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Strain-induced martensitic transformation of particles in a copper-based composite and its effect on mechanical properties

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ABSTRACT

A copper-based composite with a distribution of face-centered cubic (FCC), body-centered cubic (BCC) and martensite structured Fe—C particles has been developed, and most of FCC structured particles can be phase transformed into BCC or martensite structured particles after cold rolling at room and low temperatures, and the fraction of martensitic transformation increases as the deformation temperature is lowered. The martensitic transformation can significantly improve both the strengths and deformability of copper-based composite. A ductile fracture is still the main tensile fracture characteristic for the composite even in the cold rolling conditions. Accordingly, a cooperative deformation model was put forward in this paper.

1. Introduction

With the development of high-tech industries, such as, electronic, nuclear power, aircraft and traffic fields, the requirement of Cu alloys or Cu-based composites with the combination of high strengths and high conductivities has been greatly increased in recent years. Because the composite structures have been believed a good way to achieve high strengths and high conductivity simultaneously, many copper-based composites, such as Cu-Al_2O_3, Cu-TiB_2, Cu-TiC, Cu-C/C, Cu-SiC and Cu-Y_2O_3, have been developed by in-situ or ex-situ methods [1–9]. A poor interfacial bonding between the ceramic particles and copper matrix normally results in the lower mechanical properties of composites, especially for those prepared by ex-situ methods. In contrast, the improved strengths and wear resistance normally can be obtained by in-situ methods [1–4,7–9]. Moreover, the poor deformability of copper-based composites prepared by the ex-situ or in-situ methods also has been gradually paid more attention recently because of which directly increases the production cost and further limits their wide applications. Taking the Cu8Al–alumina composites studied in Ref. [10] as an example, even the compression yield and ultimate tensile strengths can reach 597 ± 7 MPa and 600 ± 7 MPa, respectively, but the elongation is quite low (only 1.0–1.1%). Accordingly, it is quite necessary to improve the deformability of copper-based composites by controlling microstructure or directly develop some other new composites with high strength and high deformability.

A phase transformation from face-centered cubic (FCC, with low strength and high deformability) to body-centered cubic (BCC) or martensite structure (with high strength and low deformability) normally can be obtained in the Fe—C alloys with an appropriate C content [11–13]. Accordingly, if we can introduce FCC structured Fe—C phase in copper matrix, and then the martensitic transformation of Fe—C particles can be induced by cold rolling. Finally, the cold rolled copper-based composites should possess both the high strengths and high deformability simultaneously. Based on this idea, a copper-based composite reinforced by Fe—C particles was prepared by combining a vacuum melting and rapid solidification. The strain-induced martensitic transformation of Fe—C particles in the copper-based composite and its positive effect on the mechanical properties were systematically studied in this work.

2. Experimental

A copper-based composite reinforced by Fe—C particles was prepared by vacuum induction melting pure copper and Fe-0.6wt%C alloy, and then cast into a water-cooled copper mold, followed by cold rolling from 10 mm to the final thicknesses of 2 mm at room temperature or low temperature (liquid N_2 cooling for 10 min, then followed by cold rolling). Finally, the tensile properties of copper-based composites in the different conditions were measured on an MTS 810 machine at room temperature. Hardness measurement was carried out on Shimadzu HMV-2000 Vickers Hardness (HV) instrument with a load of 200 g for 15 s. The optic microstructure of samples was examined on a Carl. ZEISS Axio Imager A2 optical microscope after etching by a mixture of 5 ml ferric chloride, 25 ml hydrochloric acid and 100 ml

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distilled water. The distribution of particles and tensile fracture morphology were characterized by a SUPRA 55 scanning electron microscope (SEM) equipped with X-ray energy dispersive spectrometer (EDS) system. The distribution and structure of Fe—C phases in the matrix were revealed by a TecnaiG2 F30 transmission electron microscope (TEM) equipped with X-ray energy dispersive spectrometer (EDS) system. Thin foils were twin-jet polished in a solution of 30% nitric acid and 70% methanol at a temperature of around −25 °C. Additionally, the structure of Fe—C phases was also characterized by X-ray diffraction (XRD) method on a M21X XRD machine using Cu Kα radiation, and operation voltage and current are 40 kV and 150 mA, respectively, the step-scanning in the 2θ range of 42°–46° with a space of 2 s was used in XRD measurement.

3. Results

3.1. Effect of Cold Rolling Deformation

A large density of spherical and irregular Fe—C particles with the size of around several microns can be found in the composite (as shown in Fig. 1(a)). Accordingly, the used cooling rate (-0.515×10^3 K/s ~ -0.773×10^4 K/s) should be enough to ensure the Fe—C particles uniformly distributing in the matrix. Compared with the copper-ceramic composites with a poor deformability [10], the developed copper-based composite possesses a much better deformability. Both the Cu matrix and Fe—C particles have a plastic deformation after cold rolling, and a good deformation cooperation of Fe—C particles with Cu matrix can be demonstrated by the elongated structure shown in the broken circle of Fig. 1. Additionally, if the composites are cold rolled at the low temperature, the microstructure changes greatly and even the refinement of spherical Fe—C particles also can be observed (broken circle in Fig. 1(c)). This difference mainly results from the fact that the stresses needed for the plastic deformation of both Cu matrix and Fe—C particles increase with the decrease of deformation temperature, and further leading to the separation or broken of aggregated spherical Fe—C particles.

