steels goes into flat-rolled products of low carbon content. The remainder is made as bars, rods, wire, plates, structural shapes, rails, and railroad wheels. No sharp division can be made between these two groups of products on the basis of physical metallurgy. They are commonly used without heat treatment subsequent to forming, but of course plain low-carbon steels can be heat treated by the user. The steels contain carbon, in amounts usually less than 1%, as the alloying element that controls the properties. They also contain limited amounts of manganese and impurities, such as sulfur and phosphorus [23].

The Initial Austenite Grain Size

The austenite without significant grain refiners added [19] forms by the nucleation of austenite grains at various locations, and their growth. Eventually they begin to impinge, and finally the pearlite disappears. At this stage, the steel has its initial austenite grain size. From nucleation and growth theory, the number of grains per unit area N_i in a planar cut through a sample is given by [4] :

$$N_i = 1.01\,(N/G)^{1/2} \quad (1)$$

therefore $N = K\exp(\Delta G_C/RT)\exp(-\Delta G_b/RT)$ (2)

and $G = K(\Delta g_v)\exp(-\Delta G_b/RT)$ (3)

where N is the nucleation rate, G is the growth rate, ΔG_C is the critical free energy change, ΔG_b is the free energy barrier change and Δg_v is the free energy change per volume. From N_i the grain size can be obtained.

Hardening of Plain Low-Carbon Steel

Hardening may be defined as rapid cooling of plain low-carbon steel from the austenite phase. The rapid cooling is obtained by immersion of the steel in a liquid bath such as water. The main purpose of hardening of the steel is, to increase hardness, strength and wear resistance, and to obtain a suitable microstructure which will have desired mechanical properties [2].

For the plain low-carbon steel, the procedure involves heating to a suitable austenitizing temperature, to dissolve the carbon and alloy in the austenitic structure existing at that temperature. The steel is then

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quenched to ambient temperature, during which time the austenite transforms. Depending on the cooling rate and the hardenability of the steel, the transformation product may be martensite, a higher temperature transformation product such as bainite, pearlite or even ferrite/pearlite, or a mixture of the various alternatives. When a fully martensitic product is obtained, the steel may contain retained austenite in amounts depending on the carbon and/or alloy content. The resulting structure is usually tempered to modify the properties of the as-quenched structure and particularly to improve the toughness [6].

Determination of Grain Size

The International Standard (ISO 643) specifies a micrographic method of determining apparent grain size in plain low-carbon steels. It describes the methods of revealing grain boundaries and of estimating the mean grain size of specimens with unimodal size distribution. The image examined on the screen (or on a photomicrograph) is compared with a series of standard charts or overlays. The standard charts at a magnification of x 100 are numbered from 00 to 10 so that their number is equal to the index G. Where the magnification g of the image on the screen or photomicrograph is not x 100, the index G shall be equal to the number M of the closest standard chart, modified as a function of the ratio of the magnifications [10] :

$$G = M + (6.64 \log g/100) \quad (4)$$

Hardness Correlations and Conversions

The deformations caused by a hardness indenter are of similar magnitude to those occuring at the ultimate tensile strength in a tension test. However, an important difference is that the material cannot freely flow outward, so that a complex triaxial state of stress exists under the indenter. Nevertheless, empirical correlations can be established between hardness and tensile properties, primarily the ultimate tensile strength, R_m. For plain low-carbon and alloy steels, a conversion chart for estimating various types of hardness from one another, and also ultimate tensile strength, is given as Table 1 [18].

2. Experimental Procedure

Plain low-carbon steels were separated as two groups, with and without silica sand covered during various heat treatment and studied to optimise the influence of single alloying additions on the mechanical properties and grain size structures. The composition (wt%) of these steels used in this study is given in Table 2. The samples were austenitized at 1000, 1100, and 1200°C for 1, 3 and 6 h.

