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Abstract
As an instantaneous high energy input method, the electric current pulses treatment (ECP) has been extensively applied in materials science and engineering. In this work, by changing the current densities, the effect of ECP on the microstructures and the mechanical properties in a Cu-Zn alloy is investigated. The results show that the elongation of samples treated after ECP is greatly improved without a sharp decrease of the tensile strength. And with current density increasing at j_{max}=12.99kA/mm^2, the comprehensive mechanical properties is improved. The possible reason can be ascribed to the increased dislocation mobility and the crack healing induced by ECP.

Key words : electric current pulses, microstructure, mechanical properties, current densities

Introduction
Since 1963, when Troitskii and Likhman first reported that moving electrons in a metal crystal may interact with dislocations [1], the following researches have indicated that high current density electric current pulses (ECP) influences the behavior of materials. Conrad et al. proposed that ECP could enhance the nucleation rate of recrystallization and refined the grain size of a cod-worked copper by accelerating the dislocations mobility [2-5]. Qin et al. demonstrated in theory that ECP could increase nucleation rate by decreasing the thermodynamic barrier during recrystallization or phase transformation (liquid-solid and solid-state) [6]. Recently, Zhou et al. obtained ultrafine recrystallized grains in a cold-rolled brass by ECP treatment [7]. With the further investigation on the application of ECP, Dai et al. proposed that the electric current direction also played a great role on the recrystallized nucleation rate [8]. Wang et al. further found that the recrystallized grains induced by ECP nucleate randomly, but with an oriented growth [9].

However, the aim to optimize the materials' microstructure is to improve the mechanical properties. Up to now, though lots of studies have been carried out about the effect of ECP on materials' microstructures, a few reports are about the corresponding the mechanical properties. In this work, the relationship between the microstructural evolution and the mechanical properties due to the application of ECP is investigated.

Experimental details
A 33% reduction in thickness direction of a cold-rolled commercial Cu-Zn alloy sheet with a composition of Cu 63.8 mass% and Zn 36.2 mass% was used as the research object in this study. By using the electrospark discharge technique, dog-bone-shaped samples with 10 mm gage length, 5 mm width, and 1 mm thick were prepared, and the sizes of the two ends were much larger than the size of the gage part. During the ECP process, the two ends of each sample were put into copper electrodes. Thus, the current density was much higher in the gage part than in the two ends. Then the temperature rise of the two ends was very small and could be regarded as room temperature. Due to the cooling effect of the two cool ends, a higher cooling rate could be obtained in the gage part of the sample during cooling. The single ECP was produced through a discharge of capacitor banks under ambient conditions, and its waveform was detected to be a damped oscillation wave using a Rogowski coil and a TDS3012 digital storage oscilloscope (Tektronix, Beaverton, Oregon). After ECP treatment, these flat samples were divided into four groups, respectively, denoted A, B , C and D, among which samples of type A did not undergo any further treatment after cold rolled, the others were treated with ECP using current density 12.50kA/mm^2, 12.70kA/mm^2 and 12.99kA/mm^2 respectively. Each group includes four standard specimens, three for uniaxial tensile test and one for microstructure observation.

To detect the microstructure characteristic, a JEOL JSM-7100F SEM (JEOL, Akishima, Japan) was used. The tensile tests at room temperature were conducted to examine mechanical properties using an Instron 1195-5500R test machine with a cross-head speed of 1mm/min.

Results and discussion

The Cu–Zn alloy selected in this study is a dual phase brass (α+β phases). During current passing, the temperature increment can be calculated as 550K, 574K, and 594K, respectively for the samples B, C and D. Apparently, the temperature caused by ECP are lower than the phase transformation temperature (953K). Therefore, the microstructural evolution shown in Fig.1 can be resulted from the formation of recrystallization caused by ECP.

Fig. 1 shows the SEM morphologies of specimens A, B, C and D. Fig. 1(a) shows lots of coarse grains randomly distribute. Also massive sliding traces and some deformation twins appeared in the primary α-phase grains of the cold-rolled Cu-Zn alloy. The coarse β grains distribute at the triple junctions of α grains. After the ECP treatment, the refined recrystallized α grains are preferentially formed at grain boundary, sliding traces and other defect areas, as shown in Fig. 1(b). With the current density increasing, the recrystallized grain growth of α-phase is taken place and the grain sizes become homogeneous. Especially, with the grains growing up, lots of annealing twins are formed and the deformed microstructures almost disappeared in Fig. 1(d). However, it can be observed that there is no significant change in the grain size distribution for β phase.

