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Full Length Research Paper

Effect of cooling rate on hardness and microstructure of AISI 1020, AISI 1040 and AISI 1060 Steels

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The object of the present work is to investigate the effect of cooling rate on microstructure and mechanical properties of AISI 1020, AISI 1040 and AISI 1060 steels. The samples were heated and treated at 1250°K for 4 h and subsequently were cooled by three different methods. For this purpose, the microhardness and microstructure of these steels after heat treatment were examined by optical microscopy and hardness tests, respectively. Experimental results have shown that the microstructure of these steels can be changed and significantly improved by varying the cooling rate. Thus, heat treatment (heating and cooling) is used to obtain desired properties of steels such as improving the toughness, ductility or removing the residual stresses, etc.

Key words: Carbon steels, hardness, microstructure, heat treatment.

INTRODUCTION

Mechanical properties of steels are strongly connected to their microstructure obtained after heat treatments that are generally performed in order to achieve a good hardness and/or tensile strength with sufficient ductility (Mebarki et al., 2004). Currently, there is a strong interest in the effect of cooling rate on the mechanical properties and microstructure of industrial processed steels. In considering the microstructure, the influence of cooling on the microstructure of vanadium bearing HSLA steels has been investigated by transmission electron microscopy (Bangaru and Sachdev, 1982). It has been shown that oil quenching produce an essentially ferrite-martensie dual phase structure with about 4 volume pct of fine particle and thin film retained ausenite. In contrast, the slower air cooling results in a larger amount (about 10 volume pct) of retained ausenite in addition to the ferrite and martensite phases. On the other hand, with the applied cooling rate increasing, the transformed structure evolves from granular bainite, lower bainite, self-tempered martensite, to finally martensite without self-tempering (Qiao et al., 2009). Among them, self-tempered martensite, obtained in the transformed specimens cooled with rates of 25 - 80°C/min, exhibits the highest hardness values due to the precipitation of fine carbides.

Because of the technological importance, the tensile behavior and microstructure of bulk, Sn-3.5 Ag solders as a function of cooling rate have been studied (Bochoa et al., 2003). It has been shown that yield strength increases with increasing cooling rate, while ultimate tensile strength and strain-to-failure is unaffected. Although many papers have been published on the effect of cooling rate on the tensile behaviours of steel (Chao and Gonzales-Carrasco, 1998; Perdrix et al., 2000; Serre and Vogt, 2008), there has been little research on the effects of cooling rate on the microstructure and microhardness (Nagpal and Baker, 1990; Lu et al., 2009). Especially, the effect of cooling rate on the microhardness of low (AISI 1020) and medium carbon (AISI 1040, AISI 1060) steels are rarely reported. The present study is aimed at understanding the effect of cooling rate on the microhardness and microstructure of these steels.

Experimental method

Chemical compositions of these steels are given in Table 1. The substrates were cut from a 2 x 2 x 20 mm^3 steel plate and annealed at 900 K for 10 h to remove potential residual stresses before microhardness tests. Then, the samples were heat treated at 1250°K for 4 h and subsequently were cooled by three different methods. Different cooling rates, namely at room condition water quenching, at room condition air cooling and at furnace condition temperature cooling were applied to steels to observe the effect on the microstructure and microhardnes of steel. The microstructure was observed by optical microscope. To determine the hardness of steels, a Vickers microhardness tester with a load of 100 g was used. Many indentations were made on the surfaces of steels to check the reproducibility of hardness data. Furthermore

Table 1. The chemical composition of steels.

Steel type	C	Si	Mn	Cr	Ni	P	S	Fe
AISI 1020 Steel A	0.20	0.22	0.66	0.055	0.18	0.015	0.028	Bal.
AISI 1040 Steel B	0.40	0.23	0.65	0.054	0.13	0.09	0.030	Bal.
AISI 1060 Steel C	0.60	0.22	0.67	0.059	0.19	0.014	0.034	Bal.

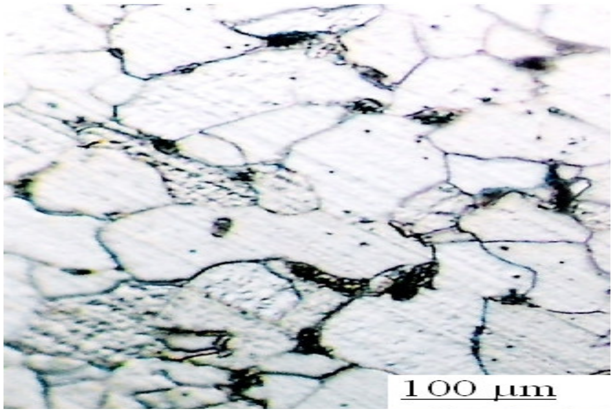

Figure 1(a). The microstructure of AISI 1020 steels.

