Thermo-mechanical Processing for In-situ Cu-based Composites

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Abstract. In-situ Cu-based composites have been investigated extensively over the past decades because of their good conductivity and high strength. The preparation technologies of in-situ Cu-based composites mainly include casting of Cu alloys, initial heat treatment, hot deformation, cold deformation, intermediate and final heat treatment. This paper primarily researched the effect of thermo-mechanical processing such as initial heat treatment, hot deformation, cold deformation, intermediate and final heat treatments on the property and microstructure of in-situ Cu-based composites, analyzed the main role and mechanism of each thermo-mechanical processing, summarized the related research work and achievements, and prospected the future main research directions of the thermo-mechanical processing for in-situ Cu-based composites.

1. Introduction

Cu-based materials with good conductivity and high strength have been the indispensable key materials in the fields of electronics, information, transportation, energy and metallurgy. They can be applied in high-strength magnetic field coil, electrified railway contact wire, integrated circuit lead frame, high-power asynchronous traction motor rotor, electric resistance welding electrode, etc. However, the conductivity and strength of Cu-based materials are usually a pair of contradictions. If the strength is high, the conductivity is low, while the good conductivity is often obtained at the expense of strength. Because the periodic potential field of copper lattice is destroyed after the solid solution of alloying elements, and the movement of free electrons is scattered by impurity atoms, which produces additional resistance.

The preparation technologies of high conductivity and high strength Cu-based materials mainly include solid solution deformation, deformation aging, rapid solidification and composite material method. The Cu-based materials prepared by composite material method could gain a good combination between conductivity and strength. Previous work found that the Nb dendrites would be transformed into the oriented fibers in the Cu matrix after severely plastic deformation of a Cu-20wt.%Nb alloy ingot. The strength of the composites can exceed 2000 MPa, and the conductivity is close to 70% IACS. Subsequent studies show that the composites composed by Cu and transition metals Fe, V, Cr, W, Mo, etc, or Ag have similar microstructural characteristics and mechanical properties with Cu-20wt.%Nb composites. The fiber in this kind of composites was produced in-situ
during preparation. Accordingly, the composites were defined as in-situ Cu-based composites, which are promising composites in the application field of high-performance Cu-based materials.

2. Preparation technology

The thermo-mechanical processing for in-situ Cu-based composites mainly include initial heat treatment of Cu alloys, hot deformation, cold deformation, intermediate and final heat treatments. Figure 1 presents the sketch map of thermo-mechanical processing from Cu alloys to in-situ Cu-based composites.

![Figure 1 Sketch map of thermo-mechanical processing from Cu alloys to in-situ Cu-based composites.](image)

2.1. Initial heat treatment

Initial heat treatment eliminates or reduces the effect of non-equilibrium solidification microstructure, precipitates solid solution atoms from Cu matrix and effectively refines the second phase dendrites in as-cast Cu alloys. Xie et al. [1] produced in-situ Cu-8Fe with 0.5Ag and 0.1Ag composites by cast, homogenization treated and cold drawn Cu alloys, and investigated the influence of homogenization treatment on the property and microstructure. The prior homogenization treatment precipitated the solid solution Fe atoms and refined the primary Fe dendrites, which increases the conductivity and strength of the composites. Wu and Meng [2] prepared in-situ Cu-12Fe and Cu-6Fe composites by cast, heat treated and cold drawn Cu alloys, studied the effects of initial heat treatments on the property and microstructure. The initial quenching and aging or initial homogenization treatment refined the microstructure, which increased the interface density of second phase Fe and Cu matrix. The fiber spacings of the composites with the initial homogenization treatment were smaller than that with the initial quenching and aging, and the strengths of the composites with the initial homogenization treatment were higher than that with the initial quenching and aging, which was due to the fact that the homogenization treatment caused more and smaller dispersive primary Fe dendrites in the as-cast alloys. The analysis above shows that initial heat treatments play significant roles in increasing the property of in-situ Cu-based composites.

