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Influence of direct current on the ageing behavior of a CuCrZr alloy

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Abstract

In recent decades, much work has been done on the effect of electric current on processing and properties of metals. And influence of an electric current on the solid state phase transformation in metals is complicated: an electric current can either enhance or retard the precipitation rate, depending on the alloy composition, the current density and the frequency of pulsed dc current. In this study, we imposed direct current during the ageing process of a CuCrZr alloy and studied the influence of current on the ageing behavior. With the imposition of current, the ultimate strength of CuCrZr alloys is improved, and the improvement in strength can be explained by finer precipitates modified by current. The effect of direct current pulses with the frequency of 1,000 Hz is most significant. The morphology of precipitates changes from spherical to cylinder with the imposition of current.

Key words: direct current; ageing; precipitate; mechanical properties; CuCrZr alloy

Introduction

Continuous efforts have been made to obtain materials that exhibit both excellent mechanical strength and high electrical conductivity for high performance applications, such as integrated circuit lead frames and high speed railway contact wire [1-3]. As an age-hardenable alloy, the excellent mechanical properties of Cu-Cr-Zr alloys are attributed to the precipitation and particle-dispersion strengthening mechanism[4, 5].

In recent decades, much work has been done on the effect of electric current on processing and properties of metals. Ageing process can be promoted by current [6,7], and electric current pulses have a remarkable effect on recovery and recrystallization [8,9]. The effects of electric current pulses on the ageing process of deformed copper alloys may be interesting. So far, very little work on this subject has been reported. In this paper, we focus on the influence of current pulses on the aging behaviors of a hot rolled-quenched Cu-Cr-Zr alloy during thermomechanical treatment. Different current were imposed and their influence on mechanical strength was evaluated by tensile test. Scanning electron microscope (SEM), optical microscope (OM) and transmission electron microscope (TEM) were applied to characterize the evolution of the microstructures, upon which detailed discussion of the mechanism was based.

Experimental procedure

Alloy with a composition of Cu-0.6 wt.% Cr-0.3 wt.% Zr was melted in a vacuum-induction melting furnace with electrolytic copper, pure chromium and copper-zirconium master alloy (Cu-50 wt.% Cr alloy), and then casted in a graphite mold with a size of 40 mm × 200 mm. The ingot was cut into a size of 30 mm × 30 mm × 120 mm before hot rolled at 850 °C to a thickness of 15 mm. The hot rolled plate was solution treated at 960 °C for 1 h, followed by quickly quenching in cold water. The solution treated plate was then planed on both sides to remove surface defects and rolled with 85% reduction at room temperature.

The cold rolled plates were cut into small plates with a size of 20 mm × 50 mm × 2 mm. The schematic diagram of ageing process is illustrated in Fig. 1. The samples were gripped on both sides to conduct current and Ar was used as a protective atmosphere. To modify the effect of joule heat, a thermal couple was fitted to the surface of the sample to accurately measure the temperature. The cold rolled pieces were aged with and without current. In this paper, direct current and a single-phase d.c. current pulse with the frequency of 50 Hz and 1,000 Hz were employed. The density of d.c. pulses was fixed below 100 A/cm². Due to the low frequency of current, the influence of skin effect can be ignored in the present study. The aging treatment was carried out in a tube furnace and current pulses were imposed from the beginning of heating.

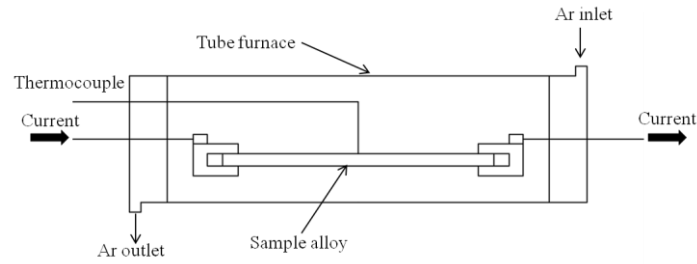


Fig. 1 Schematic diagram of ageing process

Results and discussion

Fig. 2 shows the optical micrographs of the Cu-Cr-Zr alloys under different state. In the as-cast state, typical coarse columnar grains are observed, which can be attributed to the low cooling rate of iron mold. The grains were elongated by hot rolling (Fig. 2 (b)) and grew into equiaxed grains during solution treatment (Fig. 2 (c)). However, there're still undissolved eutectic Cr particles due to its limited solubility in copper. The grains were severely elongated during cold rolled (Fig. 2 (d)) and the deformed structure remains upon ageing at 450 °C for 4 h, which indicates that work hardening is still effective. After ageing at 600 °C for 4 h, equiaxed grains appear again, indicating the onset of recrystallization .

