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Study of high-strength and high-conductivity Cu–Sn–Fe alloys

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Cu–Sn–Fe alloys with different compositions were developed by casting, normalizing treatment, cold roll and subsequent annealing treatment. The results showed that the tensile strength and resistivity of the Cu–xSn–xFe alloys (where x represents wt.%) improved with increasing the content of Sn and Fe. Compared with the as-cast alloys, the resistivity and tensile strength of the Cu–xSn–xFe alloys after normalizing and cold rolling treatment increased. In addition, the resistivity and mechanical properties of the alloys after the annealing treatment were improved significantly. Finally, a conclusion could be drawn that the annealed Cu–2Sn–5Fe alloy had good mechanical properties and resistivity, and the values of the tensile strength, mechanical elongation and resistivity reached 552 MPa, 32 % and 1.92 μΩ·cm, respectively.

Keywords: *Cu–Sn–Fe alloy; conductive material; tensile strength; resistivity*

1. Introduction

With good electrical conductivity and high strength, copper and copper based alloys are widely used for electrical components, such as electrical connectors, lead frames, conducting wires and so on [1–5]. Presently, the research of copper alloys with high strength and high electrical conductivity is concentrated on Cu–Ag [6–8], Cu–Nb [9, 10], Cu–Cr [11–17], Cu–Fe [18–21], Cu–Mg [22] and Cu–Mn [23] series. However, all these alloys have their own shortcomings, such as high cost, feeding difficulty and low conductivity. With the improvement of the industry request standards, it is an urgent demand to research and develop special-purpose copper alloys with high strength and high electrical conductivity.

However, generally speaking, copper alloys cannot have high strength and high conductivity at the same time. In order to meet the demands of different applications, the mechanism of strengthening and conducting should be investigated to manufacture the copper alloy with high-strength and high-conductivity. In this work, different compositions of Cu–Sn–Fe alloys were prepared by casting, cold work and subsequent annealing treatment. The electrical conductivity and mechanical properties of these alloys were investigated systematically by use of a four-probe direct current technique and an electronic universal testing machine, respectively. This study is aiming to obtain a new Cu–Sn–Fe material with high strength and high conductivity by designing a reasonable composition and the processing route.

2. Experimental

The Cu–Sn–Fe alloys of various compositions were synthesized from electrolytic copper, high purity stannum and iron. The raw materials with a total mass of about 500 g were melted and heated to approximately 1650 °C in the atmosphere, using a high frequency induction furnace. Then, the melts were casted into cylindrical ingots in a metal copper mould. Firstly, the ingots were put into the furnace for heat treatment at 700 °C for 30 minutes, and then they were cooled in the atmospheric environment. Subsequently, the cylindrical ingots

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of 12 mm in diameter were cold-rolled into 8 mm bars, achieving the deformation in diameter of 33 %. Finally, the cold-rolled bars were subjected to annealing treatment (500 °C, 6 h) with cooling in the furnace to 200 °C approximately. Finally, they were cooled to room temperature in the atmospheric environment.

In order to test the mechanical properties of the Cu–xSn–xFe alloys, the specimens were processed into standard samples. The ultimate tensile strength of the samples was tested on an electronic universal testing machine equipped with an extensometer with a strain rate of 2.0×10^{-4}/s at room temperature. The electrical resistance of the samples was measured by the four-probe direct current technique with an accuracy of 0.01 μΩ at ambient temperature.

According to standard metallographic procedures, the samples were cross sectioned, processed and etched. The micrographs were analyzed by using HITACHI S-4800 field emission scanning electron microscopy.

3. Results and discussion

3.1. Mechanical properties

Table 1 lists the mechanical properties of the as-cast Cu–Sn–Fe alloys of various compositions. As shown in Table 1, with an increase of the content of Sn and Fe, the tensile strength of the Cu–Sn–Fe alloys increases and the mechanical elongation decreases. For the as-cast Cu–2Sn–5Fe alloy, the value of the tensile strength and mechanical elongation is 349 MPa and 4.1 %, respectively.

