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Effects of thermo-mechanical treatment on microstructure and properties of Cu-Cr-Zr alloys

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Abstract

CuCrZr alloys are attractive metallic materials for applications on trolley wire of electric locomotive, integrated circuit and fusion reactor. The solid solution CuCrZr alloys were thermo-mechanically treated by heating up to various temperatures from 100°C to 300°C for aging treatment. Different tension elongations were exerted on the samples to accelerate the introduction of high density dislocations. The results showed that the combination of aging treatment and the simultaneous tension deformation can increase the hardness of the sample while decrease their electric conductivity. The high temperature of 300 °C resulted less reduction of electric conductivity than the low treated temperature of 100 °C. The disperse precipitation of the secondary phase were observed from the XRD and optical observations. The tension deformation leaded to the preferred orientation in the sample. The combination of aging treatment and the simultaneous tension deformation could reduce the aging temperature of CuCrZr alloys.

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Keywords: CuCrZr alloys, thermo-mechanical treatment, micro-hardness, electrical conductivity

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1. Introduction

Due to high electrical conductivity and moderately high toughness, CuCrZr alloys are the promising materials applied in Pantograph-OCS system where they play a role of conducting electricity and contacting slip orbit [1-4]. However, many modern engineering applications require a rather sophisticated combination of electrical and mechanical properties [5]. The improvement of the fatigue properties can be realized by increasing the yield stress and the defect density. The excellent endurance limit could be obtained through an aging heat treatment and the subsequent hot isostatic pressing (HIP) manufacturing step. However, the enhancement of the mechanical properties would inevitably result in the reduction of the electrical properties due to the increased electron scattering [6]. Therefore, it is meaningful to seek out the optimum from the various treatments in order to achieve a good combination of mechanical and electrical properties.

From the phase equilibrium of the CuCrZr system, a precipitation strengthening alloy can be easily obtained according to the largely different solubility of Cr in Cu matrix from 0.03 wt. % at room temperature to 1 wt. % at 940 °C [7]. In order to achieve the good performance, an aging treatment and the subsequent cold deformation are usually applied. The former aims to accelerate the dispersion of the strength phase while the later is used to create more dislocations thereby increase the dislocation sliding resistance [8-10]. However, this process performs in a low efficiency during manufacturing since the aging treatments take a long time of more than 72 hours. The deformation during aging treatments could accelerate the phase transformation as has been observed in the martensite transformation in iron system [11-13]. Therefore, the combination of the aging treatments and the simultaneous deformation were introduced in this work. The CuCrZr alloys were thermo-mechanically treated by heating up to various temperatures from 100 °C to 300 °C for aging treatments. Different tensile elongations were exerted on the materials to accelerate the introduction of high density dislocations during the aging treatments. The effects of thermo-mechanical treatment on microstructure and properties of CuCrZr high strength and high conductivity alloys were discussed.

2. Experimental procedure

The as-cast CuCrZr alloys had a nominal composition of 0.6 wt.% Cr and 0.13 wt.% Zr. The rests are copper plus other trace elements. They were solution-annealed up to 920 °C and then maintained for 1 hour, afterwards a water quenching was carried out. The thermo-mechanical deformations were conducted on an INSTRON universal testing machine equipped with a thermal cycling chamber for accurate temperature control. The rod specimens with gauge length of 40 mm were deformed at 100 °C and 300 °C respectively. In these progresses, a 30 min heating time was fixed to guarantee the homogenous temperature in the thermal cycling before tensile deformation. The deformation rate was fixed at 5×10^{-3} mm/min. At each temperature, a series of progressive advanced tensile elongation was introduced, as shown in Table 1. As the setting tensile elongation was reached, 1 hour thermal insulation was applied to ensure the separation of strength phase from the matrix.

The microstructure of the samples were investigated by means of X-ray diffraction with CuKα radiation. The metallographical observation was carried out on a Leica microscopy. The etching solution was a mixture of 100 ml H2O, 10g FeCl3, and 10 ml HCl. The electric conductivity was determined from the resistance of the sample in 31 mm length by means of a QJ36S-type standard direct-current four-probe system. The micro-hardness was measured on a HVS-1000-type hardness tester under a 50 g load and holding for 15 s.

3. Results and discussion

Hardness and electrical conductivity tests were carried out to assess the combined mechanical and electrical properties. The tests were performed on each sample. Each record consists of three independent operations. Table 1 represents the obtained hardness and electrical conductivity.
Table 1. The mechanical and electrical properties of the CuCrZr alloy at 100 °C and 300 °C with tensile elongations of 5, 10, 15 and 20 mm respectively.

