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Non-uniform carbon segregation induced by electric current pulse under residual stresses

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ABSTRACT

As-quenched carbon steel samples were treated with high density electric current pulses (ECP). After that, the carbon distribution and microstructures were examined, and the residual stresses were measured. The carbon segregation was apparent in the near-surface region, and in the internal region no carbon segregation was displayed after ECP treatment. The lath-shaped martensite remained identical before and after ECP treatment. The residual stress gradient was relatively large in the near-surface region, and small in the internal region. The theoretical analysis proved the drag force on carbon atoms due to drift electrons had a minimal effect on carbon diffusion; the Joule heat due to ECP and the quenched residual stresses were determined to be the primary contributing factors. The skin effect of ECP existed. Facilitated by the large stress gradient in the near-surface region, the metastable carbon atoms in the martensite were activated by high density ECP and diffused toward into grain boundaries and dislocations. In the internal region, the stress gradient was small, and the Joule heat due to ECP was insufficient for the diffusion of carbon atoms. The behavior of non-uniform carbon segregation is attributed to the non-uniform residual stresses and Joule heat of the ECP.

1. Introduction

Carbon segregation has a great influence on the mechanical properties of carbon steel, such as strength, fracture and fatigue, so it is important to control the carbon segregation using some materials processing technologies. Electric current pulse is a change of short duration in current intensity, which possesses short action time and is easily controlled, and is used in material processing more frequently. For example, Tang et al. (2000, 2003) used ECP to aid the cold-drawing of stainless steel wire; Klimov and Novikov (2007) and Mal Tsev (2008) used a high density current pulse to aid rolling of metals. Stolyarov (2008, 2009) used ECP to facilitate the manufacturing of nanostructured shape memory TiNi alloy. Baranov et al. (2011) developed a new metal cutting technology using high density pulse current passed through the treated area, and then Kumar et al. (2013) called it "electromagnetic jigsaw". Xu et al. (2014) found that ECP could improve mechanical properties and greatly refine microstructure of rolled 2024 Al through recrystallization. Sánchez Egea et al. (2015) used ECP to assist turning process and found it to be a feasible technique to improve the material machinability. Xie et al. (2015) studied the effect of direct-current pulses on bending property of AZ31B magnesium alloy sheet, and found that current pulse could reduce its springback. Furthermore, there are many studies on the mechanisms of effects of ECP on the materials mechanical properties, since Troitskii and Likhtman (1963) first reported the phenomenon that the electrons effected the deformation of zinc single crystals in the brittle state in 1963, which was called "electroplasticity" by Troitskii and Maistrenko (1972). Subsequently, Klimov and Novikov (1984) found this phenomenon was due to the thermal effects and electron drag force on dislocations due to ECPs. Conrad (2000) reported that this phenomenon resulted from the combined action of an electron wind force, a decrease in the activation enthalpy for plastic deformation and an increase in the pre-exponential. Li and Yu (2009) introduced a method to calculate the metal's flow stress for electroplastic effect based on the thermally activated plastic flow concept. Most of the reports indicate that the effects of ECP on the material came from the Joule heat and the electron drag force.

Although there are many studies on the applications and mechanism on materials from ECP, but few report about the effect of ECP on atom diffusion and segregation in metals or alloys.

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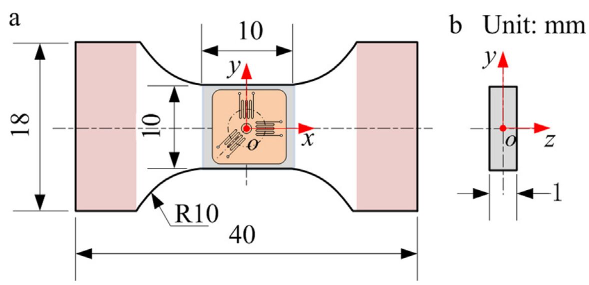

Fig. 1. Shape of samples and position of the strain rosette: (a) front view and (b) cross section view along the central line.

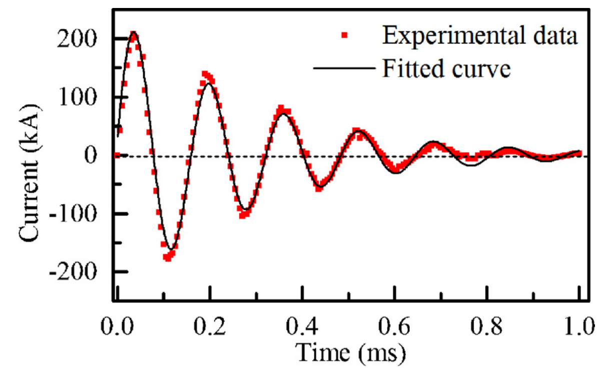

Fig. 2. Typical wave of electric current pulse treatment.

Compared to the conventional thermal process, ECP treatment has an advantage of usability because it is easily applied to metals and has good control performance.