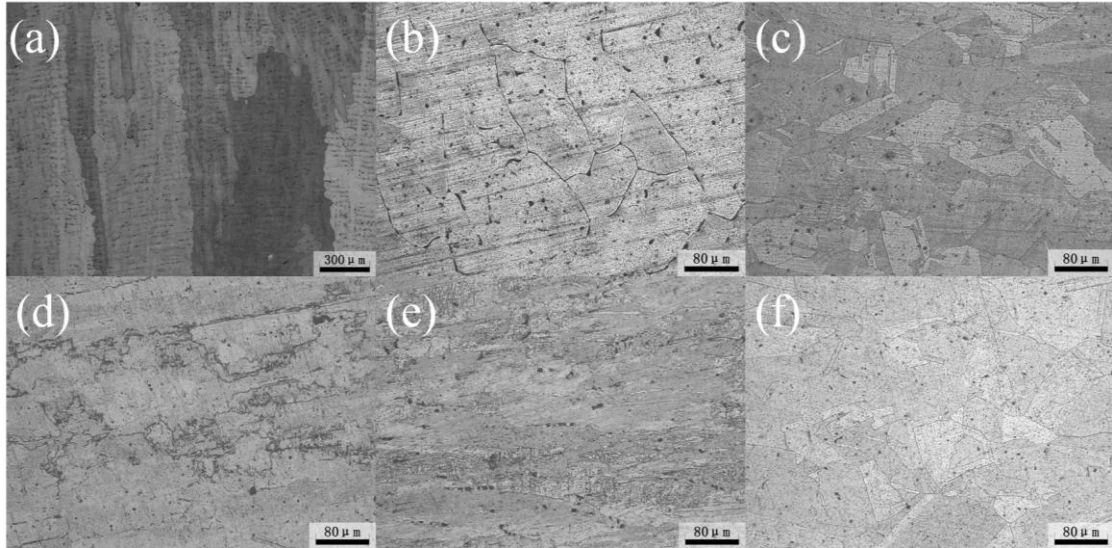


Fig.2 Optical micrographs of the CuCrZr alloys under different state: (a) as cast (b) hot rolled (c) solution-treated (d) cold rolled (e) aged at 450 °C for 4 h and (f) aged at 600 °C for 4 h

Table 1 shows the mechanical properties of CuCrZr alloys under different conditions. With the imposition of current, all the ultimate strength of aged CuCrZr alloys is improved with the exception of Sample 5. Comparing Sample 2&3 with Sample 4&5, it goes without saying that the effect of pulses is more obvious than direct current. Comparing Sample 2 with Sample 3, it seems the effect of higher frequency (1,000 Hz) is more obvious than a lower one (50 Hz). Comparing Sample 4 with Sample 5, the invariant ultimate strength of sample 5 can be attributed to the low density of current. As for the elongation of CuCrZr alloys, imposition of current shows little difference.

Table 1 Mechanical properties of CuCrZr alloys under different conditions

Number	Applied current	Frequency/Hz	density/(A/cm ²)	σ_{UTS} /(MPa)	Elongation/%
1	/	/	/	568	12
2	Positive pulses	1000	40	583	13
3	Positive pulses	50	40	574	13
4	Direct current	/	40	575	13
5	Direct current	/	20	567	14

Fig. 3 illustrates the TEM image of CuCrZr alloy aged at 450 °C for 4 h with and without current pulses. When aged at

450 °C for 4 h, spherical and tetragonal particles with an average size between 15 and 20 nm are observed, as shown in Fig. 3(a). With the imposition of direct current pulses, more ellipsoidal particles with a size of 5-10 nm are observed, as shown in Fig. 3(b). The imposition of direct current pulses reduces the size of precipitates and increases the number of precipitates.

