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Evolution of Microstructure in a Cu-Cr *in situ* Composite Produced by Thermo-Mechanical Processing

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Abstract

This paper studied the microstructure evolution of a deformation-processed Cu-7Cr *in situ* composite prepared by thermo-mechanical processing. The longitudinal and transverse sectional microstructures were analyzed using an optical microscope and a scanning electronic microscope. In the longitudinal section, the initially randomly distributed Cr dendrites in the as-cast Cu-7Cr alloy were transformed into the fibres aligned parallel to the drawing axis; the Cr dendrites experienced breaking, flattening and rotating, lapping and merging, and homogenizing and refinement during thermo-mechanical processing. In the transverse section, the initially randomly distributed Cr dendrites in the as-cast Cu-7Cr alloy were changed into the curvy ribbon like fibres; the Cr dendrites underwent breaking, flattening and rotating, folding and twisting, and irregularizing and refinement during thermo-mechanical processing.

Keywords

Cu-Cr, *in situ* Composite, Evolution, Microstructure, Thermo-Mechanical Processing

1. Introduction

Over the past several decades, deformation-processed binary Cu-based *in situ* composites such as Cu-Fe, Cu-Ag, Cu-Nb, and Cu-Cr have been the subject of extensive research due to their high strength and good conductivity [1] [2] [3] [4] [5]. However, the Cu-Fe *in situ* composite has relatively low conductivity due to the relatively high solubility of Fe in the Cu matrix and the particularly harmful effect on the conductivity of Fe atoms in solid solution [6]. Ag and Nb are expensive metals, which impede the use of the Cu-Ag and Cu-Nb *in situ* composites in large-scale applications. The Cu-Cr *in situ* composite is of particular interest due to the relatively economical cost and the high strength of Cr, and the limited solubility of Cr in the Cu matrix [7] [8].

The deformation-processed Cu-Cr *in situ* composite belong to the class of bulk nanostructured metallic materials, due to the small size of the structural constitutes produced via the *in situ* deformation processing. The Cr fibres formed in the Cu matrix ensure the high tensile strength, and the limited solubility of Cr atoms in the Cu matrix ensures the high electrical conductivity. The filamentary structure of double phases in the Cu-7Cr *in situ* composite was produced by severe cold drawing and intermediate heat treatment. The constituent concentration, cold drawing strain and heat treatment parameter strongly influence the properties [9] [10] [11]. In special, the microstructure evolution during cold drawing plays an important role in the change of the strength and conductivity with the cold drawing strain. Stepanov *et al.* [12] investigated the evolution of microstructure and mechanical properties in a Cu-14Fe *in situ* composite, and found that rolling resulted in significant microstructural refinement of the Cu-14Fe alloy. The work of Liu *et al.* [13] suggested that the eutectic colonies in Cu-Ag *in situ* composites were evolved into filamentary bundles with tight arrangement of double phases during severe cold drawing.

However, the evolution of microstructure in Cu-Cr *in situ* composites still needs further investigation because of the complex co-deformation of Cu and Cr phases. In this work, the as-cast and deformation-processed microstructures of a Cu-7Cr *in situ* composite were investigated. The microstructure evolution during cold drawing was analyzed.

2. Experimental Details

The Cu-7wt%Cr (designated Cu-7Cr) alloy was produced by melting appropriate amounts of electrolytic Cu and commercial Cr (of at least 99.9 wt.% purity) using a magnesia crucible in a vacuum induction furnace, and was casted into rod ingots of diameter, d = 36 mm. The deformation-processed Cu-7Cr *in situ* composite was prepared by homogenization treatment, hot rolling, heat treatment and cold drawing to a cumulative cold deformation strain of $\eta = 8$. The cumulative cold deformation strain η was obtained in terms of true strain as follows:

$$\eta = \ln(A_0 / A_f) \quad (1)$$

where A_0 is the initial transverse sectional area after hot rolling, and A_f is the final transverse sectional area after cold drawing. The detailed production processing has been published elsewhere [14]. The subsequent thermo-mechanical processing of the *in situ* composite of $\eta = 7$ was as follows: (i heat treated at 625˚C for 1 h, (ii cold drawn to $\eta = 8$.

