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Hardening and softening mechanisms in a nano-lamellar austenitic steel induced by electropulsing treatment

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ABSTRACT

The effects of electropulsing treatment (EPT) on the microstructure and corresponding mechanical properties of a nano-lamellar 316L austenitic stainless steel were investigated. The original 316L stainless steel features a nano-lamellar framework with high density of dislocations via cold rolling. The nanostructured stainless steel was hardened and strengthened after EPT with relatively low discharge voltage, which may result from the cooperative effect of stable nano-lamellar structure and mobile dislocations recovery. Both the microhardness and tensile strength would decrease significantly with the increase of discharge voltage due to the nucleation and growth of recrystallized grains in the steel.

1. Introduction

Electropulsing treatment (EPT), as an instantaneous high energy input method, has been widely studied and applied in materials science and engineering [1]. In the past several decades, many researchers focused on the potential effects on the performances of materials due to EPT, such as electroplasticity [2–4], electromigration [5–7], recrystallization [8–10], phase transformations [11–15] and crack healing [16,17]. Meanwhile, EPT has been widely applied to materials processing, such as cold drawing [18], cold rolling [19], refined grain size [20,21], as well as in biology and environmental protection and medicine domain [22–24]. As a novel developing process, high-density pulse current has been proved to be effective for modifying the microstructures and mechanical properties of metallic materials being treated in a short time [25,26], which is more powerful and more efficient than other methods.

However, it is still short of investigations on the electropulsing effects on the nanostructured metals. As well documented in several excellent reviews that ultra-fine grained (UFG) or nano-grained (NG) metals and alloys may be obtained by applying severe plastic deformation (SPD) to coarse-grained materials [27–29]. These materials show significantly increased strength, often with reduced ductility, compared to coarse-grained materials [30,31]. With followed annealing treatment, the ductility of the SPD processed metals may be successfully recovered with the decrease of strength to some extent [32]. We may expect similar effect as annealing even more interesting phenomenon could be detected via EPT, as a novel and more effective heating method, on the SPD processed metals. In order to confirm this idea, a common used 316L austenitic stainless steel (316Lss) was chosen in the current study for its excellent mechanical and corrosion properties and good formability [33]. The microstructural evolution and its corresponding mechanical properties of a cold-rolled 316L austenitic stainless steel after various EPT discharge voltages were investigated. It is interesting to find that the steel can be hardened via relatively low current density and softened via relatively high current density of EPT. The mechanisms of the EPT induced hardening and softening phenomenon will be discussed in detail.

2. Experimental procedure

A commercial 316Lss was used in this work. The as-received material was cold-rolled from 40 mm to 4 mm in thickness, and then the sheet was cut into dog-bone-shaped specimens with their longest edge perpendicular to the rolling direction using spark cutting. The EPT experiment was performed by discharge of a capacitor bank under ambient conditions with a home-made equipment. The discharge voltage of each pulse was selected from 8 kV to 13 kV, and the current duration was within 400 ns for a single-pulse. For comparison, we hereafter refer the samples as received to EPT − 0 kV. The dogbone-shaped EPT specimen was used to obtain a high cooling rate at their middle parts during EPT. The valid clamping length and cross section of the specimen between two electrodes were 40 mm and 4 × 6 mm^2, respectively. A damped oscillation wave was detected in situ by using a RIGOL DS1102E digital storage oscilloscope.

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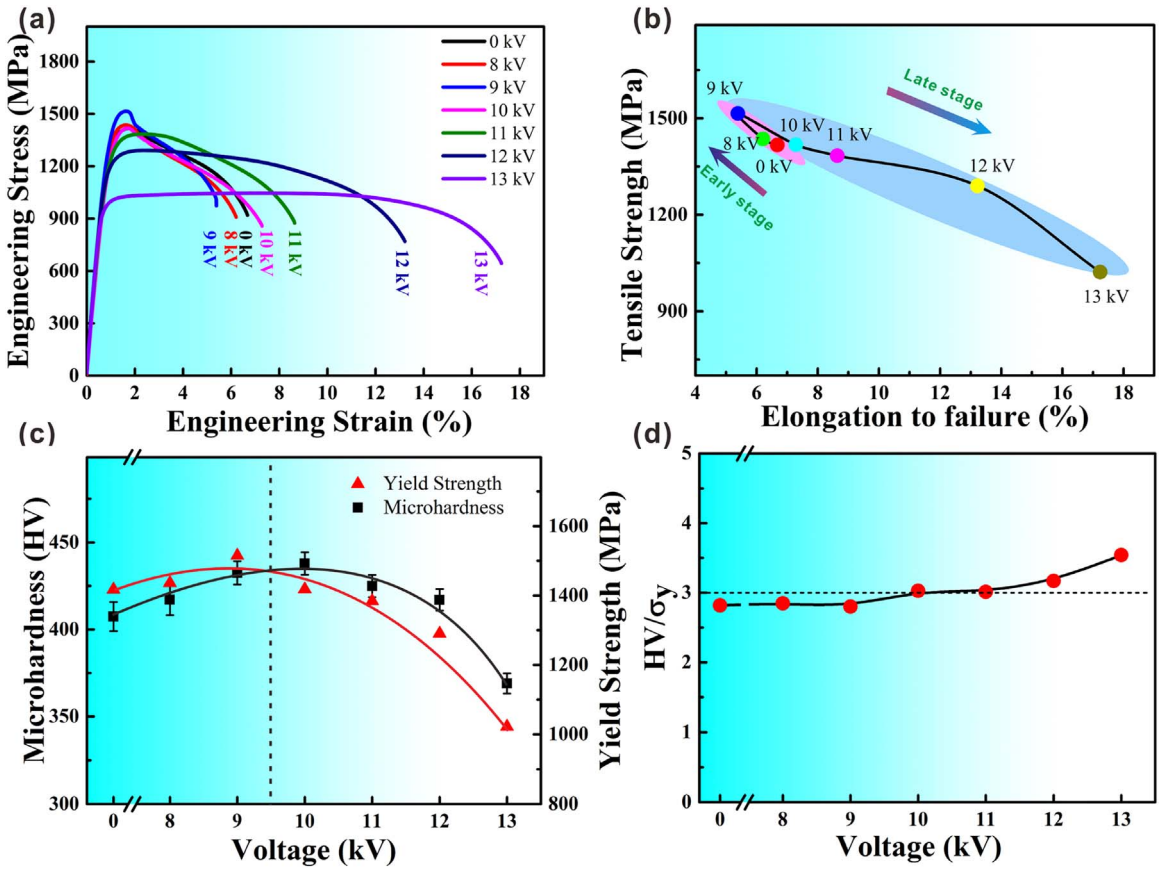