Table 1. Mechanical properties of the as-cast Cu–Sn–Fe alloys.

As-cast alloys	Tensile strength [MPa]	Mechanical elongation in [%]
Cu–1Sn–5Fe	316	5.3
Cu–2Sn–5Fe	349	4.1
Cu–3Sn–5Fe	380	3.5
Cu–5Sn–5Fe	405	2.8
Cu–3Sn–10Fe	430	2.0

Fig. 1 shows that the mechanical properties of the Cu–5Fe–xSn alloys are a function of Sn content. The tensile strength of the Cu–5Fe–xSn alloys increases with an increase of Sn content. On the other hand, the mechanical elongation of the Cu–5Fe–xSn alloys decreases with the increase of Sn content. When x = 2, the value of the tensile strength and mechanical elongation for the rolled Cu–2Sn–5Fe alloy is 610 MPa and 5.2 %, respectively. Compared with the as-cast Cu–2Sn–5Fe alloy, the tensile strength of the rolled Cu–2Sn–5Fe alloy increased by 74.8 %. The strength of the Cu–5Fe–xSn alloys processed by cold-rolling treatment was improved obviously. In contrast with the cold-rolled alloys, it can be seen in Fig. 1 that the tensile strength of the Cu–5Fe–xSn alloys after annealing treatment decreased by 15 % approximately, while its mechanical elongation was multiplied by 3 times at least. For the annealed Cu–2Sn–5Fe alloy, the value of the tensile strength and mechanical elongation reached 552 MPa and 32 %, respectively.

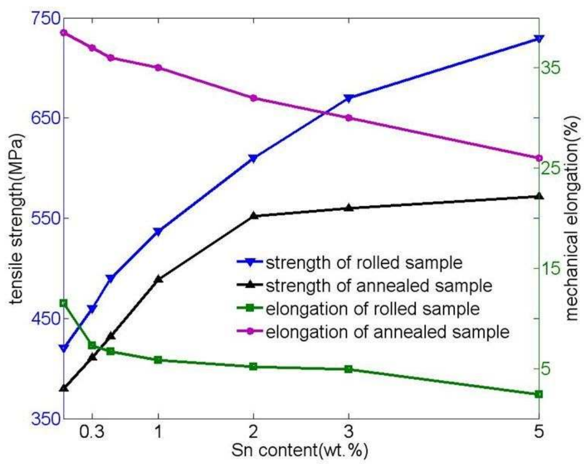

Fig. 1. The dependence of mechanical properties of the Cu–5Fe–xSn alloys on Sn content.

The dependence of mechanical properties of the Cu–3Sn–xFe alloys on Sn content is presented in Fig. 2. It can be seen that the tensile strength of all the rolled Cu–3Sn–xFe alloys exceeds 550 MPa whereas the tensile strength of the cold-rolled Cu–3Sn–10Fe alloy exceeds 770 MPa. It is by 79 % more than that of the as-cast Cu–3Sn–10Fe alloy.

Similar to the Cu–5Fe–xSn alloys, the strength of the Cu–3Sn–xFe alloys reduced and the mechanical elongation enhanced obviously due to the annealing treatment.

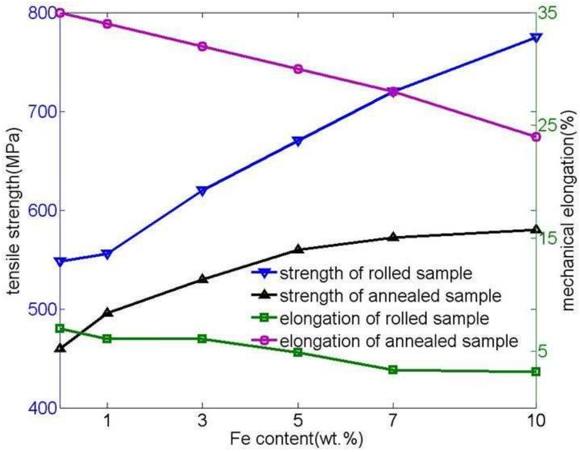

Fig. 2. The dependence of mechanical properties of the Cu–3Sn–xFe alloys on Fe content.

