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Effect of recovering damage and improving microstructure in the titanium alloy strip under high-energy electropulses

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ABSTRACT

The effect of electropulsing treatment (EPT) on the microstructure improvement and damage recovery of cold-tension Ti–6Al–4V alloy strips was investigated. The results showed that the ductility and subsequent formability of the titanium alloy were improved noticeably by EPT, which originated from the rapid recrystallization and microcracks healing at a relative low temperature. Cold-rolling was introduced as a comparison, which brought in similar damage pressing but worsens materials ductility by work hardening. The rapid recrystallization process of Ti–6Al–4V alloy under EPT was attributed to the enhancement of nucleation rate and atomic diffusion resulting from the coupling of the thermal and athermal effects. Thermal compressive effect and pinch effect of electropulses were utilized to discuss the damage healing. Therefore, it is supposed that EPT provides a highly-efficiency and energy-saving method for enhancing ductility of titanium alloy by improving microstructure and recovering damage.

1. Introduction

Ti–6Al–4V alloy, as one of the most important titanium alloy, has been widely used as an excellent structural material in many fields like aeronautic, astronautic, biomedical industries due to outstanding thermal stability, high specific strength, superior corrosion resistance and fantastic biocompatibility [1]. Nevertheless, the difficulty in processing materials is the major obstacle for widespread applications of titanium alloys.

In order to improve the ductility and formability of titanium alloy, hot working or heat-treatment has to be introduced to facilitate the materials processing [2,3]. But these processes increased the cost of the materials processing and deteriorated the mechanical properties due to high temperature and long-lasting time process. Grain coarsening, oxidation layer and gas adsorption occurred in these processes, which all increase the materials loss and worsen the surface quality.

Additionally, micro-defects in the materials processing especially the severe plastic deforming take negative effects in the machinability, mechanical properties and durability during the materials service [4]. EPT was also active in the damage healing to improve the materials formability [5,6]. Shen et al. [7] conducted a series of researches showing the ductility of the low-carbon steel under high-energy EPT might be 10-fold increase at most by closing the interior defects.

With the first discovery of electro-pulsing treatment (EPT) by Troistkii [8], as a promising processing technique, EPT has attracted much attention in solving above problems in low temperature and fast procedure improving the materials plasticity through improving the microstructure [9,10]. Conrad et al. [11] found that EPT played a significant role in the materials processing to push the dislocation motion to soften the metallic materials. Zhu et al. [12] studied elongation of Zn–Al alloy under the dynamic electro-pulsing effect to show that elongation was enhanced by 437%. Our previous results [13] studied the microstructure and mechanical properties of processing functionally graded Ti–6Al–4V alloy strips under EPT finding that electropulses is effective in improving materials ductility and microstructure.

However, the mechanism of healing damage and improving the microstructure under EPT has not been attracted much attention in enhancing the ductility and subsequent formability of titanium alloy strip. In this paper, high-energy EPT was employed in pre-stretched Ti–6Al–4V (Ti–6–4) alloy strips to recover the plastic deformation damage and improve the microstructure with the ultimate aim of improving their ductility and formability (in the follow-up cold rolling process). The mechanism of the forming recrystallized grains and healing micro-cracks in the low-temperature and ultrafast-procedure EPT process were also discussed.

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2. Experiments

The annealed commercial titanium alloy Ti–6–4 (6.66% Al, 5.13% V, 0.21% Fe, 0.03% Mo, balance Ti) was utilized as original material (ORI). All of the samples experienced cold-tension (CT) on the tensile testing machine to produce 6% of pre-deformation (predicted by Fig. 1a).

After cold-tension (CT), the titanium alloy strip is treated in 6 s under EPT (parameters are shown by Table 1). The Ti–6Al–4V strips move through two electrodes (distance is 225 mm) and the pressure between the two electrodes and the strip is accurately enough to keep good electrical contact without any deformation. A self-designed electro-pulsing generator as shown by Fig. 1b supplied the positive current pulses within the short time duration (80 μs). The electrical parameters including charge voltage, processing frequency, root-mean-square current (RMS), amplitude of the currency and duration of single each current pulse were monitored by an electrical Hall Effect sensor connected to an oscilloscope. The temperature of strips was measured by a storable K type surface contacted thermocouple.

In order to make a comparison of pressing the microcracks with the EPT, CTR process (the cold-rolling on the cold-tension sample) has been brought in the experiment, which is to implement a cold-rolling on the pre-stretched sample (cold-tension sample) as a comparison with pre-stretched samples treated by high-energy electropulsing treatment in healing the microcracks and ductility. In the rolling process, the separating force of the rolling effect has been recorded by the pressure sensor device on the rolling mill. The micro-hardness of the samples was conducted by micro-hardness tester (Struers Duramin 05656242) at ambient temperature. HK21A residual stress tester was utilized to measure the residual stress of the samples. The uniaxial tensile tests at ambient condition were carried out to measure the elongation to failure (EL) by tensile testing machine. With the help of electron backscatter diffraction (EBSD), the evaluation of the microstructure of the titanium samples under different processing methods became feasible in this series of experiments. X-ray Diffraction (XRD) was also implemented to characterize the phase constitution by a Rigaku micro-diffraction goniometer equipped with a one-dimensional detector using Cu Kα radiation operated with 40 kV/200 mA. Optical microscopes (OM) by an Olympus GX51 microscope and a HiROX KH-7700 microscope were utilized to study the microcracks of the interior material and the vertical fracture section near the fracture plane. Hitachi S-4800 FEG scanning electron microscope (SEM) was used to observe the fracture surface. The damping capacities of the samples were investigated by a dynamic mechanical analyzer (DMA) DMA-Q800 with a single cantilever vibration mode. The internal friction was measured as a function of sweeping stain amplitude in the certain frequency (1 Hz).