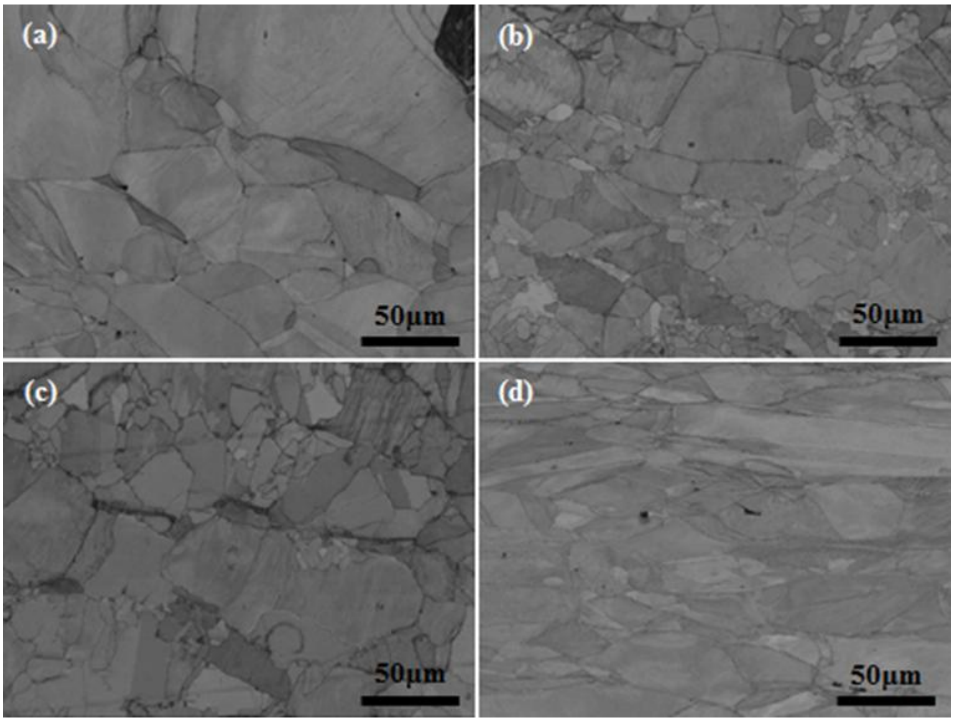

Fig. 1: Microstructural evolution of the samples treated: (a) cold-rolled, and ECP treated with (b) j_{max}=12.50kA/mm^2, (c)j_{max}=12.70kA/mm^2, (d) j_{max}=12.99kA/mm^2.

To clarify the effect of electric current on the mechanical properties, Fig. 2 plots the evolution of the mechanical properties at the different current densities. Worthy to mention that during the mechanical test, each group includes three specimens, and the data shown in Fig. 2 are the average values of the three specimens. It can be found that the tensile strength of the cold-rolled Cu-Zn alloy is significantly decreased from 477MPa to about 400MPa for the ECP treated specimens. While for the ECP treated specimens, with the ECP current densities increased, the tensile strength and the elongation of the cold-rolled Cu-Zn alloy have a saddle point for samples C with j_{max}=12.70kA/mm^2. For samples D with j_{max}=12.99kA/mm^2, the tensile strength and the elongation rate are higher than others.

The fracture surfaces of samples A-D after tensile tests are shown in Fig. 3. The dimples and cleavage modes are found on the fracture surface of the samples treated before ECP, while for electric-current-pulsed samples, the plastic dimples become more homogeneous. Especially, the cleavage modes almost disappeared in the electric-current-pulsed samples, especially as that shown in Fig. 3(d) for samples D.

From the above mentioned, it can be found that the deformed microstructure vanished gradually and recrystallized grains were obtained, which increases the materials' ductility. Because the Joule heating caused by ECP could provide temperature and energy conditions for recrystallization, the application of ECP treatment would enhance the mobility of the dislocations. The drift electrons can exert a force on dislocations when high density electric pulses are passing through the specimen [4]. The force is named after electron wind force, and it is proportional to current density. Due to the effect of electron wind force, the mobility of dislocation will be increased during ECP treatment [7], It is also wellknown that the glide and climb of dislocation and migration of atoms are important for the static recrystallization process, thus ECP treatment can produce more advanced stage of recrystallization and enhance the nucleation rate of recrystallization with the current density increasing.