The as-cast and deformation-processed samples were sectioned and the longitudinal and transverse sectional microstructures were examined using a Leica DMI5000 M optical microscope (OM) and a JSM-6360LV scanning electronic microscope (SEM). The samples were prepared by standard mechanical polishing and were etched in a solution of 120 ml H2O, 20 ml HCl and 5 g FeCl3 to reveal the Cr phase structure, prior to the OM and SEM examinations

3. Results and Discussion

3.1. Longitudinal Sectional Microstructure

Figure 1(a) shows the longitudinal sectional microstructure of the as-cast Cu-7Cr alloy. The secondary phase Cr dendrites were evenly distributed in the Cu matrix and randomly oriented with respect to the ingot axis. **Figure 1(b)** shows the longitudinal sectional microstructure of the Cu-7Cr alloy after hot rolling. The Cr dendrites were broken and changed into rod like and disk like Cr grains. However, the size and distribution of the Cr phase is no obvious change. **Figure 1(c)** shows the longitudinal sectional microstructure of the deformation-processed Cu-7Cr *in situ* composite with a cumulative cold deformation strain $\eta = 4$. There were the Cu matrix plus elongated Cr grains and thin Cr fibres parallel to the drawing direction. The deformation of the Cr grains in the Cu-7Cr was not uniform; there were still some tadpole-like Cr grains. **Figure 1(d)** shows the longitudinal sectional microstructure of the deformation-processed Cu-7Cr *in situ* composite with a cumulative cold deformation strain $\eta = 8$. The tadpole-like Cr grains in the Cu-7Cr *in situ* composite with $\eta = 4$ had been all drawn into long thin fibres. The size and spacing of the Cr fibres in the Cu-7Cr *in situ* composite with $\eta = 8$ were finer and smaller than those with $\eta = 4$. The microstructure evolution of the deformation-processed Cu-7Cr *in situ* composite is

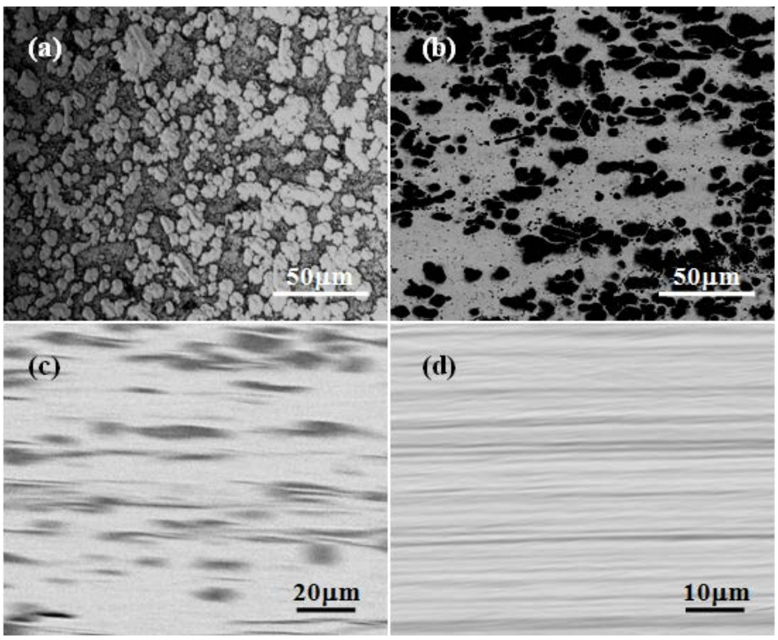

Figure 1. Longitudinal sectional microstructures of the Cu-7Cr alloy: (a) as-cast; (b) hot rolling; (c) $\eta = 4$; (d) $\eta = 8$.