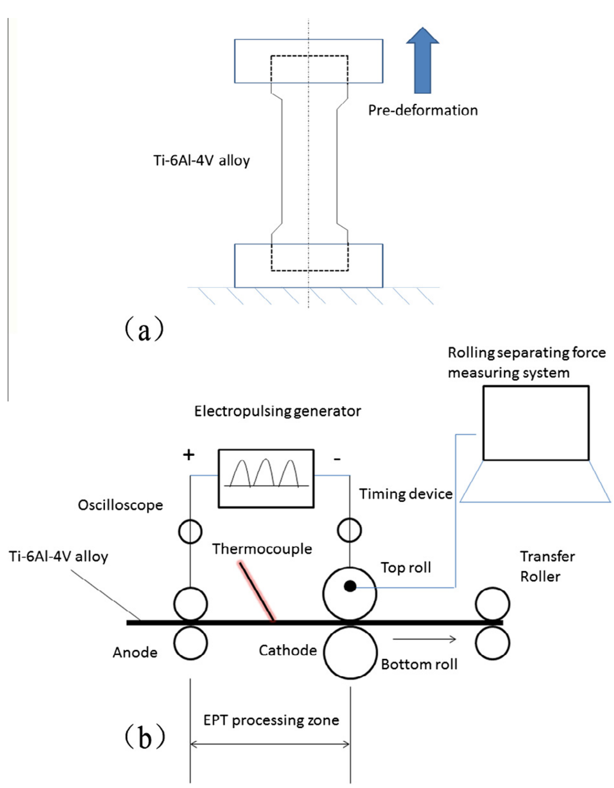

Fig. 1. Schematic views of (a) pre-tension process and (b) rolling-EPT multifunction system.

3. Results

3.1. Effects of EPT on the ductility and subsequent formability of the pre-deformed titanium strips

Fig. 2 presented the dependence of the microhardness (MH) and the elongation to failure (EL) of the EPT samples on the charging voltage (the EL of original specimen is 26%). With the increasing charge voltage of EPT the ductility has a noticeable enhancement to the maximum value (25.5%) at 48V-EPT whose microstructure is corresponding to the complete recrystallization shown by EBSD map Fig. 3d. Then EL decreased slightly with further increasing voltage by the grain coarsening as can be seen from Fig. 3e.

It is convenient to determine the relative characteristics of total EL (RCTEL) $\Delta\delta$ as measuring the effects of the EPT and CTR on the plasticity change with the changes of the charge voltage:

$$\mathrm{RCTEL} = \Delta\delta = \frac{\delta_t - \delta_{ct}}{\delta_{ct}} \times 100\% \tag{1}$$

In order to measure recovery effect of EPT and CTR on the ductility relative to the original sample EL (δ_{ori}) the recovery ratio of EL (RREL) is determined as the following style:

$$\mathrm{RREL} = R\delta = \frac{\delta_t}{\delta_{ori}} \times 100\% \tag{2}$$

where δ_t is the EL of the pre-deformed samples under EPT or cold-rolling and δ_{ct} means the EL of the CT sample. Fig. 4 showed the RREL and RCTEL evolution of the EPT samples on the EPT charging voltage and CTR sample.

48V-EPT enhances the plasticity of the CT sample greatly by 410% increment. And from Eq. (2) $R\delta$ can reach 98.08% that means under EPT nearly all the negative effect on the ductility caused by pre-stretch can be recovered, which can be seen from the micrographs Fig. 5e. The plasticity has been enhanced noticeably by these two factors together.

Whereas, from Eq. (1) $\Delta\delta$ of CTR can be −40% with the compressed microcracks shown by Fig. 5b. Although the microcracks were compressed by cold-rolling, a decline in the ductility was also introduced due to work hardening. The electropulses not only brings in internal compressive effect compressing the microcracks but also weakens the dislocation entangling and piling up to accelerate the dislocations motion which is facilitated in recrystallization process. On the contrary, the work hardening of cold-rolling process hinders the subsequent machining.

The left side of Fig. 2 shows the relationships between Vickers microhardness and EPT charge voltage. According to the results shown in Fig. 2, with the increasing parameter of high-energy electropulsing the microhardness decreased slightly accompanying by the noticeable increased ductility. Introduction of 48V-EPT brings in the dramatically enhanced ductility by about 410% compared to that of the cold-worked samples (5% is enhanced to 25.5%) but sacrificing hardness only by 33.8%. Thus noticeable increasing plasticity in a low-temperature and ultrafast procedure depicted obvious advantage of electro-plasticity technique, which has been attracted much attention and interest in the research in the long time. Obvious enhancement of the ductility and slight softening effect improves the materials formability dramatically increasing the yield rate and lowering the production cost in the meantime. Therefore, it is noticeably meaningful for producing the industrial goods and irregular shape parts in the aerospace industry and materials engineering. However, the softening effect of the materials surface is appeared in the process of EPT. In the practical materials processing, it is better to coordinate other surface modification processing techniques like the ultrasonic surface strengthening modification or shot peening to increase the surface microhardness. In fact, the coupling of high-energy EPT and surface strengthening