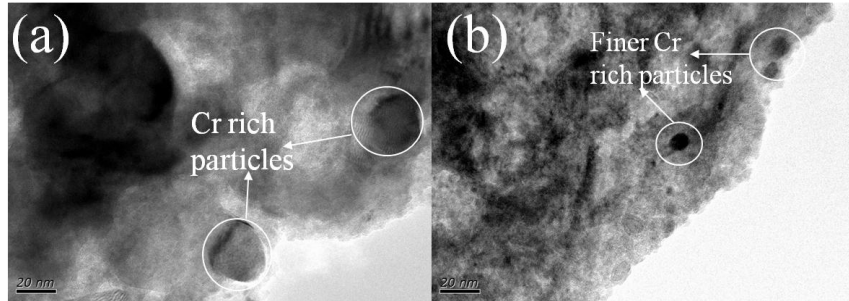


Fig.3 TEM image showing precipitated particles of CuCrZr alloys upon (a) ageing at 450 °C for 4 h (b) ageing at 450 °C for 4 h with positive pulses

For Cu-Cr system alloys under peak ageing and over ageing conditions, the strengthening is dominated by Orowan mechanism [10], the Orowan stress (T_{os}) can be expressed as

$$T_{os} = \frac{0.8Gb}{2\pi L(1-\nu)} \ln\left(\frac{2r}{r_0}\right) \quad (1)$$

Where G is the shear modulus of matrix, b is the Burgers vector of dislocations, L is the inter-precipitate spacing, ν is the Poisson's ratio, r is radius of precipitates and r_0 is the inner cutoff radius of dislocations, the value of which can be taken as equal to b . It can be inferred from Equation (1) that the Orowan stress is mainly controlled by the radius of precipitates r and the inter-precipitate spacing L . As shown in Fig. 3, the precipitates are clearly refined with the imposition of current, thus the radius of precipitates r is reduced. Finer precipitates would result in higher density of precipitates in the matrix, consequently reduce the inter-precipitate spacing L . Therefore, strengthening of Orowan mechanism is enhanced.

Fig. 4 shows the SEM micrographs of CuCrZr alloys. Apart from much finer precipitates in the matrix, the morphology of precipitates is changed by current. The precipitates change from spherical to cylinder. To confirm this change in morphology, CuCrZr alloys were aged at 450 °C for 4 h with a current density of 100 A/cm². From the results shown in Fig. 5, we can clearly see the cylinder precipitates formed during ageing with current. The precipitates' aspect ratio of sample aged under direct current is the highest, while that of sample aged under positive pulses of 1,000 Hz is the lowest. This result confirms with the effect of current on mechanical strength, as spherical precipitates are more effective than cylinder precipitates in Orowan strengthening.

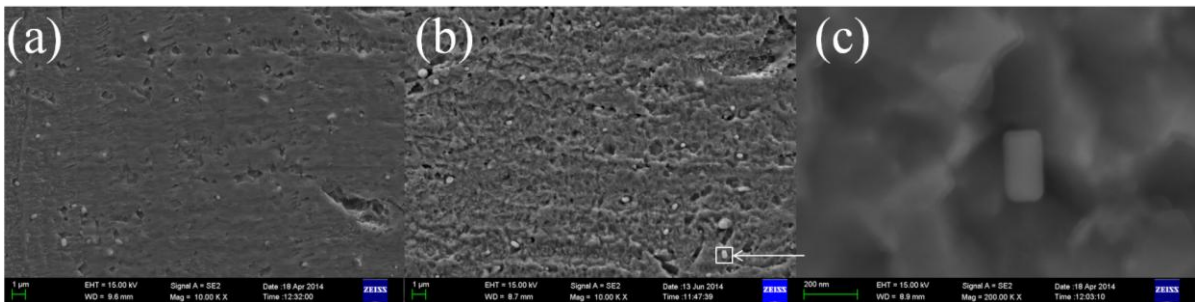


Fig.4 SEM micrographs of CuCrZr alloys (a) ageing at 450 °C for 4 h (b) ageing at 450 °C for 4 h with positive pulses of 40 A/cm² and (c) marked square area of (b)