2.2. Hot and cold deformation

Hot deformation breaks the second phase dendrites, reduces the internal defects in Cu alloys. Cold deformation makes the second phase dendrites gradually change into oriented fibers, considerably increases the strength of in-situ Cu-based composites. A sketch map forming fibers in in-situ Cu-based composites was shown in Figure 2. The second phase dendrites were transformed into disklike grains (Figure 2a) by hot deformation, then changed into oriented rodlike grains (Figure 2b), lapped and merged into oriented strip shaped grains (Figure 2c), formed into oriented slender fibers (Figure 2d) by cold deformation. Previous investigations indicated that large deformation is necessary to obtain a high strength for in-situ Cu-based composites. Sun et al. [3] researched the strength of in-situ Cu-12Fe, Cu-11Fe-6Ag, Cu-14Fe-1Ag and Cu-14Fe-3Ag composites with different cold deformation strains and found that the stress-strain curves of each composite are exponentially dependent. Zou et al. [4]
found that the strength improved with increasing strain of in-situ Cu-14Fe composites, and the improving trend increased after cold deformation strain higher than 5.7. Liu et al. [5] investigated the tensile strength of in-situ Cu-Fe composites with different cold deformation strains and found that the strength could be calculated by a modified rule of mixture at low strains and could be calculated by a modified Hall-Petch relation at high strains. The analysis above shows that hot and cold deformation are the main technology obtaining high strength for in-situ Cu-based composites.

Figure 2. Sketch map forming fibers in in-situ Cu-based composites: (a) broken dendrites; (b) flatten and rotated grains; (c) lapped and merged grains; (d) formed and homogenized fibers.

2.3. Intermediate heat treatment
Intermediate heat treatment releases the internal stress produced by cold deformation, increases the cold deformability and conductivity, which is conducive to further cold deformation of in-situ Cu-based composites. Ge et al. [6] researched the effects of intermediate heat treatment on the electrical conductivity, strength and microstructure of in-situ Cu-Fe composites. The intermediate heat treatment was beneficial to transform second phase Fe dendrites into uniform fine fibers in Cu matrix. The intermediate heat treatment had no obvious influence on the strength of the composites, but increased the electrical conductivity because of the precipitation of solid solution Fe atoms, which decreased the impurity scattering resistivity. Wu et al. [7] produced in-situ Cu-6Fe-0.3RE, Cu-6Fe-0.05RE and Cu-6Fe composites by cast, cold worked and intermediate heat treated Cu alloys. The micro-hardness and tensile strength of the composites declined but the electrical conductivity improved with improving intermediate heat treatment temperatures. In particular, the change of the hardness, conductivity and strength was remarkable at intermediate heat treatment temperatures over 400 °C. Liu et al. [8] researched the property of Cu-7Cr in-situ composites with intermediate heat treatment. The results suggested that an appropriate intermediate heat treatment could increase the plasticity and conductivity, decreased the internal stress, which was conducive to the improvement of the final comprehensive property of the in-situ composites. The analysis above shows that intermediate heat treatment is an
important intermediate technology to obtain good conductivity and high strength in-situ Cu-based composites.

2.4. Final heat treatment
Final heat treatment precipitates the residual atoms and stabilizes the microstructure of in-situ composites, which is conducive to the regulation and improvement of the comprehensive property for deformation-processed in-situ Cu-based composites. Sun et al. [9] researched the aging characteristics of Cu-Fe composites. The hardness of in-situ Cu-11Fe-6Ag and Cu-12Fe composites reached the peaks at different final heat treatment temperatures, but the change process was different with increasing temperature. The conductivity improved with improving final heat treatment temperature and reached the peaks at about 475 ℃. Wu et al. [10] reported the microstructure and properties of in-situ Cu-12wt.%Fe composites finally heat treated at different temperatures. The strength decreased slightly, and the conductivity increased obviously at final temperatures lower than 300 ℃. With increasing temperatures from 300 to 600 ℃, the strength decreased significantly while the conductivity increased considerably. At temperatures higher than 500 ℃, the second phase fibers were largely changed into equiaxial recrystallized grains. Liu et al. [11] produced in-situ Cu-14Fe with and without Ag composites by casting, cold deformation, intermediate and final heat treatments, and determined 1 h as the optimum final heat treatment time by the index Z combined strength and conductivity. The conductivity and strength of η = 7.8 in-situ composite with Ag reached 60.6 %IACS and 851 MPa, 58.9 %IACS and 931 MPa, 56.6 %IACS and 1033 MPa.

3. Conclusion
In-situ Cu-based composites have brought about extensive attention of researchers due to the good combination between electrical conductivity and tensile strength. A lot of research work has been done on the preparation technologies such as initial heat treatment, hot deformation, cold deformation, intermediate and final heat treatment, and considerable achievements have been made. However, many theoretical and application problems for in-situ Cu-based composites still need to be solved. The main research directions may be as follows.

(1) Exploring the manufacturing base of in-situ Cu-based composites to update the production technology.
(2) Investigating the influence factor of strength and conductivity to establish the preparation theoretical model for in-situ Cu-based composites.
(3) Combining the theoretical models and experimental results to develop advanced technologies industrially producing in-situ Cu-based composites.

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