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Experiment and simulation on the thermal instability of a heavily deformed Cu–Fe composite

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ABSTRACT

The thermal instability of the Fe fibers in the heavily deformed Cu–12.8 wt.%Fe composites is investigated experimentally and numerically. The fiber evolution is characterized by a field emission scanning electron microscopy (FESEM). The results show that the dominant instability of the Fe fibers is the longitudinal boundary splitting which is determined by the greater cross sectional aspect ratio (width/thickness, w/t) and the larger ratio of boundary to interfacial energy (γ_B/γ_S). The longitudinal boundary splitting makes the ribbon-like Fe fibers evolve into a series of cylindrical fibers. Then the cylindrical Fe fibers undergo the instability process in terms of the breakup, growth and coarsening concurrently. The breakup times are accurately predicted by the Rayleigh perturbation model. The growth process primarily contributes to the higher increasing rate of the fiber radius during isothermal annealing at 700 °C than that calculated by the coarsening theory developed for cylindrical fibers, since the Cu-matrix of composites is highly supersaturated after casting/cold-working process.

1. Introduction

The Cu-based in situ composites play an important role in the modern industry particularly for the attractive combination of high strength and high electrical conductivity [1–3]. Many researches concentrate on the Cu-bcc (Nb, Cr, Fe, Ta, V, etc.) deformed composites prepared by the “casting/cold working” process. The composites are attractive for such applications as transmission lines, lead frames, connectors and other electrical devices. In practical applications, the Cu-based composites undergo a temperature pulse produced by the ohmic heating such as the Cu–Nb composites used in magnets [4], which definitely causes significant microstructure changes, especially in the morphology of reinforced fibers. Consequently, the combined properties and service life of the composites will be degraded. Therefore, it is worthwhile to investigate the thermal instability of the fibers.

The Cu–Fe system is of particular interest and value because of the relatively lower cost and industrially accessible melting temperature of iron as an alloying element compared to the other possible bcc phases [5]. Many researches [6–9] have been carried on the thermal instability of Cu–Fe composites. Malzahn Kampe et al. [6] firstly propose three thermal instability models of the Fe fibers including cylinderization, boundary splitting and edge spheroidization after analyzing the microstructure evolution of Cu–14.3 vol.%Fe composites at the moderate deformation strain (η = 5.09). Courtney et al. [7] conduct an analysis on the required times of the three instability processes. In addition, the instability models proposed by Malzahn Kampe also have been applied to other Cu-bcc composites [10–13]. However, these three instability models are proposed on the basis of a moderate draw strain. If the draw strain is heavier, the morphologies of Fe fibers will be further developed and the instability processes become more complicated. In this paper, the microstructural instabilities of the Fe fibers in the deformed Cu–12.8 wt.%Fe composites with a high draw strain of 8.2 are investigated. Both the Rayleigh perturbation and Ostwald ripening models are introduced to analyze the thermal instabilities of the Fe fibers in the heavily deformed Cu–Fe composites.

2. Experimental procedure

Deformed Cu–12.8 wt.%Fe composites were prepared by the “casting/cold working” process. The initial Cu–12.8 wt.%Fe ingot (75 mm in diameter and 130 mm length) was prepared from 4 N pure Cu and Fe using the vacuum induction melting furnace. The ingot was forged to 26 mm in diameter and then drawn to different wires in diameters at room temperature. During the cold drawing processes, the reduction of the cross section was about 25% and the vacuum annealing treatments of 450 °C were applied. The draw strain is defined by $\eta = \ln(A_0/A_f)$, where A_0 and A_f are the initial and final cross sectional area, respectively.

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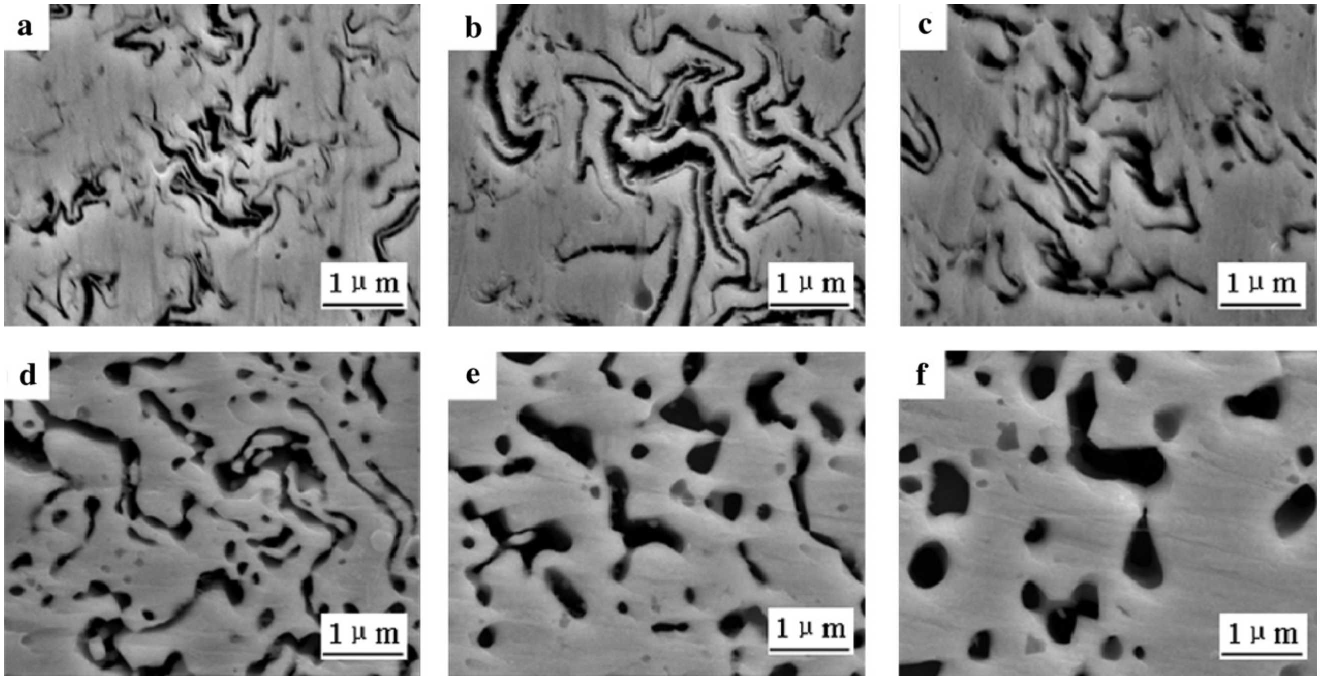