Table 1. Approximate equivalent hardness numbers and ultimate tensile strengths for carbon and alloy steels

Brinel	Vickers	Rockwell		Ultimate, R_m	
lHB	HV	H R B	H R C	MPa	ksi
627	667	-	58.7	2393	347
578	615	-	56.0	2158	313
534	569	-	53.5	1986	288
495	528	-	51.0	1813	263
461	491	-	48.5	1669	242
429	455	-	45.7	1517	220
401	425	-	43.1	1393	202
375	396	-	40.4	1267	184
341	360	-	36.6	1131	164
311	328	-	33.1	1027	149
277	292	-	28.8	924	134
241	253	100	22.8	800	116
217	228	96.4	-	724	105
197	207	92.8	-	655	95
179	188	89.0	-	600	87
159	167	83.9	-	538	78
143	150	78.6	-	490	71
131	137	74.2	-	448	65
116	122	67.6	-	400	58

Table 2. Chemical composition of experimental plain low-carbon steel, wt%

Element	Steel 27 Mn4	Steel 16 Mn4
C	0.27	0.16
Mn	1.01	1.08
Si	0.38	0.41
P	0.018	0.018
S	0.010	0.011
V	-	-
Ti	-	-
Al	0.04	0.03

The austenite grain size microstructure of all the relavant samples representative photomicrographs were taken. In order to determine the grain size, the samples were specially atched in a saturated picric acid solution at about 80°C [1]. The concentration of the acid had to be adjusted for different samples. The grain size was then measured at x 25 using a filler eyepiece.

The austenite grain size determination should be done in a magnification suited to the size of the grain so that small grains may not be lost. The degree of magnification will be limited by the fact that the picture must include a sufficient number of grains [22]. The all austenite grain size microstructures of the sample steels are shown in Fig. 1.

3. Result and Discussion

Since the austenite grain size of plain low-carbon steel is an important factor, it was necessary to compare the grain size between the different temperatures and times of the steels. The austenite grain boundaries were revealed by etching the specimens for evaluated the mean grain sizes. Table 3 shows the evaluated mean austenite grain size characteristics, Vickers hardness, and ultimate tensile strength of eighteen samples. Similarly,the relation of mean austenite grain size (μm) with austenitizing temperature (° C), time (h), Vickers hardness (HV10), and Ultimate tensile strength (MPa) is reported in Fig. 2,3,4 & 5, respectively.

The evaluation mean austenite grain size of plain low-carbon steels were shown a primary structure response. The steels were killed with aluminium and therefore they are inherently fine-grained, and can be successfully heat treated at higher temperature and hold for longer period of time without the danger of grain growth, and had major effect on retarding recrystallization. There are usually carbide and are often present in steels that have also been strengthened by precipitation and solid solution strengthening. The kinetics solution of secondary phase are strongly temperature and time dependent, so varying results can be obtained with steel depending on its temperature history. The mean grain size of austenite in many samples are similarly, because the temperatures were high and had been retarded recrystallization and grain growth by the single alloying. During overheating, a coarse grain structure is obtained, such a coarse-grained structure will have poor mechanical properties. The reasons of complication and great affected by a large number of variables which may reduce the hardness to an appreciable extent are as follows:

1) Austenitizing temperature
2) Soaking time
3) Delay of quenching
4) Type of quenching medium
5) Temperature of quenching medium
6) Agitation and circulation of liquid bath
7) Alloying elements in plain low-carbon steel
8) Mass and size of the object

4. Conclusions

The following conclusions may be drawn from the results presented in this paper:

1) Plain low-carbon steels, killed with additionally aluminium result in inherently fine-grained steels, and can be successfully austenitized at higher temperature (up to 1000°C) and hold for longer period of time (up to 6 h for steel 27 Mn4) without the danger of abnormal grain growth.

2) Prolonged heating at higher temperature results in decarburization and excessive scaling of steel.

3) Austenite grain size of plain low-carbon steel has a marked effect on its mechanical properties. A coarse-grained steel will have a comparatively smaller hardness, tensile strength as compared to fine-grained steel.

4) There is good correlation between the Vickers hardness and mean grain size of austenite.