Fig. 1. (a) Tensile engineering stress–strain curves and (b) relation between tensile strength and elongation and (c) Vickers microhardness and yield strength and (d) corresponding ratio (HV/σ_y) plotting of hardness and strength of the steel treated by EPT with different discharge voltages.

The Vickers microhardness was measured with a load of 500 g for 13 s by an AMH43 automatic micro-indentation hardness testing system. The average microhardness was determined after 10 measurements on each specimen. The dogbone-shaped tensile specimen with a gauge section of $1 \times 3 \times 15\ mm^3$ was machined from the EPT processed samples. All the tensile tests were performed at a strain rate of $10^{-3}\ s^{-1}$ using an INSTRON 5982 testing machine in air. To observe microstructural evolution caused by EPT, microstructural characterization of the middle parts of samples have been carried out via the transmission electron microscopy (TEM, FEI Tecnai F20) operated at 200 kV. Thin foils for transmission electron microscopy were prepared by twin-jet electropolishing, which was carried out in a mixture of 90% ethanol and 10% perchloric acid at − 15 °C with an applied voltage of 28 V.

3. Experimental results

3.1. Mechanical properties and electropulsing-induced hardening and softening

Fig. 1(a) illustrates the tensile stress-strain curves of the 316Lss specimens treated by EPT with different discharge voltage. It is obvious that the flow stress slightly increased when treated by relatively low discharge voltage (< 10 kV), while it decreased with increasing current density (> 10 kV). The relation between tensile strength and elongation of the steel is shown in Fig. 1(b). The strength apparently decreases with the improvement of elongation of the steel, indicating a traditional trade-off synergy, which is in accordance with the results of 316L steel treated with cold rolling and annealing [34]. However, it is worthwhile noting that the evolution of strength with the increase of EPT discharge voltage shows a two-stages phenomenon, i) the early stage with EPT discharge voltage increased from 0 kV to 9 kV shown strengthening phenomenon and ii) the late stage with EPT discharge voltage increased from 9 kV to 13 kV shown softening phenomenon.

The two-stage phenomenon can be more clearly illustrated in Fig. 1(c), which presents the evolution of Vickers microhardness and yield strength of samples treated by EPT with increasing discharge voltage. One can find that the microhardness and yield strength of the samples increase firstly and then decrease with further increasing the discharge voltage. Interestingly, the microhardness and yield strength reached to their peak value at 10 kV and 9 kV, respectively. The microhardness rose from 407 HV at 0 kV to the highest value of 437 HV at 10 kV. Similarly, the yield strength increased from 1417 MPa at 0 kV to 1515 MPa at 9 kV. That is, the microhardness and yield strength of the specimen increased by 7.4% and 6.9%, respectively. Then the microhardness and yield strength began to decrease when the electric current density exceeded 10 kV. The microhardness and yield strength dramatically decreased by 15.6% and 31% compared to those at peak state, respectively. In the current study, both the hardening and subsequent softening of nanostructured 316Lss induced by EPT with various discharge voltage have been detected. The corresponding mechanisms of the specific phenomena must be closely related to the microstructural changes and will be discussed later.

In addition, both hardness and strength usually obey a three-time empirical relationship in the work-hardened metals and some bulk metallic glasses [35]. It is believed that the combined effect of normal and shear stresses and the pilling-up behaviors make the hardness and strength obey the three-time relationship in work-hardened materials. The evolution of the microhardness to strength ratio (HV/σ_y) of 316Lss in this study is shown in Fig. 1(d). One can find that the ratio values are close to 3, which is roughly consistent with the three-times relationship. Additionally, the ratio (HV/σ_y) slightly increased with the increase of