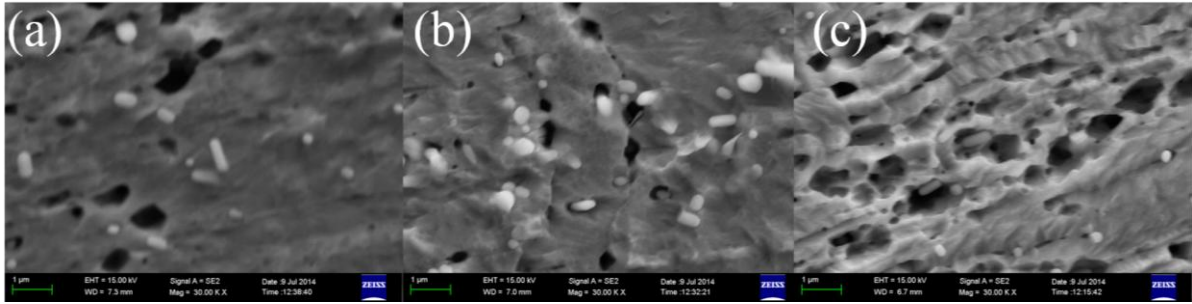


Fig.5 SEM micrographs of CuCrZr alloys aged at 450 °C for 4 h with the current density of 100 A/cm²
 (a) direct current (b) positive pulses of 50 Hz and (c) positive pulses of 1,000 Hz

The changes in morphology with the imposition of current may be partly explained by the electronwind force. For substitutional solutes like Cu-Cr-Zr alloys, aging process is a diffusion-controlled phase transformation. Therefore, it is expected that the electromigration plays a key role in influence of may be important when an electric current is introduced. According to the Nernst-Einstein equation, the atomic drift flux of atoms that occurs under the influence of an imposed electric current is given by

$$\Phi_i = \frac{N_i D_i}{kT} \left(kT \frac{\partial \ln N_i}{\partial x} - \Omega \frac{\partial \sigma}{\partial x} + Z^* e \rho j \right) \quad (2)$$

In the equation above, the term $kT \partial \ln N_i / \partial x$ is determined by the chemical potential gradient, $\Omega \partial \sigma / \partial x$ is determined by the internal stress produced by precipitates and $Z^* e \rho j$ is determined by electronwind force. With the imposition of current, the mobility of atoms is accelerated by electronwind force. The accelerated mobility along the direction of current may promote the growth of precipitates along the specific directions, thus changes the morphology of precipitates. In substitutional solute alloy systems, the effect of an electric current is complex[12]. Further study is needed to clarify the mechanism of influence of current on the aging process.

Conclusions

1. With the imposition of current, the ultimate strength of CuCrZr alloys is improved. The improvement is most significant when aged under positive pulses with the frequency of 1,000 Hz.
2. The improvement in strength can be explained by finer precipitates modified by current.
3. The morphology of precipitates changes from spherical to cylinder with the imposition of current.

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References

- [1] S. Jia, P. Liu, F. Ren, B. Tian, M. Zheng, G. Zhou (2007), *Wear*, 262, 772-777
- [2] M. Kermajani, S. Raygan, K. Hanayi, H. Ghaffari (2013), *Materials & Design*, 51, 688-694.
- [3] H.T. Zhou, J.W. Zhong, X. Zhou, Z.K. Zhao, Q.B. Li (2008), *Materials Science and Engineering: A*, 498, 225-230.
- [4] K.V. León, M.A. Muñoz-Morris, D.G. Morris (2012), *Materials Science and Engineering: A*, 536, 181-189.
- [5] M.A. Muñoz-Morris, K. Valdés León, F.G. Caballero, D.G. Morris (2012), *Scripta Materialia*, 67, 806-809.
- [6] Z. Wang, Y. Zhong, G. Cao, C. Wang, J. Wang, W. Ren, Z. Lei, Z. Ren (2009), *Journal of Alloys and Compounds*, 479, 303-306.
- [7] Z. Wang, Y. Zhong, Z. Lei, W. Ren, Z. Ren, K. Deng (2009), *Journal of Alloys and Compounds*, 471, 172-175.
- [8] H. Conrad, N. Karam, S. Mannan (1983), *Scripta metallurgica*, 17, 411-416.
- [9] H. Conrad, Z. Guo, A. Sprecher (1990), *Scripta Metallurgica et Materialia*, 24, 359-362.
- [10] Y. Pang, C. Xia, M. Wang, Z. Li, Z. Xiao, H. Wei, X. Sheng, Y. Jia, C. Chen (2014), *Journal of Alloys and Compounds*, 582, 786-792.
- [11] H. Conrad, *Materials Science and Engineering: A* 2000;287:227-37.