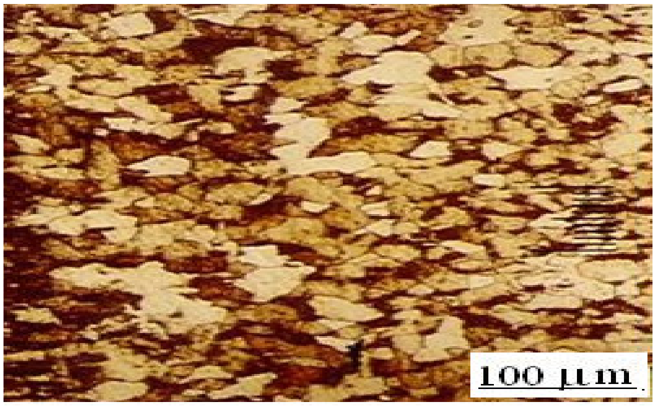

Figure 1(b). The microstructure of AISI 1040 steels.

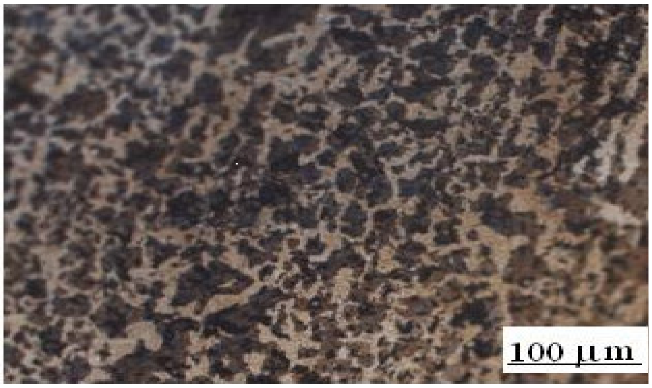

Figure 1(c). The microstructure of AISI 1060 steels.

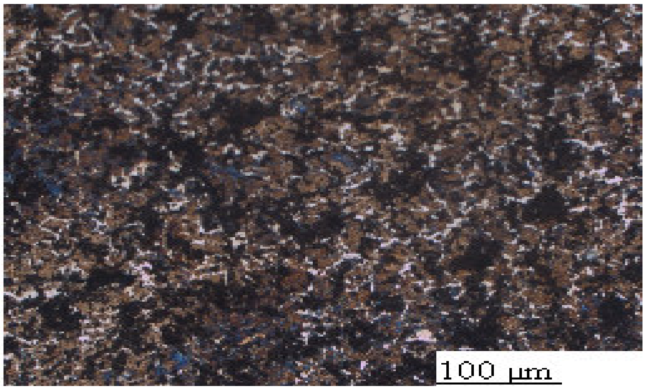

Figure 2(a) The microstructure of water quenched AISI 1020 steels.

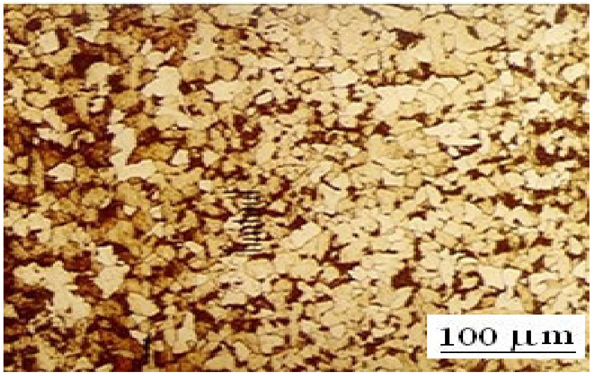

Figure 2(b). The microstructure of air cooled AISI 1020 steels.