The carbon atom diffusion under the influence of ECP of quenched carbon steel samples was studied. Generally, quenched carbon steel samples possess large magnitude residual stress, which demands a study of the effects of residual stress on carbon diffusion. Aifantis and Gerberich (1977a,b), Wilson and Aifantis (1982), Unger and Aifantis (1983) found the stress has shown to induce atoms to diffuse, and called this phenomenon "stress-induced diffusion". Galdikas and Moskalioviene (2011) used the stress to promote the nitriding process of an austenitic stainless steel. Jang et al. (2010) used an atomistic method to simulate the effect of stress on self-diffusion in bcc Fe, and found that the diffusivity was retarded by compressive pressures enhanced by shear stresses. In contrast, those papers focused on the effects of stress on diffusion only while disregarding other factors coupled on the stress, such as ECP.

In this paper, the carbon distributions and microstructures before and after ECP treatment were obtained by SEM, and residual stresses were evaluated in the experiments. Furthermore, the mechanism of carbon segregation under the coupled effects of residual stress and ECP were analyzed in detail based on experimental results.

2. Experiment

The shape of the carbon steel samples was displayed in Fig. 1, and the samples had a thickness of 1 mm. The chemical compositions were (in mass%) Fe-0.45C-0.27Si-0.44Mn. The samples were quenched and the residual stresses were primarily generated from the martensite transformation. During the quenching process, temperature of specimens rose up to 850 °C and held at isothermal conditions for 3 min until the material was completely austenitized. The samples were then put into water at 20 °C to form a sufficient quenching quality.

After quenching, some samples were randomly chosen to be evaluated by residual stresses. The distributions of residual stresses at the center point *o* (Fig. 1) of the specimens along the thickness direction from surface to interior were measured by a layer-by-layer hole-drilling method with MTS3000 test system from Sint Technology Company, while the residual stresses were calculated by the integral method (Schayer, 1988a,b). The strain rosette was pasted at the center of the sample as shown in Fig. 1.

High density ECP was used in materials processing frequently, which contained high energy and was able to have a considerable effect on properties of the samples. Therefore, designated samples were chosen to be treated by high density ECP, which was generated by a device containing a group of high-voltage and large-value capacitors (Zheng et al., 2010). The capacitance was 400 μF and the charging voltage was 2120 V, with a typical oscillating electric current pulse being generated as shown in Fig. 2; it was found that a maximum value I_m was 2×10^5 A at time $t = 3.6 \times 10^{-5}$ s and the periodic time of oscillations was 1.6×10^{-4} s. Samples were treated by a current pulse every 4 s for a duration of 40 min. Surface temperature of the sample was measured by Smart AR320 infrared thermometer. In order to study the thermal effects of ECP treatment, the same samples were chosen to be tempered, and temperature of the oven was controlled to be the same as that of the ECP treatment process. Tempering time was 40 min.

In order to study the microstructure and carbon distribution at the cross section, samples were cut through the middle where properties and structures were relatively stable. JEOL-JSM 6700 scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrum (EDS) analysis system was used for elemental analysis on carbon. The samples were etched with a solution of 10% $HClO_4$ + 90% C_2H_5OH at 20 V for 30 s. The EDS mapping of carbon atom distribution was carried out at 10 kV. The SEM images were obtained at an accelerating voltage of 20 kV and a beam current of 30 nA.

3. Results

3.1. Distribution of residual stresses

The distribution of residual stresses was shown in Fig. 3. The internal residual stresses, σ_x and σ_y, were tensile and became compressive in the near-surface region of the sample. At the surface, σ_x was relatively large, up to −600 MPa, and residual stresses changed slowly in the internal region and severely in the

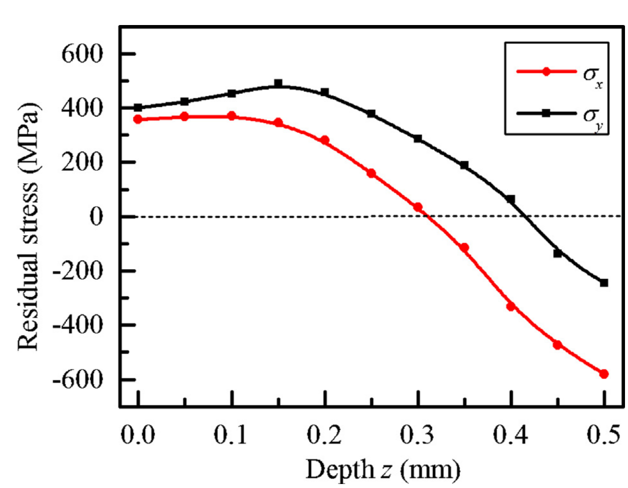

Fig. 3. Distributions of residual stresses from center ($z = 0$ mm) to surface ($z = 0.5$ mm) of the quenched carbon steel samples (σ_x and σ_y are residual stresses in the *x* and *y* directions, respectively).