similar to those reported in previous research [9] [10] [15]. **Figure 2** shows the schematic diagram of formation of fibres in deformation-processed Cu-based *in situ* composites along the longitudinal section. The hot deformation broke the dendrites to form the rod like and disk like grains, as presented in **Figure 2(a)**. The cold drawing flattened the grains and rotated the grains parallel to the drawing axis, as presented in **Figure 2(b)**. With increasing cumulative cold deformation strain, the flattened and rotated grains were lapped and merged into fibres, as presented in **Figure 2(c)**. With further cold drawing, the lapped and merged fibres were further refined and homogenized, as presented in **Figure 2(d)**. The initially randomly distributed secondary dendrites in the as-cast microstructure were transformed into fibres aligned parallel to the drawing axis, with fibre aspect ratio increasing with increasing η.

3.2. Transverse Sectional Microstructure

Figure 3(a) shows the transverse sectional microstructure of the as-cast Cu-7Cr alloy. Similar to the longitudinal sectional microstructure, there were the Cu matrix and randomly oriented Cr dendrites. **Figure 3(b)** shows the transverse sectional microstructure of the Cu-7Cr alloy after hot rolling. Similar to the longitudinal sectional microstructure, there were rod and disk like Cr grains in the Cu matrix. **Figure 3(c)** shows the transverse sectional microstructure of the deformation-processed Cu-7Cr *in situ* composite with a cumulative cold deformation strain $\eta = 4$. There were circular Cr grains and ribbon like Cr fibres in the Cu matrix. **Figure 3(d)** shows the transverse sectional microstructure of the deformation-processed Cu-7Cr *in situ* composite with a cumulative cold deformation strain $\eta = 8$. The circular Cr grains in the Cu-7Cr *in situ* composite with $\eta = 4$ had been all changed into ribbon like fibres. The size and spacing of the ribbon like Cr fibres in the Cu-7Cr *in situ* composite with $\eta = 8$ were finer and smaller than those with $\eta = 4$. The ribbon like morphology is attributed to the deformation producing Cr fibres with a <111> fibre texture, which promoted plane strain deformation rather than axially symmetric flow. However, the Cu matrix did deform in an axially symmetric manner during wire drawing, which

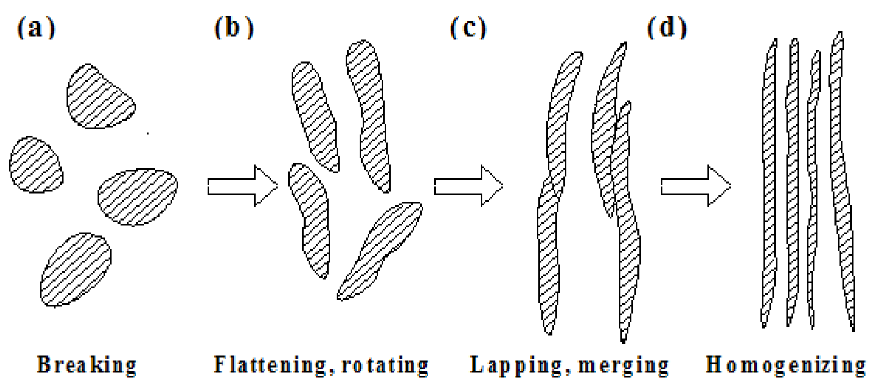

Figure 2. Schematic diagram of formation of fibres in deformation-processed Cu-based *in situ* composites along the longitudinal section: (a) breaking of dendrites; (b) flattening and rotating of grains; (c) lapping and merging of fibres; (d) homogenizing of fibres.

constrained and forced the Cr fibres to fold or twist about the wire axis to maintain compatibility with the matrix and produced the irregular transverse section [16]. **Figure 4** shows the schematic diagram of formation of fibres in deformation-processed Cu-based *in situ* composites along the transverse section. Similar to the longitudinal section, the hot deformation formed the rod like and disk like grains, and the cold drawing flattened and rotated the grains parallel to the drawing axis, as presented in **Figure 4(a)** and **Figure 4(b)**. With increasing cumulative cold deformation strain, the flattened and rotated grains were folded and twisted into curvy ribbon like fibres, as presented in **Figure 4(c)**. With further cold drawing, the folded and twisted fibres were further refined and irregularized, as presented in **Figure 4(d)**. The initially randomly distributed secondary dendrites in the as-cast microstructure were changed into curvy ribbon like fibres, with fibre aspect ratio increasing with increasing η.

