Achieving High Strength and High Electrical Conductivity in a CuCrZr Alloy Using Equal-Channel Angular Pressing

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Abstract

In the present work, a CuCrZr alloy characterized by ultrafine grains and nanoscale particles was prepared by equal-channel angular pressing (ECAP) at 450 °C. A desired combination of a tensile strength (580 MPa) and an electrical conductivity (81% International Annealed Copper Standard) is simultaneously obtained in the as-ECAP-processed CuCrZr alloy without additional aging treatment. The improved properties can be mainly attributed to the ultrafine grains and nanoscale precipitates. This processing may pave a way to develop the CuCrZr alloys having high strength and high electrical conductivity for engineering applications.

Keywords Microstructure · CuCrZr · Equal-channel angular pressing · Strengthening

1 Introduction

CuCrZr alloys have attracted much attention because of their high mechanical strength, excellent electrical conductivity, good fatigue property and thermal stability [1–5]. Thus, these alloys have been widely used in many engineering fields. In some conditions, the high-strength CuCrZr alloys are usually required to simultaneously have high electrical conductivity. Several methods have been proposed to meet such a requirement, including solution strengthening by alloying of solute atom [6, 7], grain refinement [8] and precipitation strengthening [9, 10]. Among them, the first two methods increase mechanical strength accompanied by a great sacrifice of electrical conductivity resulting from the scattering of electrons by solute atoms or dislocations/grain boundaries [3]. The last one has been proved to be an effective method to

simultaneously optimize mechanical strength and electrical conductivity [11].

In recent years, equal-channel angular pressing (ECAP) has been used to refine the microstructure of CuCrZr alloys [12, 13]. Accordingly, the mechanical strength was obviously improved and the electrical conductivity was greatly reduced. For example, the tensile strengths of 500–688 MPa were obtained in the as-ECAP-processed CuCrZr alloy [2, 8, 14], while the electrical conductivity of Cu–0.8Cr–0.08Zr alloy decreased from 75% IACS to 33% IACS after ECAP [14]. The reduced electrical conductivity can be recovered by the precipitation of Cr through subsequent aging [14]. However, the aging parameters have to be carefully controlled since the precipitation kinetics of the as-ECAP-processed alloy is accelerated by a large number of lattice defects and the grain boundaries, which is dependent on the ECAP processing parameters [15]. This causes the complexity in designing and tailoring of multifunctional properties.

In this work, a one-step ECAP deformation was proposed to simultaneously obtain high strength and high electrical conductivity in a CuCrZr alloy. The influence of ECAP on the microstructure, mechanical properties and electrical conductivity was investigated and discussed.

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2 Experimental Procedure

A commercial alloy of Cu–0.36Cr–0.49Zr (wt%) produced by GMBH J.P. Schumacher was studied. Before ECAP processing, the alloys were annealed at 960 °C for 2 h and then quenched into water, which is specified as the initial state. The initial samples having a diameter of 10 mm and a length of 60 mm were processed by ECAP at a temperature of 450 °C for up to eight passes. The channel intersection angle of the die is 120°. This temperature was chosen because the precipitation temperature of Cr particles was found to be about 440 °C in the as-ECAP-processed CuCrZr alloy [8]. The pressing route Bc was used. Before each pass, the rod was kept at 450 °C for 10 min in a furnace and then quickly moved to the preheated die and pressed at a rate of 15 mm s^{−1}.

Microstructure of the samples was observed by a FEI Nano430 field emission gun scanning electron microscopy (SEM) and a JEOL JEM2100 transmission electron microscopy (TEM). TEM observations were operated at 200 kV using a double-tilt sample stage. The TEM foils were prepared by mechanical grinding and twin-jet electropolishing. The electrolyte solution consists of 25% nitric acid and 75% methanol in volume. The composition of second phase was carried out on a JXA-8230 electron probe micro-analyzer (EPMA) equipped with wavelength-dispersive X-ray (WDX) spectrometers. Vickers microhardness measurements and tensile tests were carried out at room temperature. The gauge dimension of the tensile sample is 6.5 mm × 2.0 mm × 1.0 mm. The tensile tests were conducted in an Instron 3365 tensile machine. The electrical conductivity was measured using eddy current method at room temperature.

3 Results and Discussion

Figure 1 shows the SEM image of initial CuCrZr alloy. The microstructure is characterized by the irregularly shaped grains with some black and white particles embedded into the matrix. The grain size is estimated to be 26 μm. The white particles are Cu_{38.6}Cr_{23.8}Zr_{37.6} phase and the black particles are Cu₃Zr₂ phase according to WDX results. The size and volume fraction of the particles cannot be significantly changed by ECAP processing [16].

After processing at 450 °C for eight passes, the grain size of CuCrZr alloy was reduced to about 0.50 μm, as shown in Fig. 2a. The blurry subgrain boundaries were also observed. Figure 2b shows the distribution of the precipitates in the as-ECAP-processed sample. A large number of the nanoscale precipitates were identified to be the particles containing Cr and Cu₄Zr particles according to the selected

Fig. 1 SEM image of the initial CuCrZr alloy

area electron diffraction results shown in Fig. 2c, d. The same precipitates have been found in aged CuCrZrCe [6] and CuCrZrMg alloys [17]. The average size of the particles was estimated to be about 5 nm. These particles may form during preheating and ECAP. The high-density dislocations introduced during deformation can serve as the nucleation sites of precipitation, which favors in increasing the amount of particles.

