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Effect of electropulsing treatment on microstructure and mechanical properties of cold-rolled pure titanium strips

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ABSTRACT

Commercially pure titanium strips were successfully processed by electropulsing treatment (EPT) at relatively low temperature compared to the traditional heat treatment. The results indicated that the ductility of titanium materials is dramatically improved by electropulse while remaining uniaxial tensile strength unchanged, with the increased volume fraction of fine recrystallized grains through electron back-scattered diffraction analysis. However, too high-frequency EPT brought in the coarsened grains and worsened mechanical properties. A mechanism for rapid recrystallization and grain growth in low temperature during EPT was proposed based on the reduction of nucleation thermodynamic barrier and enhancement of atomic diffusion. It is supposed that high-efficiency EPT could provide a highly efficient method for the intermediate-softening annealing of titanium sheet/strips within well-designed process.

1. Introduction

Titanium and its alloy have been widely used as an excellent structural material in many fields. It was reported that the most titanium application in the world-wide is commercially pure titanium (CP Ti) sheets (2012). However, the poor plasticity in the materials processing at ambient condition restricted the widespread application of titanium materials due to high processing cost and difficulty.

The well-known difficulty of forming the titanium materials in the ambient or low-temperature conditions has attracted many researchers attention on improving the microstructure and plasticity. Gurao et al. (2013) found that the lower formability of the cross-rolled commercially pure titanium samples is attributed to grains orientation hardening near the basal texture. Additionally, in order to improve the ductility of titanium many kinds of processing or assisted processing methods including the traditional heat treatment have been introduced to decrease the resistance of deformation through improving microstructure in the deformation. Liu et al. (2014) designed subtransus triplex heat treatment on the pure titanium samples on the basis of the traditional method significantly reducing the continuous grain boundary α phase, and the materials ductility is noticeably improved. It is regrettable that most of the solutions to improve the microstructure and ductility are not yet perfect due to high-temperature and low-efficiency.

It is fortunate that a novel style of assisted processing technology, high energy electro-pulsing treatment (EPT), has emerged aiming to improve the materials microstructure and mechanical properties. Electro-plasticity can be applied within a short time and lower temperature in the process. Zhu et al. (2009) conducted tensile deformation of ZA22 alloy with high-energy EPT and found that the elongation of the material is increased by 437% at ambient temperature. Zhu et al. (2013) and Ye et al. (2014) applied the electropulses in assisted rolling process to improve the materials deformability and final mechanical properties. Previous research also successfully applied the EPT in processing FGM (functionally graded materials) Ti–6Al–4V alloys to control the linear distribution of microstructure and mechanical properties (2014). In addition, the coupling of the high-energy EPT and ultrasonic striking made a novel and promising surface strengthening technique with the formation of nano-crystalline microstructure under recrystallization process (2015, 2007). Moreover, the EPT-induced surface oxidation found by Ye et al. (2014, 2015) in the

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Table 1
Electropulsing parameters for treatment of the cold-rolled pure titanium strips.

Sample number	Frequency (Hz)	Duration (μs)	J_e (A/mm^2)	J_m (A/mm^2)	Measured temperature (°C)
EPT1	160	80	16.6	137	243.4
EPT2	180	80	17.8	139	274.4
EPT3	200	80	15.7	145	307.6
EPT4	220	80	17.4	133	333.6
EPT5	240	80	16.2	130	384.9
EPT6	260	80	16.4	136	408.7
EPT7	280	80	18.8	128	419.8
EPT8	300	80	21.4	139	420.9
EPT9	320	80	22.5	144	433.0
EPT10	340	80	25.6	150	444.2
EPT11	360	80	31.6	139	466.6

Notes: J_e represents the root-mean-square (RMS) value of current density in EPT processing and J_m is the amplitude of current density of the high-energy electropulses.

experimental procedure was a big step in this field to improve the materials corrosion resistance and biocompatibility.

However, the novel method of on-line EPT applied to facilitate the recrystallization process of commercially pure titanium in the low-temperature and ultrafast procedure in order to enhance the mechanical properties has not been reported much. The effect of EPT on the microstructure evolution and mechanical properties of as-rolled commercially pure titanium strips are investigated in this paper. The mechanism of the relative phenomena is also discussed.