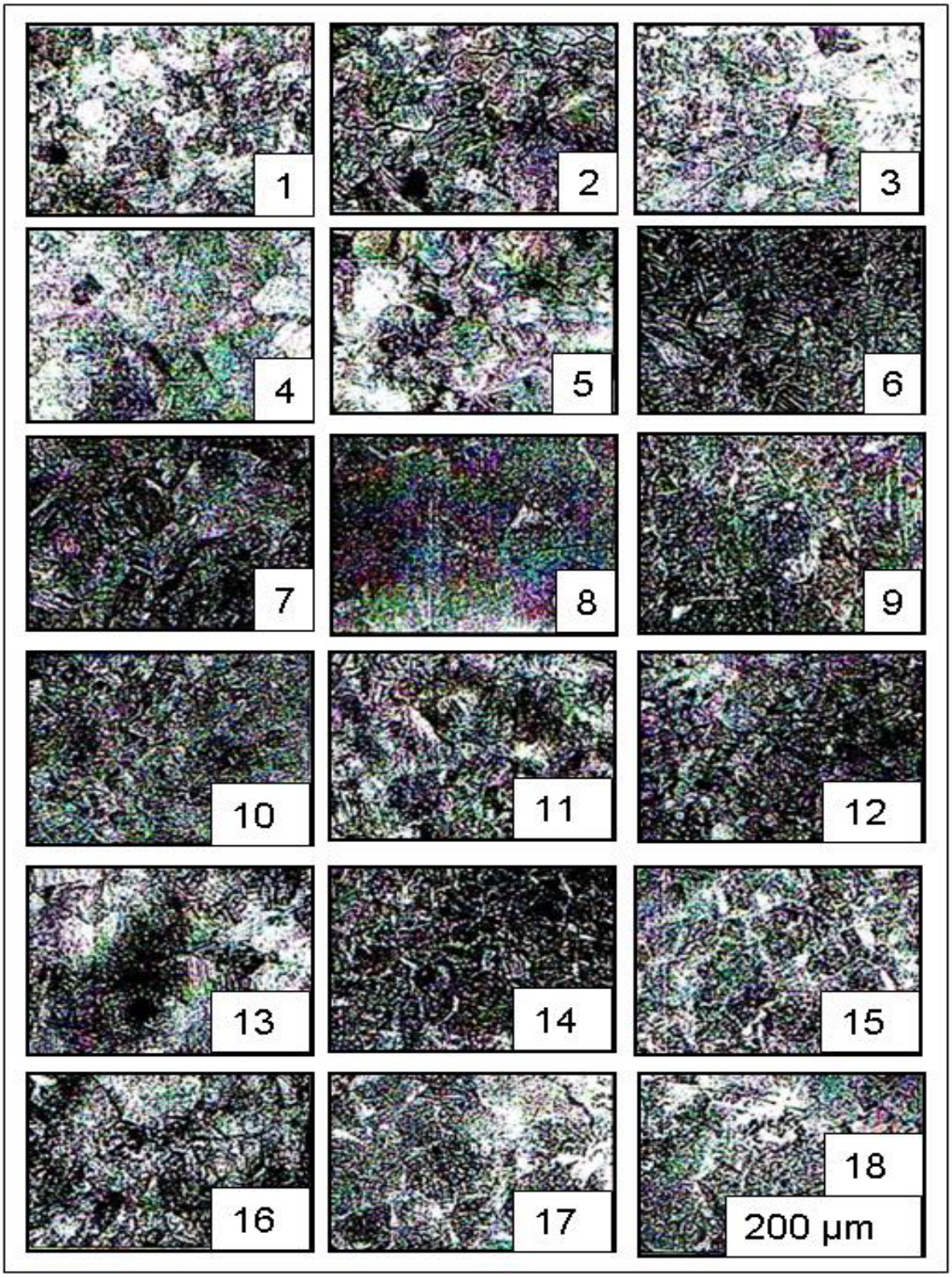

Fig. 1 Optical austenite microstructure of the eighteen samples (in the same magnification)

Table 3 Evaluated mean austenite grain size characteristics according to International Standard (ISO643), Vickers hardness, and Ultimate tensile strength of plain low-carbon steels [10,18]

