Enhanced Strength and Electrical Conductivity of Cu–8Fe Composite by Adding Trace Ag and P

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Cu–8Fe–0.5Ag–0.02P (mass%) *in situ* composites were fabricated by inductive melting and then the as-casted sample drew heavily at room temperature to refine the microstructure and optimize the mechanical and electrical properties. The microstructure evolution of the composite during drawing was investigated, while the tensile strengths and electrical conductivity of the as-drawn samples were measured. Comparing to Cu–8Fe composite, the tensile strength and electrical conductivity were enhanced largely by adding trace Ag and P. The results show that trace Ag refines the primary Fe dendrites and promotes the precipitation of secondary phase Fe particles. Trace P reacts with the solid solution Fe atoms and then facilitates ellipsoid Fe₃P particles precipitation. The mechanical strength and electrical conductivity of Cu–8Fe–0.5Ag–0.02P were improved obviously, which is attributed to the combined effects of trace Ag and P. [doi:10.2320/matertrans.M2013260]

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1. Introduction

Cu-based *in situ* composites (i.e., Cu–Nb, Cu–Ag, Cu–Fe and Cu–Cr) have been widely investigated over the past two decades due to their excellent combination of strength and electrical conductivity.^{1–18} In particular, Cu–Fe system has attracted considerable attention because of low cost compared to other alloying elements. However, the higher solubility of iron in Cu at high temperature, coupled with sluggish kinetics of iron precipitation at low temperature increases the solute scattering and seriously deteriorate the electrical conductivity, namely $9.2 \mu\Omega \text{ cm/mass\%Fe}$,² which limits its commercial use. Therefore, the key to develop Cu–Fe composite is to remove much the iron from Cu matrix. Conventional methods to remove iron are thermo-mechanical treatments and homogenization treatment. However, two methods decrease the amount of solute Fe atoms in Cu matrix at the expense of sacrificing the strength. Recent research has reported that a third alloying element can refine the microstructure and enhance the properties of Cu-based composites. Song *et al.*^{14,15} reported that the 0.1 mass% Ag refined the primary Fe dendrites in the as-cast microstructure of Cu–9 mass%Fe. Gao *et al.*^{16,17} reported that Cu–11Fe–6Ag (mass%) *in situ* composites had higher tensile strength and conductivity (1020 MPa/70.5%IACS, respectively) at strain of 10 compared to Cu–12Fe. Lu *et al.*¹⁹ introduced 0.02P to Cu–0.6Fe (mass%) alloys and obtained a better combination of strength and conductivity (500 MPa/80%IACS). Kim *et al.*^{20,21} reported that Cu–2.5Fe–0.1P (mass%) alloys have particularly high strength and electrical conductivity with the precipitation of coarse Fe₃P and fine γ -Fe and α -Fe particles during heat treatment. Cao *et al.*²² observed the micro-hardness of deformed Cu–2.2Fe–0.085P (mass%) was enhanced due to the pinning effect caused by fine Fe₃P particles. It is obvious that trace Ag or P can increase the strength and meanwhile the conductivity of

Cu–Fe composite. So far, in the published literatures, few researches have investigated the combined effects of Ag and P on Cu–Fe composites. In the present work, we focus on the combined effect of trace Ag and P on the microstructure and properties of Cu–8Fe composite, aiming to further improve the strength and electrical conductivity. The microstructure, strength and electrical conductivity were studied and compared to the Cu–8Fe composite.

2. Experimental Procedure

Cu–8Fe and Cu–8Fe–0.5Ag–0.02P (mass%) alloys were prepared using medium frequency induction furnace by melting high-purity Cu, commercial pure Fe (99.9 mass%), high-purity Ag (99.9 mass%) and Cu–85P (mass%) master alloys and then cast into cylindrical ingots under an Ar atmosphere at pressure of $0.4 \times 10^5 \text{ Pa}$. The ingots were swaged from 12 to 6 mm in diameter at room temperature, and then drawn into wires to a minimum diameter of 0.6 mm using successively smaller dies. The cold drawing strain η is described by $\eta = \ln(A_0/A)$, where A_0 and A are the original and final cross-section areas respectively.

The microstructure was characterized by optical microscopy (OM) and transmission electron microscopy (TEM, JEM-2010) equipped with X-ray energy-dispersive spectroscopy (XEDS), operating at 200 KV. The ultimate tensile strength of the wires was conducted on a united machine equipped with an extensometer with a strain rate of $5.0 \times 10^{-4} \text{ s}^{-1}$ at room temperature. The electrical resistivity of the samples was measured using a digital micro-ohmmeter with precision of $1 \mu\Omega$ at room temperature.

3. Results and Discussions

Figure 1 shows the microstructure of as-cast Cu–8Fe and Cu–8Fe–0.5Ag–0.02P (mass%) alloys, both which consist of two phases: Fe-rich dendritically secondary phase and Cu matrix. The average size of the Fe-rich phase is about 3.5 μm

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Fig. 1 Optical microstructure of as-cast alloys (a) Cu-8Fe and (b) Cu-8Fe-0.5Ag-0.02P.