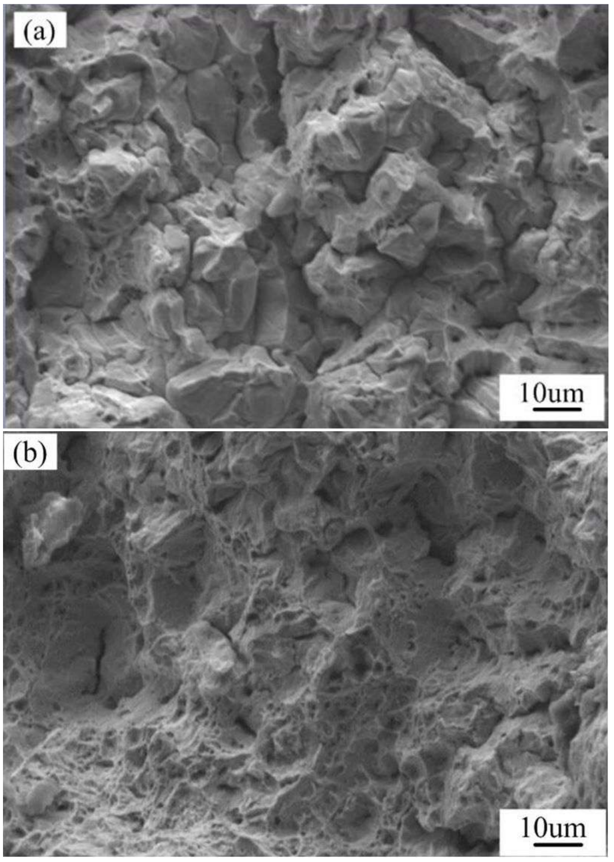

Fig. 3. SEM images of tension fractures of Cu–2Sn–5Fe alloys: (a) fracture surface of the rolled Cu–2Sn–5Fealloy, (b) fracture surface of the annealed Cu–2Sn–5Fe alloy.

Fig. 3a shows the fracture surface of the samples subjected to tensile tests, for the rolled Cu–2Sn–5Fe alloy. It can be seen that the fracture surface of the rolled Cu–2Sn–5Fe alloy shows a variety of polyhedral-shape rocky patterns. From these shapes it can be inferred that the fracture is of intergranular type. It means that the plasticity of the rolled Cu–2Sn–5Fe alloy is low. As presented in Fig. 3b, the fracture surface of the annealed Cu–2Sn–5Fe alloy is composed of ductile dimples of all sizes and tearing edges. So, the character of this fracture is ductile. Because the grains of the annealed alloys were obviously improved, the deformation coordination of the alloys was improved and the dislocation pile-up decreased. Therefore, it can be concluded that the Cu–Sn–Fe alloys achieved a superior plastic deformation due to the annealing treatment.

3.2. Electrical resistivity

Fig. 4 and Fig. 5 indicate that the resistivity of the Cu–5Fe–xSn and the Cu–3Sn–xFe alloys depend on the content of Sn and Fe. It can be seen that the resistivity of the Cu–5Fe–xSn and the Cu–3Sn–xFe alloys increases with increasing the content of Sn and Fe.

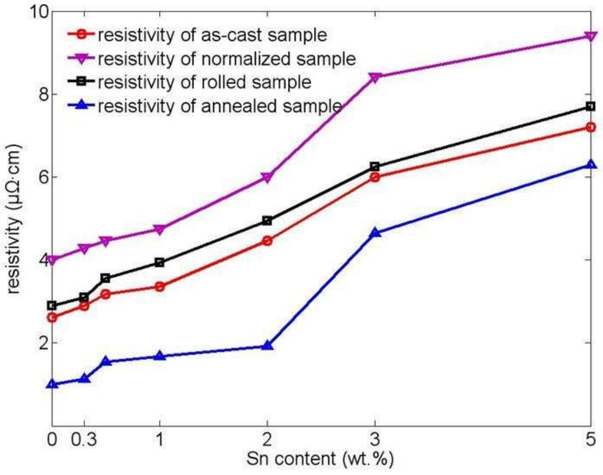

Fig. 4. Influence of the Sn content on resistivity of the Cu–5Fe–xSn alloy.