1	2	3	4	5	6	7	8	9	10
Temp.; time (°C) (h)	Number of the closest standard chart (M)	Equivalent index of grain size x 25 (G)	Estimated grain size (Index) x 100 (G)	Mean diameter of grain, μm ($\bar{d}$)	Mean intersected segment, μm (l)	Vickers Hardness (HV10)	Ultimate tensile strength, MPa (R_m)	Yield strength, MPa (R_e)	Elongation % (A)
1000 ; 1	7	3	7	31.2	28.3	503	1710	1163	33.5
1000 ; 3	6	2	6	44.2	40	414	1357	923	28.7
1000 ; 6	6.5	2.5	6.5	37.7	34.2	452	1507	1025	30.0
1100 ; 1	6.5	2.5	6.5	37.7	34.2	440	1467	983	33.3
1100 ; 3	5	1	5	62.5	56.6	350	1100	737	32.7
1100 ; 6	5	1	5	62.5	56.6	357	1122	752	27.7
1200 ; 1	5	1	5	62.5	56.6	357	1122	729	29.3
1200 ; 3	4	0	4	88.4	80	283	896	582	29.7
1200 ; 6	4.5	0.5	4.5	75.5	68.3	332	1040	676	30.3
1000 ; 1	7.5	3.5	7.5	26.7	24.2	528	1813	1233	30.3
1000 ; 3	5.5	1.5	5.5	53.4	48.3	382	1222	831	28.0
1000 ; 6	4.5	0.5	4.5	75.5	68.3	332	1040	707	33.3
1100 ; 1	5.5	1.5	5.5	53.4	48.3	382	1222	819	27.3
1100 ; 3	4	0	4	88.4	80	298	943	632	25.3
1100 ; 6	3.5	-0.5	3.5	106.7	96.5	239	759	509	32.0
1200 ; 1	5	1	5	62.5	56.6	353	1109	721	30.0
1200 ; 3	3	-1	3	125	113	222	705	458	29.3
1200 ; 6	3	-1	3	125	113	217	687	447	32.3

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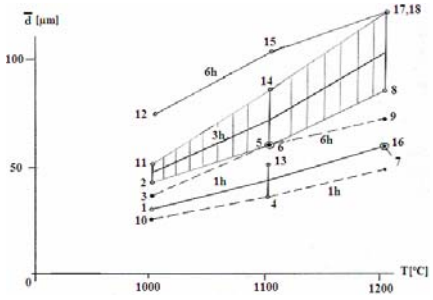

Fig. 2 The relation between mean austenite grain size and temperature in eighteen samples

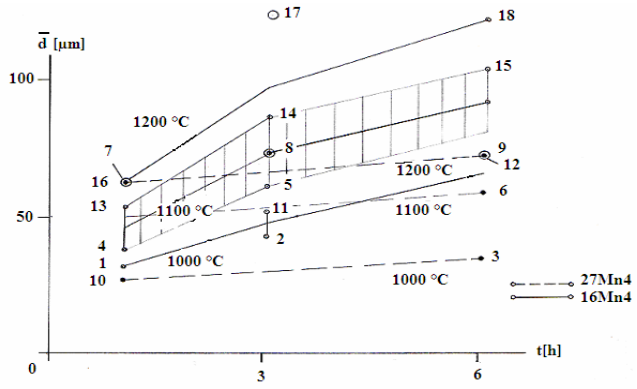

Fig. 3 The relation between mean austenite grain size and time in eighteen samples as different temperature

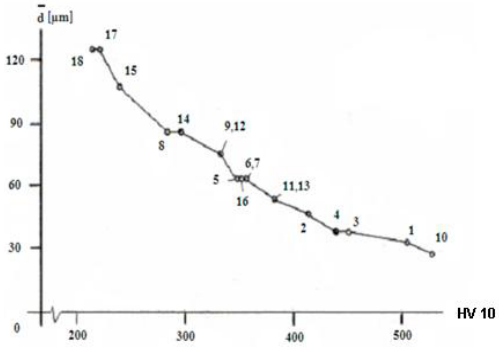

Fig. 4 The relation between mean austenite grain size and Vickers hardness of eighteen samples.

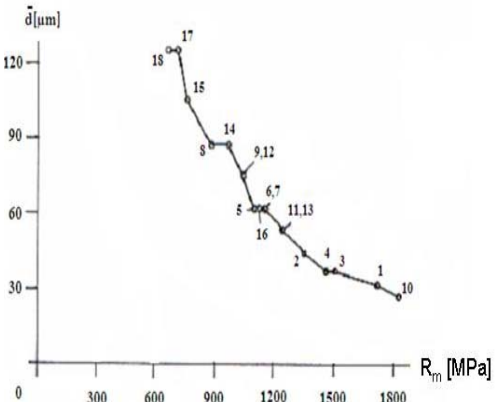

Fig. 5 The relation between mean austenite grain size and ultimate tensile strength of eighteen sample

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