Fig. 1. The cross-sectional microstructures for Cu–12.8 wt.%Fe composites (a) before annealing and after annealing at (b) 400 °C, (c) 500 °C, (d) 600 °C, (e) 700 °C and (f) 800 °C for 1 h.

The Cu–Fe composite wires with a heavy draw strain of 8.2 (1.14 mm in diameter) were selected for this investigation. The wires were sealed in the quartz tubes evacuated to a pressure of 1.3×10^{-2} Pa, and annealed at the temperatures of 400, 500, 600, 700 and 800 °C for 1 h followed by air cooling, respectively. On the other hand, the isothermal treatments at 700 °C were also investigated and the holding times ranged from 1 to 84 h.

The samples were prepared by the standard mechanical polishing method and etched in a solution of 120 ml H_2O, 20 ml HCl and 5 g $FeCl_3$. The morphologies of the Fe fibers were observed by a field emission scanning electron microscopy (JSM-7001F, FESEM) with a resolution of 3.5 nm. The thickness, *t*, and width, *w*, of the Fe fibers were quantitatively identified from the FESEM pictures of the as-drawn wires to obtain the average cross sectional aspect ratio w/t [2].

3. Experimental results

Figs. 1 and 2 show the cross-sectional and longitudinal microstructure evolutions of Cu–12.8 wt.%Fe composites, respectively. The observation of the as-drawn microstructures (Fig. 1a) demonstrates that the ribbon-like Fe fibers formed from the dendrites uniformly distribute in the Cu matrix. The average aspect ratio w/t is 17.65 by way of the quantitative measurement. When the composites are annealed at the temperatures of 400 and 500 °C, there are no significant changes in the morphologies of Fe fibers (Fig. 1b and c) compared with the as-drawn Fe fibers (Fig. 1a). When the annealing temperature is further elevated to 600 °C which is approximate to the recrystallization temperature of pure iron [8], the recrystallization of the Fe fibers is driven, and the thermal grooves of the Fe fibers occur and gradually become apparent. The development of thermal grooves promotes the longitudinal splitting. The longitudinal splitting causes the edge recession of the Fe fibers, resulting in the ridges along the fiber length (Fig. 1d). Consequently, the Fe fibers gradually evolve into a series of cylinders with different diameters (Fig. 1e). The diameters of the cylindrical Fe fibers are in the range of 0.3–0.6 μm and the average diameter is 0.41 μm in terms of the statistical analysis. In addition, an observation of the microstructure in the longitudinal section (Fig. 2b) reveals that the breakup firstly takes place in the cylindrical fibers with relatively smaller sizes. When the annealing temperature reaches 800 °C, the breakup and growth of the cylindrical fibers are pronounced concurrently (Figs. 1f and 2c).

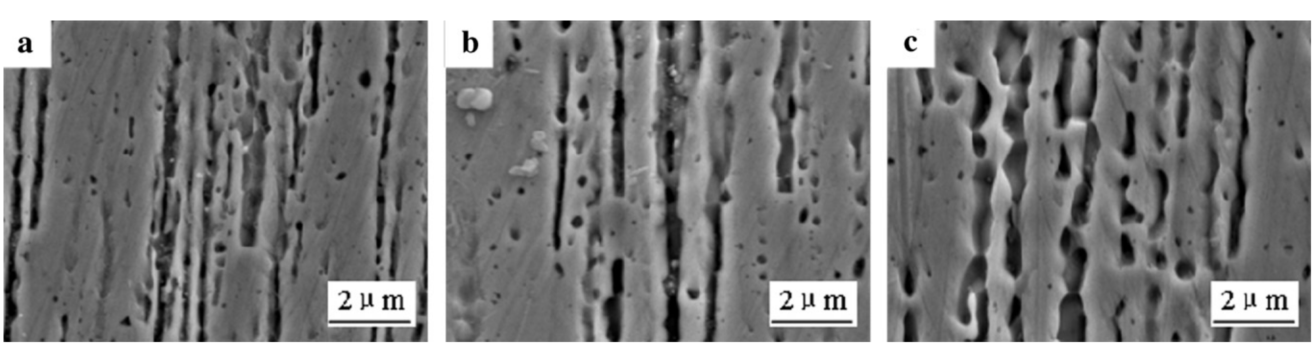

Fig. 2. The longitudinal-section microstructures for Cu–12.8 wt.%Fe composites annealed at (a) 600 °C, (b) 700 °C and (c) 800 °C for 1 h.