Figure 3a shows the effect of ECAP pass number on the microhardness and electrical conductivity. The microhardness increases obviously after the first pass and then slowly with the increase in pass number. This is quite similar to the previously reported results [16, 18]. An unusual dependence of electrical conductivity on pass number is observed. The electrical conductivity increases with the increase in pass number. The highest value of the electrical conductivity can reach up to 81% IACS. This is different from the previously reported results on CuCrZr alloys processed at room temperature in which the electrical conductivity decreases with increasing pass number [16, 18, 19]. In principle, the decrease in electrical conductivity is ascribed to the scattering of electron resulting from grain boundaries, dislocations and solute atoms dissolved in the matrix [3]. It is generally accepted that for CuCr alloy, one of the effective methods to improve the electrical conductivity is to reduce the content of solute atoms in the matrix through precipitation [20]. Therefore, it is suggested that the precipitations of the particles containing Cr and Cu₄Zr particles are responsible for the increased electrical conductivity.

Fig. 2 TEM images of the as-ECAP-processed CuCrZr alloy **a**, **b**, selected area electron diffractions **c**, **d**

Fig. 3 **a** Effect of pass number on the microhardness and electrical conductivity of the CuCrZr alloys processed at 450 °C, **b** typical stress–strain curves of the alloys before and after ECAP

Figure 3b shows the stress–strain curves of the initial sample and the sample processed for eight passes. As compared to that of initial sample, the mechanical behavior of the as-ECAP-processed samples is characterized by high strength, reduced elongation, small uniform elongation and ductile fracture. The tensile strength increased from 303 MPa to 580 MPa. The above results indicate that it is possible to obtain simultaneously high mechanical properties and high electrical conductivity for CuCrZr alloys without additional aging treatment.

Figure 4 compares the present results with the reported results in which the ECAP was carried out without subsequent aging. The detailed values and processing parameters are also summarized in Table 1. It is seen that when the processing temperature is below 450 °C, ECAP at room temperature may lead to the strongest strengthening effect accompanied by the largest reduction of electrical conductivity. With the increase in processing temperature, the

Fig. 4 Tensile strength and electrical conductivity of CuCrZr alloys processed by ECAP without additional aging treatment. The data were obtained from the present work and the reported results

strengthening effect becomes weak while the electrical conductivity decreases. This can be rationalized by the microstructural evolution of CuCrZr alloys characterized by refined grain size and a large number of dislocations [2, 16, 19]. When the processing temperature is increased to 450 °C, the precipitations of the particles containing Cr and Cu₄Zr particles are involved, as shown in Fig. 2. As a result, the balance between the mechanical strength and the electrical conductivity is achieved. This can be due to the following influencing factors, including the ultrafine grain, dislocation and precipitation. It is suggested that the dislocation may take a minor role since a large number of the dislocations usually improve the mechanical strength at the obvious expense of the electrical conductivity. Therefore, the ultrafine grains and large amount of nanoscale particles should be responsible for this simultaneous improvement of mechanical strength and electrical conductivity. Further work will be carried out to clarify the detailed mechanism.

At the point of the engineering applications, the following advantages of the present processing should be highlighted. First of all, the conventional ECAP procedure can be directly implemented in ECAP-conform processing which has been developed to prepare long-length wires or rods in recent years [21]. Then, the CuCrZr alloy processed at 450 °C shows good thermal stability. As an example, the as-ECAP-processed CuCrZr alloy was annealed at 300 °C for 2 h. The results show that the tensile strength obviously increased to 612 MPa and the electrical conductivity slightly increased to 82% IACS. Therefore, it is expected that this strategy can be used to fabricate the CuCrZr alloy with high strength and high electrical conductivity for the engineering applications through the optimization of the processing parameters further.

Table 1 UTS and electrical conductivity of some as-ECAP-processed CuCrZr alloys

Alloy	Processing	UTS (MPa)		Electrical conductivity (% IACS)		References
		Initial value	After ECAP	Initial value	After ECAP	
Cu–0.36Cr–0.49Zr	ST + ECAP at 450 °C for 8 passes	303	580	48	81	Present work
Cu–0.8Cr–0.08Zr	ST + ECAP at RT for 8 passes	189	618	67	35	[2]
Cu–0.3Cr–0.5Zr	ST + ECAP at 400 °C for 4 passes	200 ^a	510 ^a	34 ^a	31 ^a	[16]
	Aging + ECAP at 400 °C for 4 passes	330 ^a	575 ^a	48 ^a	34 ^a	
Cu–0.87Cr–0.06Zr	ST + ECAP at 200 °C for 12 passes	365	550	79	68 ^a	[19]
	ST + ECAP at 300 °C for 12 passes	365	520	79	66 ^a	
	ST + ECAP at 400 °C for 12 passes	365	465	79	74 ^a	

ST solution treatment

^aMeans that the data were estimated from the figures

4 Conclusions

The desired combination of the tensile strength of 580 MPa and the electrical conductivity of 81% IACS was simultaneously obtained in Cu–0.36Cr–0.49Zr (wt%) alloy by a one-step ECAP process at 450 °C. This can be mainly ascribed to the ultrafine grains and nanoscale precipitates. This processing paves a way to develop the CuCrZr alloy having high strength and high electrical conductivity for engineering applications.

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