Fig. 2 Longitudinal microstructure evolution of Cu-8Fe-0.5Ag-0.02P with strains.

for Cu-8Fe-0.5Ag-0.02P sample, which size for Cu-8Fe composite is about $7\mu\text{m}$. The Fe-rich dendrites are refined obviously by adding trace Ag. The refinement mechanism can be explained based on the classical nucleation theory which indicates that Ag reduces the interface energy between liquid Cu and $\gamma\text{-Fe}$ during solidification process and increases the nucleation rate of $\gamma\text{-Fe}$.⁵⁾ Therefore, the primary Fe dendrites are refined with presence of Ag in Cu-8Fe-0.5Ag-0.02P alloys.

The microstructure of the Cu-8Fe-0.5Ag-0.02P sample after deformation with a different strain was shown in Fig. 2, which shows that the Fe-rich phase was elongated after deformation and distributed along the drawing direction. When the strains are less than 2.4, the Fe-rich dendrites develop many blocks distributed in Cu matrix (Figs. 2(a)–2(c)). With increasing strain (to $\eta = 4.2$), the Fe-rich phase completely transferred into filamentary microstructures. The

average spacing size between Fe-rich filaments is about $3.7\mu\text{m}$, less than that of as-cast alloys ($\sim 12\mu\text{m}$). The dense and finer Fe filamentary microstructures are ascribed to the smaller primary Fe dendrites refined by Ag.

Figure 3 shows the TEM image of Cu-8Fe-0.5Ag-0.02P alloy. Large amount of second phase particles with size of about 20–30 nm are precipitated in the Cu matrix, as shown in Fig. 3(a). A closer examination of the second phase particles in TEM reveals that two types of particles exist in the sample: Fe_3P and $\alpha\text{-Fe}$ particles, as shown in Figs. 3(b) and 3(c), respectively. These two types of the particles can be distinguished by the size and shape. The mean size of the beetle-like Fe_3P particles and bean-like $\alpha\text{-Fe}$ particles is about 40–50 nm (Fig. 3(b)) and about 20–30 nm (Fig. 3(c)), respectively. Fe_3P particles mainly located on the grain boundary and have strong effect on grain boundaries motion, which is conformed to the previous work reported by Cao *et al.*²²⁾

Fig. 3 TEM image of Cu-8Fe-0.5Ag-0.02P (a) precipitated particles, (b) Fe₃P, (c) α-Fe.

Fig. 4 Effects of strain on (a) strength and (b) electrical conductivity of Cu-8Fe and Cu-8Fe-0.5Ag-0.02P.

The effect of strain on the strength and electrical conductivity is shown in Fig. 4, which reveals that with the increasing of strains the strength increases and the electrical conductivity decreases gradually. This result is in accordance with our previous work.^{2,3,5,6} At the same strain level, the strength and electrical conductivity of Cu-8Fe-0.5Ag-0.02P is the higher than that of Cu-8Fe *in situ* composites. The increment of the strength and electrical conductivity is about 35 MPa and 3% IACS, respectively. The strengthening mechanism for Cu-8Fe-0.5Ag-0.02P is that trace Ag refines the as-cast microstructure⁵) and Fe₃P precipitates inhibit the motion of Cu grain boundaries by typical secondary phase strengthening.^{19,22}) Therefore, fine as-cast microstructure produces small Fe filament spacing and the precipitated Fe₃P particles pin the grain boundaries, which increases the strength of the composites. At the same time, extensive

investigations showed that the electrical conductivity of Cu-Fe *in situ* composites was primarily controlled by the resistivity of the Cu matrix, which could be portioned into the contribution of four scattering mechanism follows:^{23–25}) $\rho_M = \rho_{pho} + \rho_{dis} + \rho_{int} + \rho_{imp}$, where ρ_{pho} is the resistivity contribution from phonon scattering, ρ_{dis} is the dislocation scattering, ρ_{int} is the interface scattering and ρ_{imp} is the impurity scattering. At room temperature, the resistivity contribution from phonon can be ignored and the dislocation density of Cu matrix was constant with the change of strains,²⁶) furthermore, the difference in ρ_{int} between composites was small.²⁴) The difference in the electrical conductivity is only attributed to the lower amounts of dissolved Fe in the Cu matrix. In this study, trace Ag was ever reported to inhibit the solubility of Fe in Cu,⁵) meanwhile trace P reacts with solute Fe in Cu matrix and

precipitate Fe₃P particles, which further reduce the amount of dissolved Fe. Simultaneously, there no interaction between Ag and P after adding trace Ag and P, therefore, the strength and electrical conductivity of Cu–8Fe–0.5Ag–0.02P can be improved further compared to Cu–8Fe.

4. Conclusion

The effect of adding trace Ag and P simultaneously on the microstructure and properties of Cu–8Fe was investigated. There no interaction between Ag and P atoms and the strength and electrical conductivity of Cu–8Fe–0.5Ag–0.02P can be improved further with the microstructure refinement and the precipitation of second phase Fe₃P and α -Fe particles. Comparing to Cu–8Fe, the increment of the strength and electrical conductivity is about 35 MPa and 3%IACS, respectively.

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