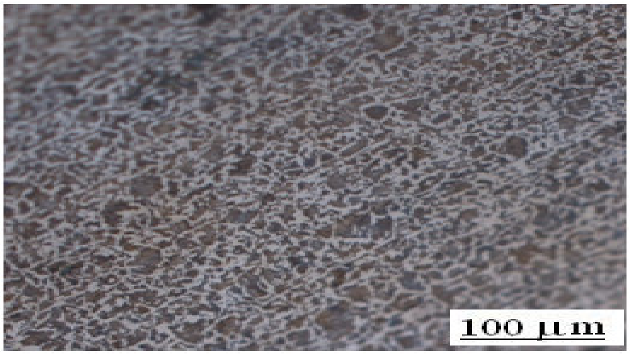

Figure 2(c). The microstructure of furnace cooled AISI 1020 steels.

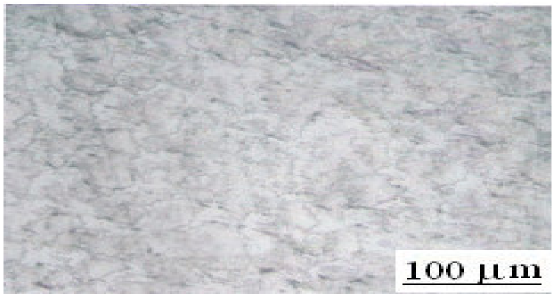

Figure 2(d). The microsture of water quenched AISI 1040 steels.

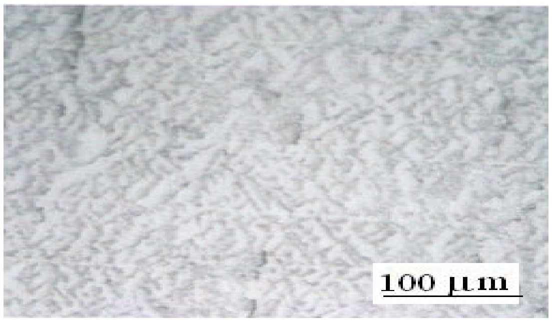

Figure 2(e). The microstructure of air cooled AISI 1040 steels.

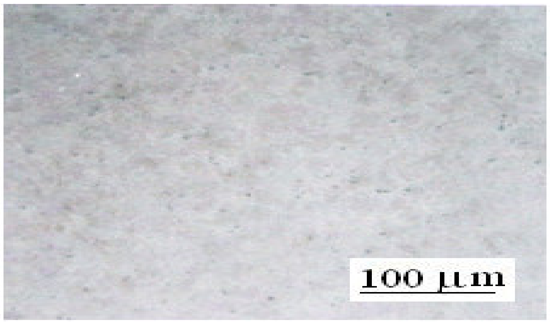

Figure 2(f). The microstructure of finance cooled AISI 1040 steels

Figure 2(g). The microstructure of water quenched AISI 1060.

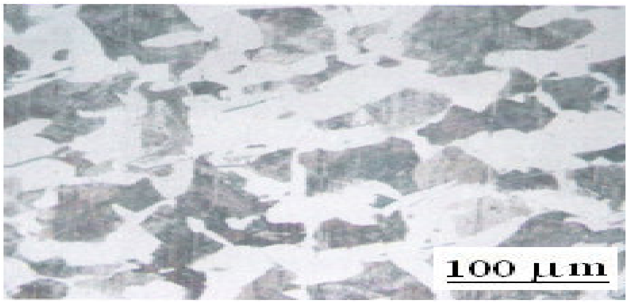

Figure 2(h). The microstructure of air cooled AISI 1060 steels.

Figure 2(i). The microstructure of furnace cooled AISI 1040 steels.

experimental details have been previously described by Calik and Ozsoy (2002).

RESULTS AND DISCUSSION

A mean cooling rate is defined as the time derivative of the spatial mean temperature, $Q(t) = dT(x,t)/dt$. This cooling rate is a function of time but it is considered approximately constant, since the function T (x, t) is found to be approximately linear in the temperature range in which most of the segregation occurs (Craievich and Olivieri, 1981; Maveety et al., 2004). In the present study, AISI 1020 (steel A), AISI 1040 (steel B) and AISI 1060 (steel C) have a microstructure of ferrite and pearlite (FP) two-phase in the normalized state (Figures 1a, 1b and 1c). Microstructural characteristics of these steels were parameterized by the pearlite volume (dark region) fraction. The microstructure of steel A, B and C contained pearlite 25, 50 and 75 % depending on the carbon content, respectively (Figures 1a, 1b and 1c). The percentages were determined by optical microscopy. As seen in these figures, the percentage of pearlite changes with change in carbon content of steels. The percentages of phases obtained using the optical microstructure photographs (Figures 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h, and 2i) of steels after heat treatments were given in Table 2. From Table 2 we see that the ferrite and pearlite percenttages changes with cooling rate and carbon content. On

Table 2. The percentages of phases after heat treatments.

