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Influence of Austenization with Pulsed Electric Field on a Low-Carbon Steel

Wei Kong,[1,*] **Da-Qiang Cang**[1] **and Jia-Hui Song**[1]

[1] School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing, China

Abstract. This paper studied the effects of Austenization with pulsed electric field (PEF) on a low-carbon steel. The results showed that the vol. % lath martensite and Brinell hardness of the specimens quenched with the PEF decreased, especially under the condition of higher frequency, lower voltage, shorter processing time and lower capacity. In addition, the heat treatment with the PEF increased the Ac1 point to a higher temperature as much as 90°C at least and maintained Ac3 point unchangeably. The PEF was able to refine martensite structure.

Keywords. PEF, low carbon steel, microstructure, quenching.

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C	Si	Mn	S	P	Al
0.068	0.12	0.36	0.026	0.024	0.012

Table 1. Composition in mass % of the steel employed in the present study.

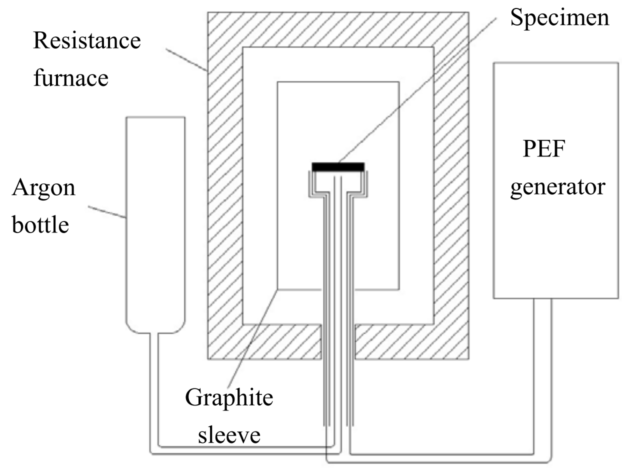

Figure 1. Schematic of experimental arrangement.

1 Introduction

In prior work [1–6] it was found that an external DC electric field applied during the heat treatment changes some properties of carbon steel. As an expansion of previous studies, the present one proposed that pulsed electric field (PEF) also exerts influence on the microstructure of low-carbon steel. The objectives of the present investigation were twofold: (1) to find out the effects of the PEF on the hardness and the microstructure of lath martensite and parent austenite; (2) to explain these phenomena produced by the field.

2 Experimental

Test specimens of the steel (20.5 mm outer diameter × 2.5 mm wall thickness × 130 mm long) were cut from the steel pipe. These specimens were then austenitized at 855 ± 2 °C for 30 min and quenched in 10% NaCl aqueous solution at room temperature (18–24 °C). During the austenitizing process, an external pulsed electric field applied can provide 0–1200 V voltage, 0–30 kHz frequency, and 0–2000 μF capacity by EPM-C (homemade PEF generator). A schematic of apparatus employed for heat treating the specimen with, and without, a PEF is given in Figure 1. Experimental scheme are listed in Table 2. After quenching, the specimens were cut transversely into small rings near their one end and polished for Brinell hardness measurements. They were then further polished and etched for optical microscopy. The microstructure and properties evolution of the steel specimens were studied by Leica DM5000 (metalloscope), TH600 (Brinell hardness tester) and QuantLab-MG (quantitative metallographic analysis software).

3 Results and discussion

Optical microscopy revealed that the specimen quenched without a field contained ∼100 vol.% lath martensite; see Figure 2. Under the condition of low carbon, the corresponding Brinell hardness was 404BHW2.5/187.5. While the vol.% martensite (others were ferrite) and Brinell hard-

Corresponding author: Wei Kong, School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China; E-mail: kongwei0668@126.com.

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	Factors					
Serial number	Frequency (Hz)	Voltage (V)	the PEF processed time (min)	Capacity (μF)	the vol.% martensite (%)	Brinell hardness (BHW2.5/187.5)
1	9	500	3	1200	30	115
2	9	800	3	1200	70	143
3	9	1200	3	1200	40	158
4	3	500	3	1200	60	177
5	9	500	3	1200	30	115
6	15	500	3	1200	30	119
7	9	500	3	1200	30	115
8	9	500	6	1200	50	131
9	9	500	9	1200	90	170
10	9	500	3	400	0	129
11	9	500	3	800	60	133
12	9	500	3	1200	30	115
0	–	–	–	800	100	404

Table 2. Parameters and results of test.