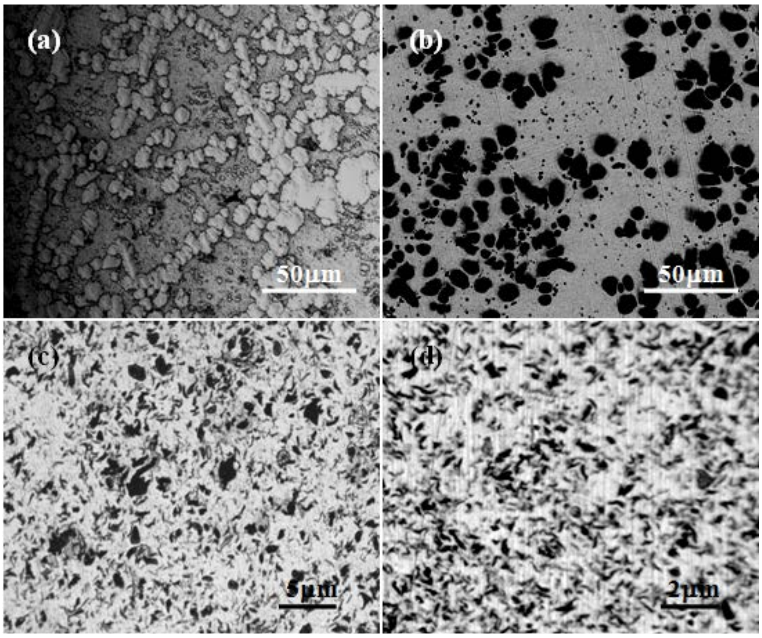

Figure 3. Transverse sectional microstructures of the Cu-7Cr alloy: (a) as-cast; (b) hot rolling; (c) $\eta = 4$; (d) $\eta = 8$.

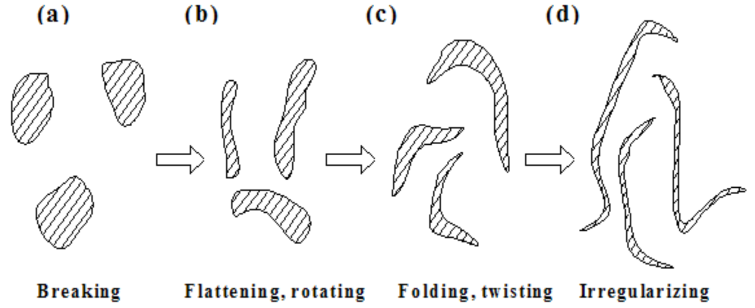

Figure 4. Schematic diagram of formation of fibres in deformation-processed Cu-based *in situ* composites along the transverse direction: (a) breaking of dendrites; (b) flattening and rotating of grains; (c) folding and twisting of fibres; (d) irregularizing of fibres.

4. Conclusions

1) In the longitudinal section, the initially randomly distributed Cr dendrites in the as-cast Cu-7Cr alloy were transformed into the fibres aligned parallel to the drawing axis.

2) The longitudinal sectional microstructure of the *in situ* composite experienced breaking of dendrites, flattening and rotating of grains, lapping and merging of fibres, and homogenizing of fibres during thermo-mechanical processing.

3) In the transverse section, the initially randomly distributed Cr dendrites in the as-cast Cu-7Cr alloy were changed into the curvy ribbon like fibres.

4) The transverse sectional microstructure of the *in situ* composite underwent breaking of dendrites, flattening and rotating of grains, folding and twisting of fibres, and irregularizing of fibres during thermo-mechanical processing.

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