2. Experimental

2.1. Materials and EPT processing

The cold-rolled commercially TA2 pure titanium strips (1.6 mm thick CP Ti) were utilized as the experimental material. The as-rolled titanium strips are processed dynamically by high-energy EPT under different processing frequency (as listed by Table 1 and the whole experimental procedure can be illustrated by Fig. 1). The titanium strips move rapidly through two electrodes and the pressure between the two conductive electrodes and the strips is accurately enough to keep good electrical contact but without any deformation. In the EPT system, a self-designed electro-pulsing generator supplied the positive current multi-pulses within the short time duration (80 μs), which is thus called high-energy electro-pulses. EPT was then applied to the moving strips in the meantime, which takes effect in the EPT zone with various discharge frequencies. The electrical parameters including charge voltage, processing frequency, root-mean-square current (RMS), amplitude of the currency and duration of single current pulse were all monitored by an electrical Hall Effect sensor electrically connected to an oscilloscope. The temperature of treated strips was concurrently measured by a storable K type surface contacted thermocouple and the recorded temperature could be analyzed in the real-time temperature-time evolution monitoring system.

2.2. Measuring and characterizing

The mechanical properties of treated specimens are conducted on the uniaxial tensile machine at ambient condition and 0.6 mm/min tensile speed (strain rate is 5×10^{-5} s^{-1}). Each group of specimens are set as six parallel tests for obtaining average results. With the help of electron backscatter diffraction (EBSD) and scanning electron microscope (SEM), the evaluation of the microstructure of the titanium samples became more accurate and conceivable.

3. Results

3.1. Effect of EPT on the mechanical properties of cold-rolled pure titanium strip

EPT enhances noticeably the materials ductility while keeping the strength nearly unchanged as shown by the typical engineering stress-engineering strain curves of EPT samples in Fig. 2. Introduction of 220 Hz-EPT4 improves the elongation to failure of the titanium strip by 34.6% while just sacrificing 7.8% strength value. Increasing applied frequency to 300 Hz-EPT8 further increases the materials ductility even by 132.4%, and keeps the strength unchanged at the same time. When EPT frequency continued to be 340 Hz, both of the strength and ductility got decreasing by 6.5% and 21.5%.

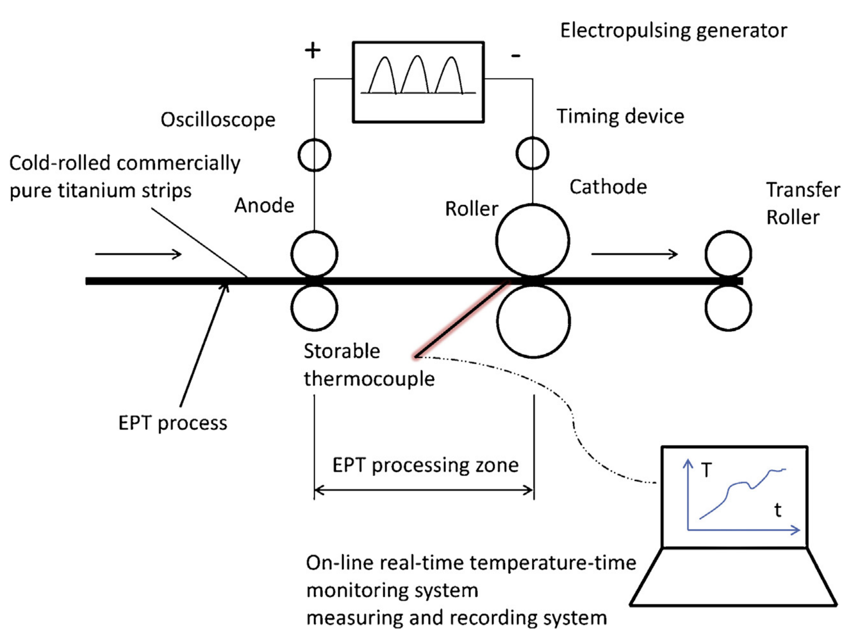

Fig. 1. Schematic diagrams of EPT process and relative on-line temperature monitoring system