Influence of electropulsing treatment on residual stresses and tensile strength of as-quenched medium carbon steel

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Abstract. With the development of the technique of the high energy electric current pulse, the electropulsing treatment (EPT) is used in manufacturing more frequently. The effects of EPT on residual stresses and tensile strength of as-quenched medium carbon steel are investigated by experiments. The results show that EPT can reduce residual stresses, and improve tensile strength of the specimens. With the increase of the current density, the residual stresses decrease, and the tensile strength increases. The increase of the tensile strength is due to the decrease of the residual stresses.

1. Introduction

With the development of the technique of the high energy electric current pulse, EPT is widely used in manufacturing, such as current-pulse-aided rolling [1, 2], current-pulse-aided cold drawing [3], electromagnetic jigsaw [4, 5]. Furthermore, the effects of EPT on the material properties are studied by many researchers. For example, EPT can improve the plasticity of the metals which is called “electro-plasticity” [6-9], affects the tensile properties and bending behavior of Ti6Al4V alloy sheet [10], and facilitate the nanocrystallization of the materials [11]. However, there are a little of reports about the effects of EPT on the quenching stresses. Stepanov and his co-workers did some works about this study [12-15], but they did not study the effects of EPT on the quenching stresses. Hence, the effects of the EPT and tensile strength are studied in this paper, which enriches the results of this research area.

2. Material and Methods

Table 1. Chemical composition of medium carbon steel

| Element | C    | Si    | Mn    | P≤   | S≤   | Fe   |
|---------|------|-------|-------|------|------|------|
| W.t %   | 0.452| 0.271 | 0.442 | 0.035| 0.040| Bal. |
The material used in this study was commercial medium carbon steel, and its chemical composition was shown in Table 1. The specimens were 1 mm thick plate (see Fig. 1a), and treated by quenching. During the quenching process, temperature of specimens rose up to 850 °C and held at isothermal conditions for 3 minutes until the material was completely austenitized. The specimens were then put into salt brine at 20 °C to form a sufficient quenching quality.

Specimens were treated by high density EPT, which was generated by a device containing a group of high-voltage and large-value capacitors [16]. The capacitance was 400 μF and the charging voltage was from 450 V to 2000 V, with a typical oscillating EPT being generated as shown in Fig. 1b. It was found that the periodic time of oscillations was 1.6×10⁻⁴ s. Specimens were treated by a current pulse every 4 s for a duration of 40 minutes.

The surface residual stresses at the center point o (Fig. 1a) were evaluated using the laboratory non-destructive residual stress measurement system LXRD of PROTO. The specimens were produced according to ASTM E8M-04 Standard Test Methods for Tension Testing of Metallic Materials [17], the selected target material was Cr, and the diffraction plane was {2 1 1} with diffraction angle 156°. Tensile tests were conducted at a constant strain rate of 1×10⁻³ s⁻¹ at room temperature using CMT 5205 electromechanical universal test systems of MTS Systems Corporation.

Figure 1. (a) Dimensions of specimen, and (b) waveforms of EPTs at different charging voltage

Figure 2 Curves of residual stress (a) \( \sigma_x \) and (b) \( \sigma_y \) verse time at different charging voltage
3. Results and discussions

3.1 Residual stresses
The residual stresses of the as-quenched carbon steel specimens decreased after EPT as shown in Fig. 2. The residual stresses decreased rapidly at the beginning of the treatment, and tended to be stable after some treating time. \( \sigma_x \) was small and its reduction was small; \( \sigma_y \) was large and its reduction was large too. The changes of the residual stresses were different after the specimens treated by different EPT. The decrease rates \( \eta_x \) of \( \sigma_x \), \( \eta_y \) of \( \sigma_y \) were shown in Fig. 3. The charging voltage was larger, the current density through the specimens was larger, and the decrease rates were larger. It was found that EPT can reduce the residual stresses, and the decrease rates increased with the current density increasing.

![Decrease rate of residual stresses versus maximum current density](image)

Figure 3. Decrease rate of residual stresses versus maximum current density

3.2 Tensile strength
The engineering strain – stress curves of the specimens after EPT as shown in Fig. 4. The EPT of different charging voltage had different effect on the tensile strength. The tensile strength increased with the charging voltage increasing. The result showed that EPT can improve the tensile strength of the as-quenched carbon steel specimens, and the tensile strength increased with the current density increasing.

![Strain – stress curves of specimens after EPT at different charging voltage](image)

Figure 4. Strain – stress curves of specimens after EPT at different charging voltage
3.3 Relationship between residual stresses and tensile strength

According to the von Mises yield criterion, the von Mises stress $\sigma_v$ (or equivalent tensile stress) due to the residual stresses is

$$\sigma_v = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y}.$$  (1)

The von Mises stress $\sigma_v$ and the tensile strength $\sigma_t$ were shown in Fig.5. With the increase of the maximum current density $J_{\text{max}}$, $\sigma_v$ decreased and $\sigma_t$ increased, and both had a good linear relationship. During tensile test, when the sum of tensile strength $\sigma_t$ and residual stress $\sigma$ exceeds the tensile strength $\sigma_C$ of samples with no residual stresses, the sample fractures, which directly indicates that the decrease of residual stresses can improve the tensile strength. Hence, the decrease of residual stresses is the primary factor of the increase of the tensile strength.

4. Conclusions

The as-quenched medium carbon steel specimens were treated by EPT of different charging voltage, and the residual stresses and tensile strength were investigated. The relationship between residual stresses and tensile strength was analyzed. The major results and conclusions of this study are summarized as follows:

1) EPT reduces the residual stresses of specimens, and the decrease rates of residual stresses increase with the current density increasing;
2) EPT improves the tensile strength of specimens, and the tensile strength increase with the current density increasing;
3) After EPT, the increase of the tensile strength is primary due to the decrease of the residual stresses.

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