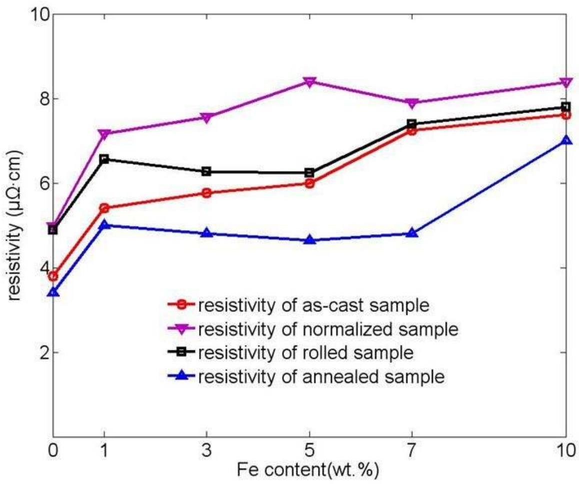

Fig. 5. Influence of the Fe content on resistivity of the Cu–3Sn–xFe alloy.

In order to relieve the casting stress, refine the grains and increase the deformation in plasticity, all the as-cast Cu–Sn–Fe alloys were subjected to normalizing treatment. However, compared with the as-cast alloys, the resistivity of the normalized Cu–xFe–xSn alloys increased because the solubility of Sn and Fe in the Cu matrix was increased due to the normalizing treatment. In contrast to the alloys subjected to the normalizing treatment, the resistivity of the Cu–xSn–xFe alloys after cold rolling decreased. Moreover, in Fig. 4 and Fig. 5, it can be seen that the resistivity of the Cu–5Fe–xSn and Cu–3Sn–xFe alloys reduced dramatically due to the annealing treatment. Especially, as shown in Fig. 4, for the Sn content less than 2 wt.%, the value of the resistivity of Cu–5Fe–xSn alloys after annealing treatment is lower than the standard resistivity, where the standard resistivity for conversion to 100 % IACS is taken as 1.7241 μΩ·cm.

Extensive investigations showed that the resistivity of Cu-based alloys can be contributed from the scattering components of phonons, dislocations, solute and interfaces [19, 24, 25]. The contribution of phonon scattering to the resistivity hardly changes at room temperature. Therefore, the resistivity is mainly determined by scattering levels of the solute, dislocations and interface. Because of an increase in dislocation density caused by the cold rolling, it is apparent that the contribution of the dislocation scattering and solute scattering to the resistivity is predominant in the rolled Cu–xSn–xFe alloys. Due to the occurrence of dynamic recrystallization of the Cu matrix and precipitation of the solute in the process of annealing, the annealing treatment reduced the solute scattering level. Therefore, the conductivity was distinctly improved because of the Fe and Sn precipitation from supersaturated matrix, although the precipitation also increased the interface scattering level. Because the Sn precipitation in the annealing treatment resulted in more significant reduction in the resistivity of Cu–5Fe–xSn alloys, the contribution of solute scattering to the resistivity in Cu–5Fe–xSn alloys can be considered as more predominant than that in Cu–3Sn–xFe alloys.