ness of the specimens quenched with the field decreased, as shown in Table 2. To be noted in Table 2 is that under the condition of higher frequency, lower voltage, shorter processed time and lower capacity, the vol.% martensite of the specimens quenched with the field was lower. Even in the case of 9 Hz, 500 V, 3 min, and 400 μF, there was no martensite. However, the dispersed granular carbides in matrix are shown in Figure 3. That is, in austenite, because carbides did do not dissolve totally, undissolved carbide points (high carbon zone) grew up to be the granular pearlite during the process of heating. To analyze the effect of the PEF on the austenitizing temperature, another set of contrast tests without the PEF were processed held for 30 min at 705°C, 735°C, 765°C, 795°C, 825°C, 855°C, 885°C, and 915°C. It was experimentally determined that from the granular carbides situation (at 765°C) like the situation shown in Figure 3 to the ∼30 vol.% martensite situation (at 795°C, the difference of their austenitizing temperature was 30°C. From the ∼30 vol.% martensite situation (at 795°C) to the ∼60 vol.% martensite situation (at 825°C), the difference of their austenitizing temperature was 30°C. From the ∼60 vol.% martensite situation (at 825°C) to the ∼90 vol.% martensite situation (at 855°C) in which the vol.% martensite was like that of shown in Figure 4, the difference of their austenitizing temperature was also 30°C. Therefore, it can be inferred that with the PEF annealing, the Ac1 point can be increased at least 90°C, which is the temperature difference between the granular carbides situation and the ∼90 vol.% martensite situation on the basis of the contrast test result mentioned above, and maintains Ac3 point unchangeably. As a result, two-phase zone between austenite and ferrite can be narrowed, and the spheroidal annealing temperature range is able to be expanded, indicating that there would be wider quenching temperature range.

Since vacancies in a metal lattice and the charge generated by the PEF may have the same charge (an electrochemical potential generated from the surface to the interior) [7], a possible effect of the PEF on the above situations may be suggested by its influence on vacancy and carbon-vacancy complex flux from the surface to the interior, and in turn restrains the diffusion of carbon. This could lead to the difficulty of austenite formation.

To be noted in Figure 2 and Figure 4 is that the PEF was able to refine martensite (along with the refinement of the parent austenite). And the grain refinement can prevent the increase of brittleness of the steel because of the coarse martensite formation and quenching crack phenomenon. It can be explained as follows:

Firstly, the effect of the PEF on the nucleation energy leads to the variation of nucleation rate ($\dot{N}$) [8]; see the following equation:

$$\dot{N} = K_v \exp\left(-\frac{16\pi\sigma^3}{3kT\,(\Delta G_P + \Delta G_{\mathrm{PEF}} - E\varepsilon^2)^2}\right) \times \exp(Q/kT), \quad (1)$$

where, K_v is a constant, k is the Boltzmann constant, Q is the diffusion activation energy, ΔG_P is the difference of free energy between two-phase per unit volume, ΔG_{PEF} is the activation energy by the PEF, $E$is the elastic modulus,

Figure 2. Microstructure of the specimen quenched without the PEF treatment ×50.

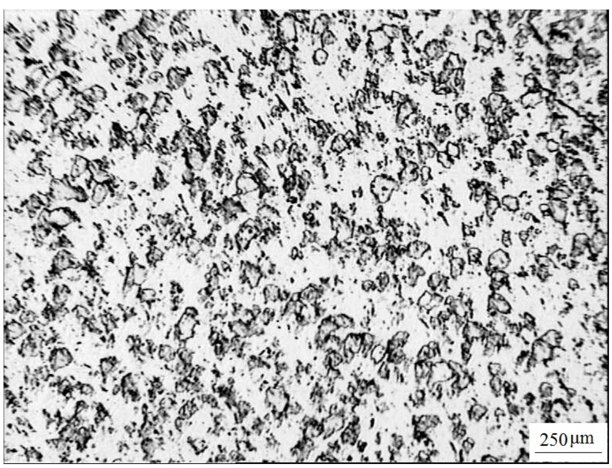

Figure 3. Microstructure of the specimen quenched with 9 Hz, 500 V, 3 min and 400 μF ×120.

ε is the linear strain, and σ is the interfacial energy per unit area. The increase of ΔG_{PEF} increases the $\dot{N}$ of austenite, which can lead to the refinement of austenite.

Secondly, since the PEF increases the grain coarsening temperature of austenite, the formation and growth of austenite are retarded.

4 Conclusions

(1) The vol.% martensite and Brinell hardness of the specimens quenched with the PEF decreased, especially under condition of higher frequency, lower voltage, shorter processed time and lower capacity.

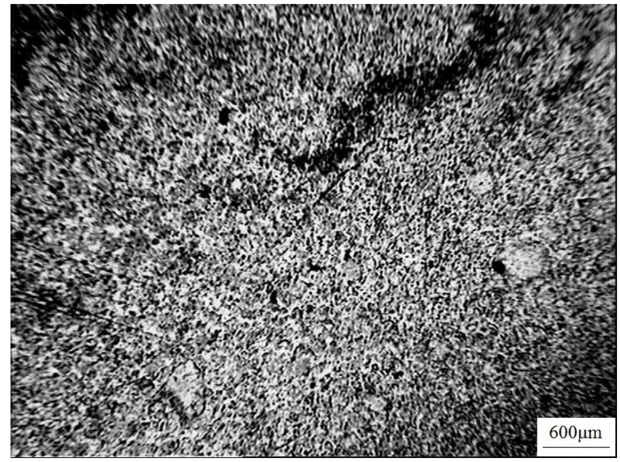

Figure 4. Microstructure of the specimen quenched with 9 Hz, 500 V, 9 min and 1200 μF ×50.

(2) The heat treatment with the PEF increased the Ac1 point to a higher temperature as much as 90° at least and maintains Ac3 point unchangeably.

(3) The PEF can refine martensite (along with the refinement of the parent austenite).

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