Heat treatment	Steel type	Ferrite (%)	Pearlite (%)	Martensite (%)	Retained austenite (%)
Water-quenched	A	15	70	5	10
	B	20	60	20	-
	C	5	60	30	5
Air-cooled	A	45	55	-	-
	B	30	50	20	-
	C	30	65	5	-
Furnace- cooled	A	55	45	-	-
	B	50	40	-	10
	C	50	50	-	-

Table 3. The microhardness values after various heated treatments of steels.

Steel type	Hardness ($HV_{0.1}$)		
	Water quenched	Air cooled	Furnace cooled
Steel A	476	149	125
Steel B	521	166	149
Steel C	610	203	167

the other hand, a higher cooling rate can be used to reach a martensitic state in the present study. It was concluded that the cooling rate and carbon content have an effect on the microstructure of steels. Massalski (1990) has reported that when the steel is cooled at intermediate rates to room temperature, carbon can diffuse relatively far and the spacing of the carbon rich phase Fe_3C is greater. The resulting pearlite is called coarse pearlite. When steel is cooled at a faster rate, carbon can diffuse only a short distance to result fine pearlite in carbon steels.

Yankovskii et al. (1979) have reported that the heat treatment of steel 45 (austenitizing at 900°, cooling at 30 - 40°/s to 600 - 550°, then in air) leads to formation of a dispersed ferritic-pearlitic structure and improvement of the mechanical properties in comparison with the normalized condition. The mechanical properties of steel 45 subjected to cooling interrupted at 600° hardly differ from the properties obtained after quenching and tempering at 600° σ_b = 74 - 76 kgf/mm^2, σ_T = 46 - 48 kgf/mm^2, σ_5 = 18 - 21%,a $=_v$ $^{+20}$ =810 kgf-m/cm^2. Replacing steel "D" with steel 45 having a controlled chemical composition in combination with heat treatment including interrupted cooling makes it possible to increase the yield strength, reduce the safety factor, and thus reduce the weight of tanks.

Because of dual phase strengthening, the plain carbon ferrite -pearlite (FP) steels have a good balance of strength and ductility. However, the plain carbon FP steels generally have a lower strength than the high strength low alloy steels (HSLA) with tempered martensitic microstructures (Tsuchida et al., 2002). Table 3 shows the influence of the carbon content and cooling rate on the microhardness of steels. It can be seen from Table 3 that the microhardness of steels increases with the increasing of cooling rate and also carbon content. Additionally, the microhardness increases with increasing pearlite percentage. The microhardness of steels increases rapidly as the martensite percentage is increased. The microhardnesses of the water-quenched samples is increased by a factor close 3 and 3.5 compared to the microhardness values obtained from air and furnace-cooled steels, respectively (Table 3). This is because martensite is one of the most common strengthening phases in steels. In general, the microhardness increases because of the refinement of the primary phases after rapid cooling (Wang et al., 2007). It is well known that the water quenching creates a supersaturated solid solution, and vacancies increase with carbon content in water-quenched samples (Oca et al., 2001). Thus, high hardness correlates with high resistance to slip and dislocation. In martensite, the carbon dependence of hardness is attributed to carbon atoms trapped in the octahedral interstitial sites of martensitic crystal structure (Kurdjumov and Khachaturyan, 1972*)*. We claim that the increase in the microhardness is due to the delay in the formation of ferrite which promotes the formation of pearlite and martensite at a higher cooling rate. Thus, the increase of microhardness with the water quenched steels can be explained by the increasing relative volume of pearlite and martensite after quenching. On the other hand, the hardness of martensite increases sharply with increasing carbon content. Sim et al. (2004) showed that the carbon content affects mechanical strength of steels by controlling pearlite volume fraction. "Saritaş, in 1995, showed that at room temperature the solubility of carbon in α-iron is almost zero". So, it separates from the crystal structure and forms a chemical compound with iron known as cementite. Cementite and ferrite may show a kamelar structure, which is known as perlite.

Conclusion

In conclusion, differences in the cooling rate appear to provide dramatic effects on the microhardness of steels, depending on the carbon content of steels. The microhardness increases with the increasing cooling rate and carbon content due to solid solution hardening and formation of the martensite phase. Thus heat treatment (heating and cooling) is used to obtain desired properties of steels such as improving the toughness, ductility or removing the residual stresses.

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