3.3. Microstructure of Cu–Sn–Fe alloys

Fig. 6 shows the microstructures of the as-cast Cu–2Sn–5Fe and Cu–3Sn–10Fe alloys. The energy dispersive spectrometer analysis indicated that the substrate consists of Cu-rich solid solution containing Sn and Fe atoms (Fig. 6a). The Cu-rich grains with the size of 10 to 30 μm in diameter have an equiaxed crystal structure. There are no Fe-rich dendrites in the microstructure of the as-cast Cu–2Sn–5Fe alloy. Just as denoted by the arrow 'A' in Fig. 6a, a few primary equiaxed Fe-rich grains with the size of approximately 3 μm in diameter exist in the microstructure. A few eutectic microstructures containing Cu, Fe and Sn components, indicated by the arrow 'B', can be seen in Fig. 6a. They might be formed in the process of solidification and distributed on the boundaries of Cu-rich grains. In addition, some fine Fe and Sn particles of nanosize, which are denoted by the arrow 'C', have precipitated from Cu-rich matrix. As presented in Fig. 6b, the Fe-rich phases with the morphology of dendrite and equiaxed crystal are distributed in the Cu-rich matrix. Due to nucleating in the earlier stage, some Fe-rich grains developed into dendritic structures with secondary dendrite arm spaced of about 2 to 5 μm. Meanwhile, in the microstructure of the as-cast Cu–3Sn–10Fe alloy, there appeared also some equiaxed Fe-rich grains with the size of 2 to 5 μm in diameter. In addition, many Fe-rich sediments of nanosize are dispersed in the Cu-rich matrix, as presented in Fig. 6b. Compared with Fig. 6a, the size and amount of the Fe-rich dendrites are larger in Fig. 6b. Due to the Fe-rich phase with high strength and high resistivity, both the strength and resistivity of the Cu–3Sn–10Fe alloy are higher than those of the Cu–2Sn–5Fe alloy.

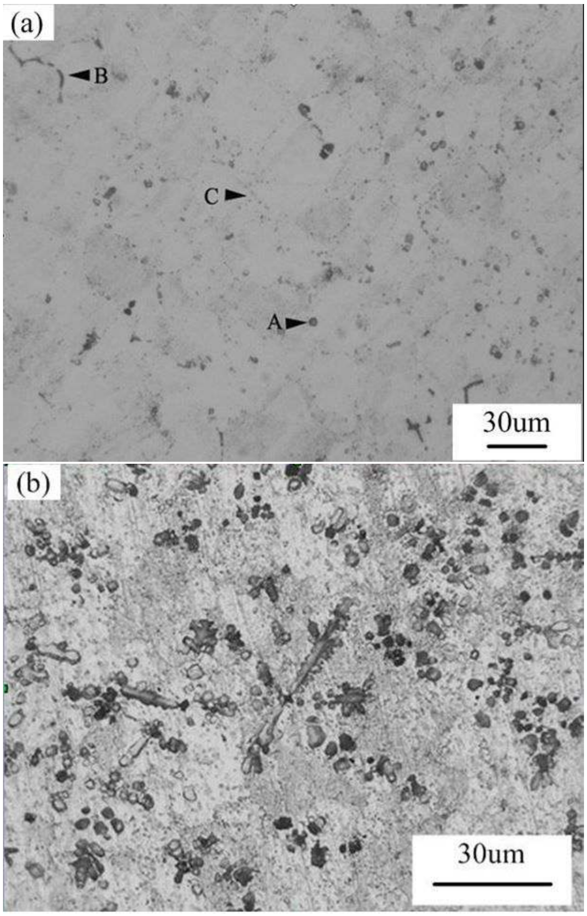

Fig. 6. Microstructures of the as-cast Cu–Sn–Fe alloys: (a) Cu–2Sn–5Fe alloy, (b) Cu–3Sn–10Fe alloy.

Fig. 7a shows the microstructure of the cold-rolled Cu–2Sn–5Fe alloy. It is apparent that the Cu-rich grains in the microstructure of the cold-rolled Cu–2Sn–5Fe alloy tend to be elongated along the direction of deformation, which is marked by the arrows going back and forth in Fig. 7a. By contrast, the form of the equiaxed Fe-rich particles has hardly changed. It might be caused by the resistance of these Fe-rich particles to deformation of Cu-rich matrix. Thus, the strength of the cold-rolled Cu–2Sn–5Fe alloy increased. Because the sediments of Sn and Fe distributed on the boundary of the Cu-rich grains moved with the deformation of the Cu-rich grains and produced the stress of the grain boundaries between the Cu-rich grains, the grains boundaries were hardened and their strength increased.