In order to better analyze the phase transformation of Fe—C particles during cold rolling, the XRD pattern of copper-based composite in the different conditions is shown in Fig. 2. Both $(111)_{Cu}$ and $(101)_M$ diffraction peaks appear in the as-cast state, which indicates that the martensitic transformation of Fe—C phases can be induced during the rapid solidification. Certainly, the diffraction peak of Fe—C austenite phase may also exist, but cannot be observed just due to the similar diffraction angle as that of Cu matrix. Additionally, the observed deviation of $(110)_{\alpha\text{-Fe}}$ diffraction peak may be resulted from the interfacial diffusion of Cu atoms as discussed in the following part. After cold rolling 80% at room temperature, the $(111)_{Cu}$ diffraction peak becomes much wider, which should be resulted from both strain widening and the formation of much more strain-induced martensite phases. The $(110)_{\alpha\text{-Fe}}$ diffraction peak also moves back to the right position after cold rolling (indicating that a gliding dislocation acting as a stress amplifier to start the lattice change). Accordingly, the martensitic transformation of Fe—C particles in the composite can be really induced by cold rolling at room temperature. For the sample cold rolled at the low temperature, not only the $(111)_{Cu}$ diffraction peak becomes much wider, but also its peak angle moves to the angle of $(101)_M$ much more, indicating that the fraction of phase transformation increases as the deformation temperature is lowered. Additionally, the clear $(110)_{\alpha\text{-Fe}}$ diffraction peak also can be seen in this condition. All these results further demonstrate that the martensitic transformation of Fe—C particles can be induced by both the cold rolling methods, but the transformation fraction increases as the decrease of deformation temperature.

Fig. 3 shows the TEM microstructure of copper-based composite in the different conditions. Lots of nano-sized spherical particles (around 50 nm) can be found in the alloy matrix in the as-cast state. Some fine particles with the "lobe contrast" arising from spherically symmetrical coherency strain in the electron micrographs can be observed (particle A shown in Fig. 3(a)), this kind of particles normally are named as γ-Fe particles with an FCC structure coherent or semi-coherent with alloy matrix [14]. Additionally, the twinned martensite structures of Fe—C particles also can be clearly seen in the alloy matrix. A detailed SAD analysis on them shows that they are α-Fe particles with a BCC structure, the

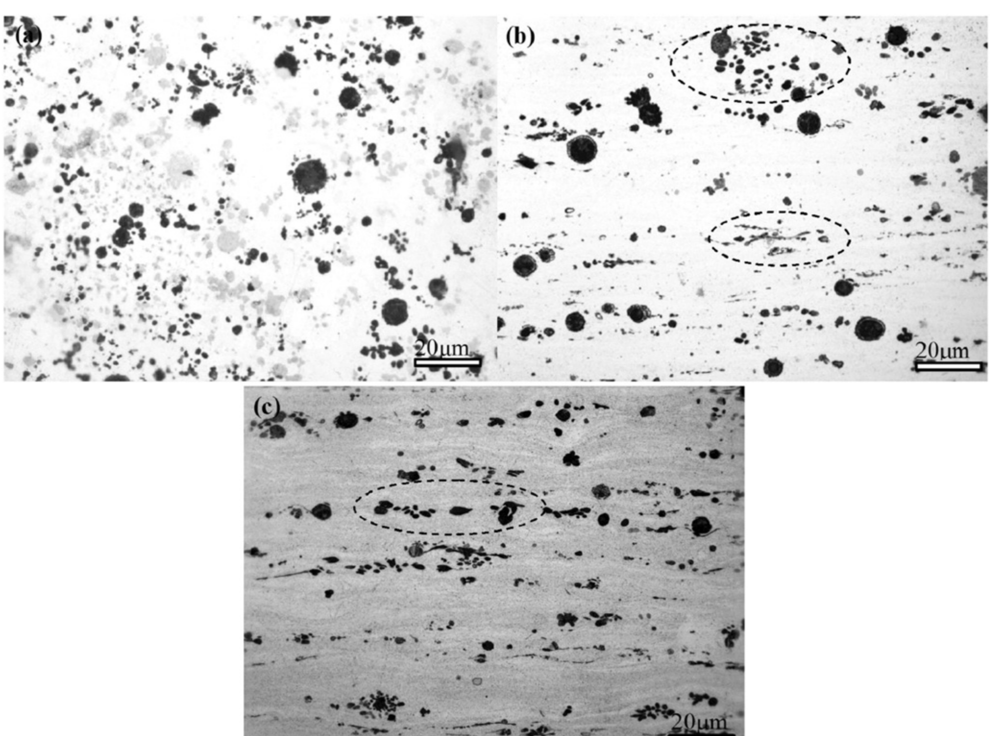

Fig. 1. The optic microstructure of copper-based composite in the different conditions (a) as-cast state, (b) cold rolling 80% at room temperature, (c) cold rolling 80% at low temperature.