Strength and electrical conductivity of UFG Cu-Fe alloys subjected to HPT

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Abstract. This paper investigates the strength and specific conductivity of UFG Cu-Fe alloys processed by high-pressure torsion (HPT). The effect of an ultrafine-grained structure and further heat treatment on the increase of microhardness and specific conductivity is examined. The results of the structural study of the UFG samples by electron back-scatter diffraction (EBSD) are presented.

1. Introduction

It is known that pure Cu is widely used in electrical-engineering products as a material with a high conductivity. At the same time, for the application under high mechanical loads, e.g. in electrical connectors or contacts, conductive thermally stable materials with enhanced strength characteristics are required. In such cases where an industry does not require a high electrical conductivity, the manufacturers prefer using cheaper bronzes of brass. In recent years, due to the low cost of iron, copper-iron alloys and composites have been gaining popularity, as they have higher strength and lower electrical conductivity as compared to pure copper [1].

On the other hand, in recent years, special interest is aroused by ultrafine-grained (UFG) materials having an average grain size of below 1 μm that are able to exhibit unique mechanical properties (high strength and enhanced endurance limit) [2, 3]. Besides, it is known that at room temperature grain boundaries make a smaller contribution into the enhancement of electrical resistance as compared to alloying element atoms, which creates conditions for the preservation of the initial values of electrical conductivity in UFG copper materials [4, 5]. All this provides prerequisites for achieving in UFG samples of Cu alloys a combination of high strength and improved electrical conductivity.

In this paper, we examine the effect of the UFG structure of a Cu-Fe alloy on the strength enhancement by means of grain refinement and improvement of electrical conductivity by reducing the concentration of impurities and alloying element atoms as a result of their migration to grain boundaries.

2. Materials and research methods

As the initial material for the study, we selected the copper alloys Cu-0.15Fe, Cu-0.5Fe, Cu-2Fe and Cu-3.5Fe. The initial as-cast samples were subjected to homogenizing annealing at a temperature of 1070 °C for 4 hours with cooling in water. The heat treatment of the samples was carried out in a Nabertherm muffle furnace.
Nanostructuring was implemented by the high-pressure torsion (HPT) method at room temperature. For this purpose, disks with a diameter of 20 mm and thickness of 2 mm were cut off from the initial rods and subjected to high-pressure torsion (6 GPa) for 10 revolutions.

In order to study the thermal stability of the UFG samples, we studied the variation of microhardness and electrical conductivity after annealing in a temperature range of 200-600 °C with 30 minutes’ exposure. Microhardness (HV) was tested by the Vickers method using a Micromet 5101 device with a load of 100 g and an exposure time of 10 seconds.

Specific conductivity was measured by the eddy-current method using a VE-27NTs/4-6 device. The measurement range of specific conductivity was 3.5-60 MS/m, the maximum permissible error was ±3%. The data are presented in % IACS (International Annealed Copper Standard).

Structural studies by electron back-scatter diffraction (EBSD) were performed using a scanning electron microscope FEG-SEM TESCAN MIRA 3 LMH, with an accelerating voltage of 20 kV and a scanning step of 50 to 150 nm. To analyze the Kikuchi lines, we used the CHANNEL 5 software by Oxford Instruments. The error in measuring the crystal lattice orientation was not more than 0.6°.

3. Results and discussion
The testing of strength reveals that the maximum microhardness value of 1770 MPa was achieved in the UFG Cu-2Fe samples at an annealing temperature of 300 °C (figure 1 a). The maximum values of specific conductivity 74% and 80% IACS were achieved in both the UFG Cu-0.5Fe and Cu-0.15Fe samples at an annealing temperature of 450°C (figure 1 b). On the basis of the obtained data, the alloys Cu-0.5Fe and Cu-2Fe were selected for further structural analysis.

Figure 2 a presents an EBSD image for the Cu-0.5Fe alloy subjected to HPT and annealing at a temperature of 350 °C for 30 minutes. A heating temperature of 350 °C was selected because at this temperature one can observe the best combination of strength and electrical conductivity (figure 1). It can be seen that the samples have a UFG structure with an average grain size of 650 nm (table 1). The fraction of high-angle grain boundaries is 39.9%, the fraction of special boundaries Σ3 is 2.45%.

Figure 2 b presents the results of the EBSD analysis of the Cu-2Fe alloy subjected to HPT and annealing at a temperature of 450 °C for 30 minutes. It can be seen that such a processing has produced a UFG structure with an average grain size of 230 nm (table 1). The fraction of high-angle grain boundaries is 37.3%, the fraction of special boundaries Σ3 is 4% (table 1).

It should be noted that there are papers that investigated the structure and properties of the alloys and composites based on Cu-Fe [6-9]. In particular, the papers [7, 8] examined the formation of a supersaturated solid solution in Cu-Fe composites with Fe content 12 at.% [7] and 15 wt.% [8] subjected to HPT, but did not touch upon the studies of electrical conductivity. There is also a paper that examined the strength and electrical conductivity of the Cu-14Fe composite, but in that paper the samples were produced by extrusion and further heat treatment, resulting in UTS=900 MPa and electrical conductivity of 57% IACS [9]. Meanwhile, in the present paper we have demonstrated that the formation of a UFG state enables achieving microhardness in a range of 1750-1500 MPa and electrical conductivity of 45-80% IACS, depending on the Fe content and the heat treatment regimes.
Figure 1. a – microhardness, b – specific electrical conductivity of the Cu-Fe alloys under different heat treatments.
Figure 2. a – EBSD image for the UFG Cu-0.5Fe alloy, b – EBSD image for the HPT-processed UFG Cu-2Fe alloy.

Table 1. Summarized data from the EBSD analysis.

| Alloy    | HPT processing | Heat treatment | Average grain size, nm | Fraction of LABs, % | Fraction of HABs, % | Special boundaries Σ3, % |
|----------|----------------|----------------|------------------------|---------------------|---------------------|-------------------------|
| Cu-0.5Fe | HPT 20 °C 10 rev. | HT 350 °C       | 653                    | 60.1                | 39.9                | 2.45                    |
| Cu-2Fe   | HPT 20 °C 10 rev. | HT 450 °C       | 235                    | 62.7                | 37.3                | 4                       |

4. Conclusions

Based on the results of the studies of strength and electrical conductivity, the following conclusions can be made:

1. HPT processing and further heat treatment in a temperature range of 300-450 °C have produced a UFG structure in the copper alloys Cu-0.5Fe and Cu-2Fe, which contain a fraction of high-angle boundaries 37.3-39.9% and a fraction of special boundaries Σ3 2.45-4%.

2. UFG samples of copper alloys of the Cu-Fe system with Fe content in a range of 0.15-3.5 wt.% can exhibit microhardness in a range of 1750-1500 MPa and electrical conductivity of 45-80% IACS, depending on the Fe content and the heat treatment regimes.

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