<table>
<thead>
<tr>
<th>Sample</th>
<th>electric resistance/μΩ</th>
<th>IACS%</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Solute</td>
<td>15.2</td>
<td>70.8%</td>
<td>181.8</td>
</tr>
<tr>
<td>100°C×5mm</td>
<td>18.5</td>
<td>59.3%</td>
<td>189.4</td>
</tr>
<tr>
<td>100°C×10mm</td>
<td>23.4</td>
<td>51.3%</td>
<td>212.5</td>
</tr>
<tr>
<td>100°C×15mm</td>
<td>22.5</td>
<td>53.9%</td>
<td>221.9</td>
</tr>
<tr>
<td>100°C×20mm</td>
<td>25.1</td>
<td>54.4%</td>
<td>240.6</td>
</tr>
<tr>
<td>300°C×5mm</td>
<td>17.8</td>
<td>61.5%</td>
<td>203.6</td>
</tr>
<tr>
<td>300°C×10mm</td>
<td>17.6</td>
<td>64.0%</td>
<td>223.2</td>
</tr>
<tr>
<td>300°C×15mm</td>
<td>18.4</td>
<td>66.4%</td>
<td>237.4</td>
</tr>
<tr>
<td>300°C×20mm</td>
<td>20.7</td>
<td>63.6%</td>
<td>242.7</td>
</tr>
</tbody>
</table>

The solid solution sample had a hardness of HV=181.8 and electric conductivity of 70.8% IACS. In contrast, the treated sample demonstrated reduced electric conductivity and increased hardness, indicating the conflicts between the mechanical properties and the electrical properties. However, in spite that the samples treated at 300 °C presents similar hardness, their electric conductivities are clearly higher than those of the samples treated at 100 °C. This suggests that the higher aging temperature aids to achieve the combined performance for CuCrZr alloys. In addition, it is found that with increasing the tensile elongation the sample hardness increased whereas their electric conductivities demonstrate no principal variation. It is properly related to the slipping of the connector during the tension process.

Fig. 1 presents the typical XRD patterns of the samples. The solid solution sample was the copper matrix with a certain amount of Cr solid solution. Three peaks of Cu(111), (200), (220) can be identified clearly as shown in Fig.1(a). Fig.1(b), (c) are the XRD patterns of the samples treated at 100 °C and 300 °C with the sample tensile elongations. It can be seen that the Cu(220) peak was disappeared after the aging treatment with a simultaneous tension deformation, suggesting the tension deformation may result in the preferred orientation. Additionally, the positions of Cu(111) and (200) peaks in Fig.1(b), (c) show a small shift toward to the low angel, suggesting the separation of the solid solution atomics from the matrix, which leads to the reduction of lattice distortion. However, from the XRD patterns, the grains size did not demonstrate any evident variations.
The colored optical micrograph of the solid solution CuCrZr alloy is shown in Fig. 2(a). When the alloy was solution-treated at 920 °C for 1 h, the composition distribution became more homogeneous and the equiaxed grain structure with an average size of 40-100 µm generated by recrystallization. Some primary precipitates distributed in the Cu matrix and there was a certain segregation of Cr solute in Cu dendrites. Fig. 2(b) and (c) showed the micrographs of the samples treated at 100 °C and 300 °C with the sample tensile elongations. From the micrograph it seems that the tensile deformation refined the grains size and the grains were elongated along the tension direction. Additionally, more secondary phrase was precipitated in the interdendritic area of the supersaturated Cu matrix. These results are in consistent with the analysis of XRD. It is worth to note that the spherical secondary particles appeared as the sample was treated at 300 °C, which is related to the combined action of high temperature and deformation.

It is well known that the martensite transformation can be accelerated by large deformation during the heating process. The dispersion of secondary phase from the matrix may present the similar effects, which would result in the increasing of dislocation density and stored energy, and finally contributed to the improvement of both mechanical and electrical properties. It is also expected this new treatment would decrease the aging time and even reduce the aging temperature. However, the improvement of both mechanical and electrical properties really demonstrated a stronger conflict as shown in Table 1. The high aging temperature showed smaller effects on the electric conductivities of the CuCrZr alloys. The precipitation process of secondary phase could moderate lattice distortion [14, 15]. At the same time, precipitated phase processes much smaller scattering power than the solution phase in matrix on the basis of Mathiessen theory [16]. In addition, bypassing a grain with abundant volume precipitates makes dislocations require more energy than transect it, in accordance with the Orowan mechanism [17]. These would contribute to the increase of the material strength while decreased the electric conductivity.

N.Gao reported similar results where the heavily pre-deformed alloy significantly accelerates the recrystallization process at difference amounts of prior strains. The sample pre-deformed by 0.9 strain and aged for 12 min at 510 °C took shorter aging time to produce larger new grains than the sample pre-deformed by 0.5 strain [18]. Kreye and Hornbogen studied a supersaturated and cold deformed Cu-2.8 at.% Co alloy and concluded that recrystallization was inhibited by precipitate particles at small amounts of deformation (<10% reduction). However, the recrystallization was already completed before precipitation at large amounts of deformation (>20% reduction) [19]. Those results open a way to another possible manufacturing strategy that is combining the aging treatment with cold working step in the large-deformation and low temperature process. This process could possible accelerate production cycle of CuCrZr alloy.
4. Conclusion

(1) The combination of aging treatment and the simultaneous tension deformation can increase the hardness of the sample while decrease their electric conductivity. The high temperature of 300°C resulted less reduction of electric conductivity than the low treated temperature of 100°C.

(2) The disperse precipitation of the secondary phase were observed from the XRD and optical observations. The tension deformation leaded to the preferred orientation in the sample.

(3) The combination of aging treatment and the simultaneous tension deformation could reduce the aging temperature of CuCrZr alloys.

Acknowledgements

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Reference:


