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Meeting-report

Study of a CuAg Alloy from Microscale to Atomic Scale

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Cu-matrix composites containing Ag filaments exhibit both high strength and high conductivity [1, 2], making them particularly suitable for applications in high-field magnets [3]. This enhanced conductivity is attributed to the low solubility of Ag in Cu and vice versa. Additionally, their remarkable strength, which surpasses what would be expected from a simple rule-of-mixture calculation for Cu and Ag, is credited to the abundance of nanosized Ag fibers. These fibers predominantly originate from small silver particles within the as-cast composites. To achieve optimal properties in the final product, a detailed examination of the microstructure of the cast composites at the nanoscale or even atomic scale is essential [4]. Past investigations have revealed the complexity of the microstructure in Cu-Ag composites. Therefore, comprehensive characterization demands a thorough analysis of the microstructure in three dimensions (3D) and a deep understanding of the interfaces at the atomic level.

An ingot (Cu-25wt%Ag) of 50 mm in diameter was casted in vacuum. The samples were sectioned from the ingot to provide transverse direction view in a Scanning Electron Microscope (SEM) with Focused Ion Beam (FIB). 3D images were obtained in a SEM/FIB Thermo Fisher Helios G4 UC with 30 kV of ion beam voltage (Ga) and a current of 24 nA and the SEM images were acquired at 2 kV and 1.6 nA with an in-column backscattered detector. Detailed microstructure studies were undertaken using High-Angle-Annular-Dark Field (HAADF) Scanning Transmission Electron Microscope (STEM) on a JEM-ARM200CF operated at 200 kV.

SEM images showed proeutectic Cu component and eutectic component (Fig. 1). We observed distinct interfaces between eutectic Ag and proeutectic Cu. In the SEM, the interfaces appeared round and showed no facets, indicating that the interfaces formed from the solidification. Proeutectic component indeed formed from melt at higher temperatures, at which high Ag content was dissolved in Cu. During cooling, the solubility of Ag in Cu gradually increased until the melt reached it maximum solubility and the melt reached eutectic temperature. Below eutectic temperature, the solubility of Ag in solidified proeutectic Cu decreased, leading to the solid-state reaction of the precipitation of fine Ag particles (bright contrast in Fig. 1) in proeutectic Cu. We believe that such fine Ag precipitates strengthened the proeutectic Cu. The eutectic component showed a higher volume fraction of Ag than Cu. SEM images in 3D showed a connection of eutectic Cu and Ag, but no connections between proeutectic Cu and eutectic Cu, indicating that Ag was the nuclei for eutectic reaction, which formed at or below eutectic temperature (Fig. 2). At the proeutectic Cu/eutectic Ag solid solution interface region, we observed relatively wide Ag and Cu areas that do not have the precipitated opposite element. The Ag area indicated depletion of Cu in the liquid near the solidified Cu. The depletion of Cu led to nucleation of Ag on the interface between the liquid and proeutectic Cu. Analyzing the 3D structure of the CuAg composite would provide insights into the spatial distribution and connectivity of phases, which can be useful in understanding their properties.

In the eutectic area with both Cu and Ag, we selected a region using electron backscatter diffraction to prepare TEM sample using FIB. We were able to section the TEM sample with a zone axis close to [001]. In the HAADF-STEM image of the eutectic region, we observed relatively distinct interfaces between Cu and Ag. Cu and Ag phases, which were formed during the eutectic reaction, were on cube-on-cube orientation relationship (see inset in Fig. 3A). The atomic resolution HAADF-STEM image in the [001] zone axis showed the eutectic Ag and proeutectic Cu interface (see Fig. 3B). This interface was not edge on, but a little inclined, as there were Moire fringes at the Ag side. The misfit dislocations were about 0.15 nm apart and released the 11% misfit between Cu and Ag. Although eutectic Ag and proeutectic Cu formed at different stages of solidification, our data showed that they had cube-on-cube orientation relationship (see inset in Fig. 3B). This orientation relationship indicated that Ag acted as nuclei for eutectic reaction on proeutectic. The small Ag particles inside proeutectic Cu also have the cube-on-cube orientation relationship (Fig. 3D and 3C).

In summary, both SEM 3D microstructure examination and atomic resolution HAADF STEM revealed a connection between eutectic Cu and Ag, yet no connections were observed between proeutectic Cu and eutectic Cu. In the proeutectic Cu phase, both SEM and HAADF STEM exhibited nanosized Ag precipitates, which were formed during a solid-state reaction. Cu and Ag were found to have a cube-on-cube orientation relationship. Within the eutectic region, both 3D SEM and HAADF STEM showed micron-sized Cu and Ag particles with a cube-on-cube orientation relationship. It was observed that eutectic Ag and proeutectic Ag also exhibited a cube-on-cube orientation relationship, suggesting that Ag precipitates first during the eutectic reaction [6].

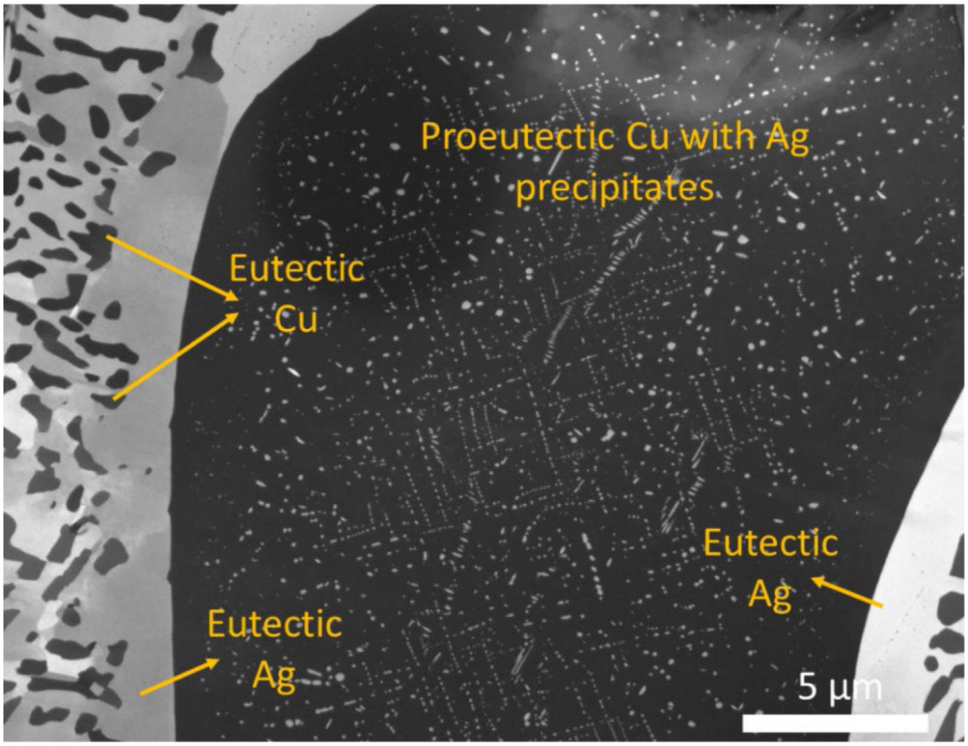

Fig. 1. SEM image showing the contrast between Cu and Ag in a cast Cu-25wt%Ag alloy. The areas with the darkest contrast are composed of Cu and areas of light contrast are Ag. The center region is proeutectic Cu with fine Ag precipitates. The other two regions are eutectic products, which are composed of Cu and Ag. B) 3-D image of a eutectic region showing the connections in the eutectic Cu phase inside the Ag.

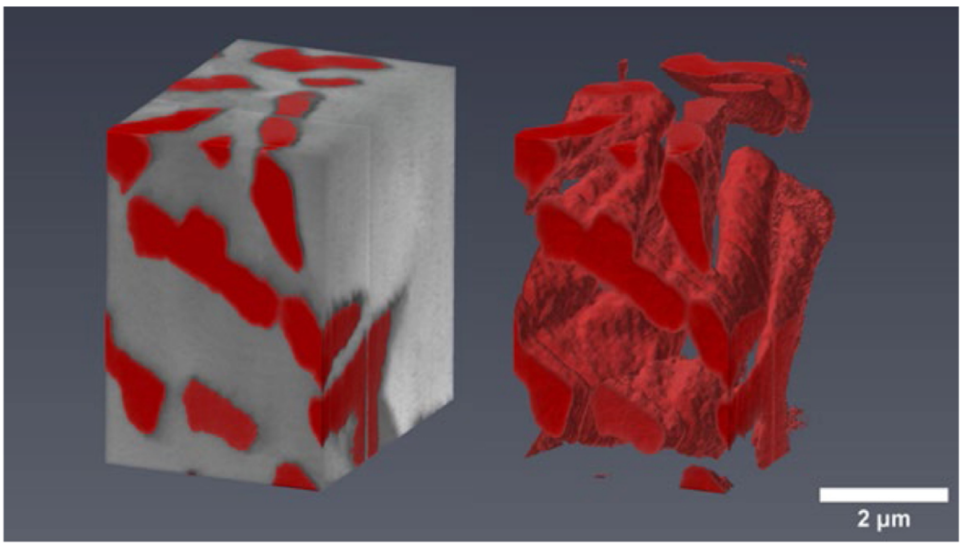

Fig. 2. SEM/FIB 3-D image of a eutectic region showing the connections in the eutectic Cu phase (red) inside the Ag phase (gray).

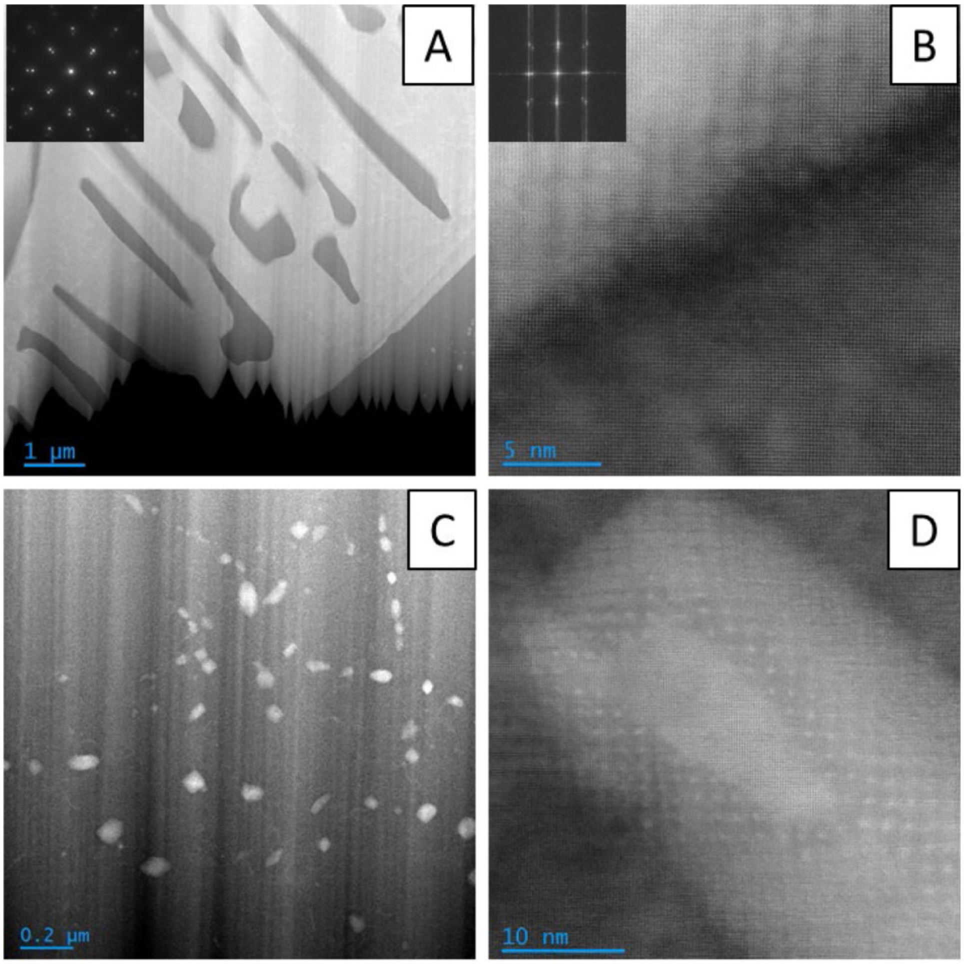

Fig. 3. A) Low magnification HAADF-STEM and a selected area diffraction pattern (inset). B) Atomic resolution HAADF-STEM image showing an interface between eutectic Ag and proeutectic Cu. Inset shows FFT diffraction pattern. C) Small Ag particles inside proeutectic Cu. D) Atomic resolution HAADF-STEM of one Ag particle showing cube-on-cube orientation relationship.

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