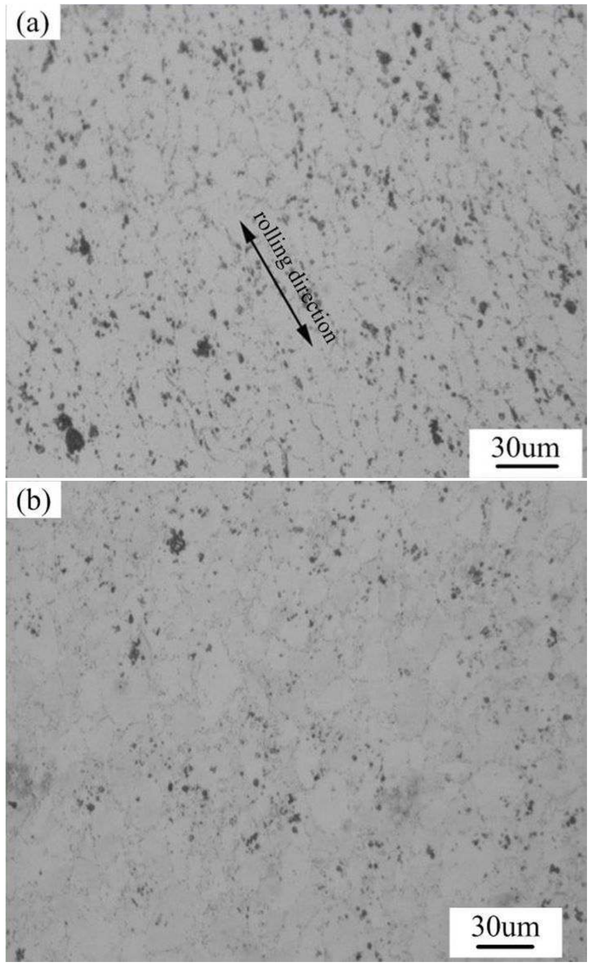

Fig. 7. Microstructures of the treated Cu–2Sn–5Fe alloys: (a) the cold-rolled Cu–2Sn–5Fe alloy, (b) the annealed Cu–2Sn–5Fe alloy.

As presented in Fig. 7b, due to the occurrence of dynamic recrystallization of the Cu matrix, the grains in the microstructure of the Cu–2Sn–5Fe alloy recovered to the morphology of equiaxed crystal by the annealing treatment. It was found that dimensions of the crystal decreased and the grain boundary increased in the microstructure of the annealed Cu–2Sn–5Fe alloy. So, the annealed

Cu–2Sn–5Fe alloy preserved still very high strength. On the other hand, some Sn and Fe atoms precipitated from Cu-rich grains and spread in the Cu-rich grain boundary. This might reduce the distortion stress of the Cu lattice and the resistance to the motion of free electrons. Thus, the resistivity of the annealed alloys decreased dramatically.

4. Conclusions

The tensile strength and resistivity of the Cu–Sn–Fe alloys with different ingredients were investigated. The results showed that the tensile strength and resistivity of the Cu–Sn–Fe alloys increased with increasing the content of Sn and Fe. Compared with the as-cast alloys, the resistivity and strength of the Cu–Sn–Fe alloys after normalizing and rolling treatment increased. In addition, the resistivity and mechanical properties of the alloys improved obviously by the annealing treatment. The mechanical properties and conductivity of the annealed Cu–2Sn–5Fe alloys was good, and the tensile strength, mechanical elongation and resistivity reached 552 MPa, 32 % and 1.92 $\mu\Omega\cdot$cm, respectively. So, the conclusion can be drawn that Cu–Sn–Fe material with high strength and high conductivity could be obtained by designing the reasonable composition and the processing route.

Acknowledgements

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