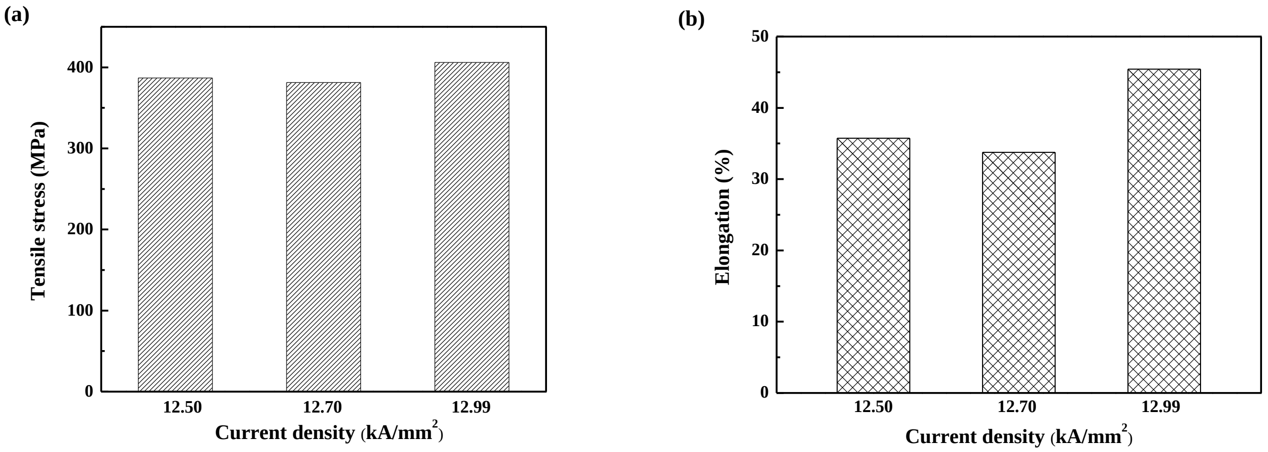

Fig. 2: Relationship between the mechanical properties and the current densities (a) the tensile stress, (b) the elongation rate.

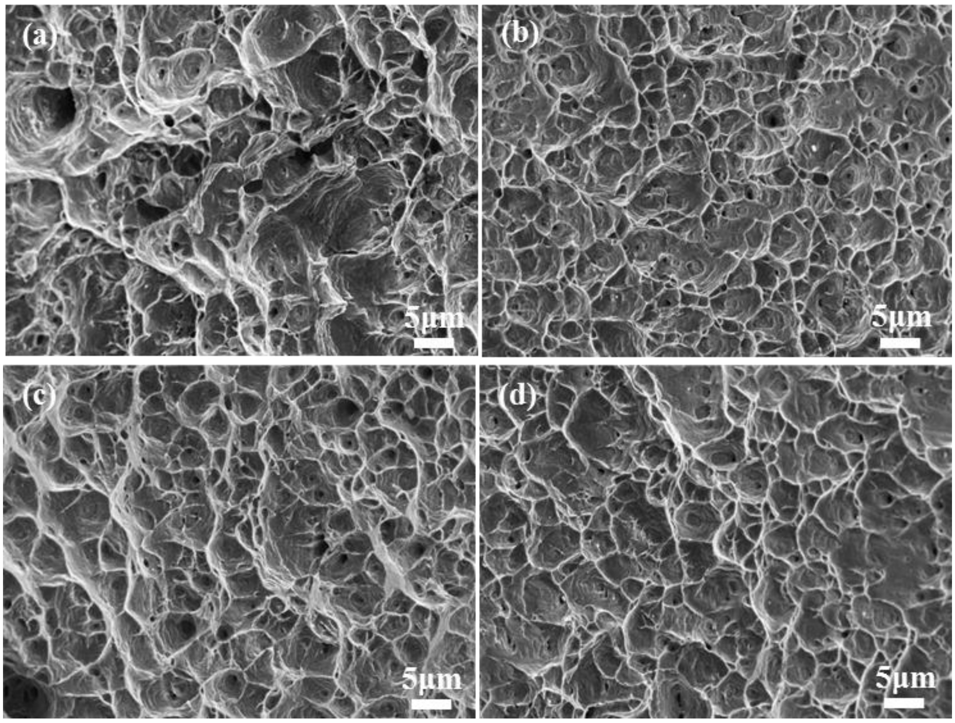

Fig. 3: SEM fractographs of the samples (a) cold-rolled, and treated with ECP at (b) j_{max}=12.50 kA /mm^2, (c) j_{max}=12.70 kA /mm^2, (d) j_{max}=12.99 kA /mm^2.

In addition, the ECP treatment has a selective effect. When the high density electric pulses are passing through a metal sample, due to the larger local resistivity and the stronger detour of the electric current, the Joule heating and the transient thermal compressive stress are stronger in the defectiveness area. Then the change of the temperature in the area with a defect is higher than other sides. Because of existence of these defects, inhomogeneous physical field in a metal is generated. Under these effects, the microcrack can be closured or healed [10]. Therefore, the ECP treatment is an effective method to heal the damage, which is also an important influence on the improvement of the mechanical properties.

The above results indicate that the difference of the mechanical properties can be resulted from the different microstructure induced by different current densities. Obviously, the improvement of mechanical properties should be ascribed to the homogeneous distribution of the grain size after the ECP treatment. In addition, an optimum combination of ductility and strength in the cold-rolled Cu-Zn alloy could be achieved by the ECP treatment.

Conclusions

(1) The improvement of the mechanical properties induced by ECP can be ascribed to the different effect of electric current density on the microstructural evolution. With increasing current density, a degree of recrystallization is increased. The effect of ECP includes not only the thermal effect, but also the electric current special effect.

(2) The ECP treatment has an important effect on the damage healing in cold-rolled Cu-Zn alloy, which gives a significant increase in total elongation.

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