Article ID: 1003－6326(2003)02－0307－04

Structures and properties of deformation-processed Cu-16Fe-2Cr in-situ composites①

SUN Shi-qing(孙世清)[1, 2], MAO Lei(毛 磊)[1], GUO Zhi-meng(郭志猛)[2], YIN Sheng(殷 声)[2]
(1. School of Materials Science and Engineering, Hebei University of Science and Technology,
Shijiazhuang 050054, China;
2. School of Materials Science and Engineering, University of Science and Technology Beijing,
Beijing 100083, China)

Abstract: Microstructure and properties of deformation-processed Cu-16Fe-2Cr and Cu-18Fe in-situ composite wires obtained by cold drawing combined with intermediate annealing were investigated. At lower strains($\eta < 2.52$), most of the Fe(Cr) phases were elongated into filaments except some remain granular because of their higher hardness. The ultimate tensile strengths of Cu-16Fe-2Cr and Cu-18Fe are approximately equal at the same drawing strains, suggesting the increase of strength of Cu-16Fe-2Cr due to higher strength of Fe(Cr) filaments than that of Fe filaments which is counteracted by the somewhat coarse Fe(Cr) filaments in Cu-16Fe-2Cr at the same drawing strains. The increase of the electrical conductivity of Cu-16Fe-2Cr and Cu-18Fe after intermediate annealing is attributed to the precipitation of Fe, Cr atoms, which dissolved during melting processing. Electrical conductivity of the Cu-16Fe-2Cr in-situ composites is higher than Cu-18Fe in-situ composites at the same drawing strains. The addition of Cr to Cu-Fe system can increase mechanical stability of the filaments in the composites.

Key words: in-situ composite; deformation processing; intermediate annealing; electrical conductivity; strength
CLC number: TB 323 **Document code:** A

1 INTRODUCTION

The Cu based in situ composites, which consist of Cu matrixs reinforced with bcc or fcc metals such as Nb[1-3], Ta[4], Cr[5-6], Fe[8, 9] and Ag[10, 11] have been developed to meet the increasing industrial requirements for materials with higher strength and higher electrical conductivity. These so called in situ composites are generally manufactured by vacuum casting or powder metallurgy followed by heavy cold drawing or rolling, and are superior to the artificial composites such as carbon filament reinforced copper composites due to their economic competitiveness and cold deformability.

The Cu-Fe system is of particular interest because of the relatively low cost of iron compared to the other possible insoluble bcc metals. However, the relatively high solubility of iron in copper at high temperatures in the Cu-Fe system, coupled with the slow kinetics of iron precipitation at low temperatures, is known to reduce the electrical conductivity[12]. For this reason, studies aimed at optimizing strength and conductivity have employed thermal/mechanical treatments[13].

While much attention was paid to the development and understanding of binary Cu-bcc and Cu-Ag alloys, less efforts were made to widen the spectrum of in situ composites towards ternary Cu based alloys. Some recent investigations aimed at filling this gap, for example, Raabe et al. on Cu-10%Cr-3%Ag alloys, and Verhoevrn et al. on Cu-15%Nb-2%Ag alloys[14]. Taking a practical perspective, the development of ternary Cu-based composites usually follows two criteria: first, further improving the physical properties of conventional binary alloys without severely deteriorating their mechanical properties; second, moving from binary alloy to ternary alloys for the sake of cost reduction. Adding a third element allow one to exploit a large variety of possible kinetic paths for attaining a certain flow stress-conductivity profile. In other words, the variation in possible thermo-mechanical treatment increases with the number of elements added.

In this study, the structure and property in thermo-mechanically processed Cu-Fe based in situ composites alloyed with the third alloying element such as Cr are examined. The primary purpose of this study is to investigate the effect of the third alloying element on the microstructure and properties of deformation processed Cu-Fe-Cr in situ composite wires.

2 EXPERIMENTAL

The Cu-18Fe and Cu-16Fe-2Cr alloys were pre-

---

① **Foundation item:** Project(598191) supported by Natural Science Foundation of Hebei Province, China
Received date: 2002－04－12; **Accepted date:** 2002－06－23

Correspondence: SUN Shi-qing, associate professor, doctor, E-mail: hbkdssq@163.com

pared by melting pure copper (99.98%, mass fraction), industrial pure Fe and pure Cr at about 1 500 ℃ in a vacuum induction furnace. The liquid alloy was held at this temperature for 10 min before being poured into a water-cooled steel mold in the vacuum furnace. Cylindrical billets obtained were about 80 mm in diameter and about 120 mm in length. Hot forging of cylindrical billets was carried out at 800 ℃, reducing the billets diameter from 80 mm to 30 mm. The forged rods had their rough surfaces machined off, and were then rod rolled to 12 mm in a series of steps and subsequently drawn into wires, using successively smaller dies, to a minimum diameter of 0.8 mm with intermediate annealing treatments at 450 ℃ and the cooling rate is 20 ℃/h. The cold drawing strain η after rod rolling is up to $\eta = 5.42$, where $\eta = \ln(A_0/A)$ and A_0 and A are the original and final cross sectional areas, respectively. The reduction in areas during cold drawing is 99.56%. Cu-18Fe ($\eta = 3.79$) and Cu-16Fe-2Cr ($\eta = 3.79$) wires were annealed at different temperatures (200～700 ℃) to evaluate mechanical stability of the filaments in the composites.

The evaluation of tensile mechanical properties of wires was carried out on a Instron-6027 machine using specially designed wire grips. All the tests were performed at room temperature using a cross-head speed of 1 mm/min. Electrical resistivity measurements were made using a standard four-probe technique.

The evolution of the microstructure was examined by optical microscope and transmission electron microscopy (TEM, H-800). The average size of Fe or Fe(Cr) particles was determined using an image analyzer.

3 RESULTS AND DISCUSSION

3.1 Microstructure

After hot forging, Fe or Fe(Cr) dendrites in the as-cast billets were in the form of particles. The average size of Fe phase and Fe(Cr) phase are 4.1 μm and 4.0 μm, respectively.

Fig. 1 shows optical micrographs of the as-drawn Cu-16Fe-2Cr in-situ composites at different strains. At lower strains ($\eta = 2.52$), most of the second phases have been elongated into filaments while some still remain granular because of their higher hardness. After heavily cold drawn, the alignment of the filaments with wire axis is readily apparent. The ribbon-like morphology of the filaments is evident on the transverse section (Fig. 1 (d)).

From the EDX analysis results, Cr atoms mostly dissolved in the filament and Cu matrix is almost free from Cr atoms. The Cr content in Fe phase is higher than that in the whole material (2%) because the chemical potential of Cr in Fe is larger than that of Fe in Cu. The higher content of Cr in Fe phase provides solid solution hardening to Fe fiber and changes the deformation behavior of Fe fiber.

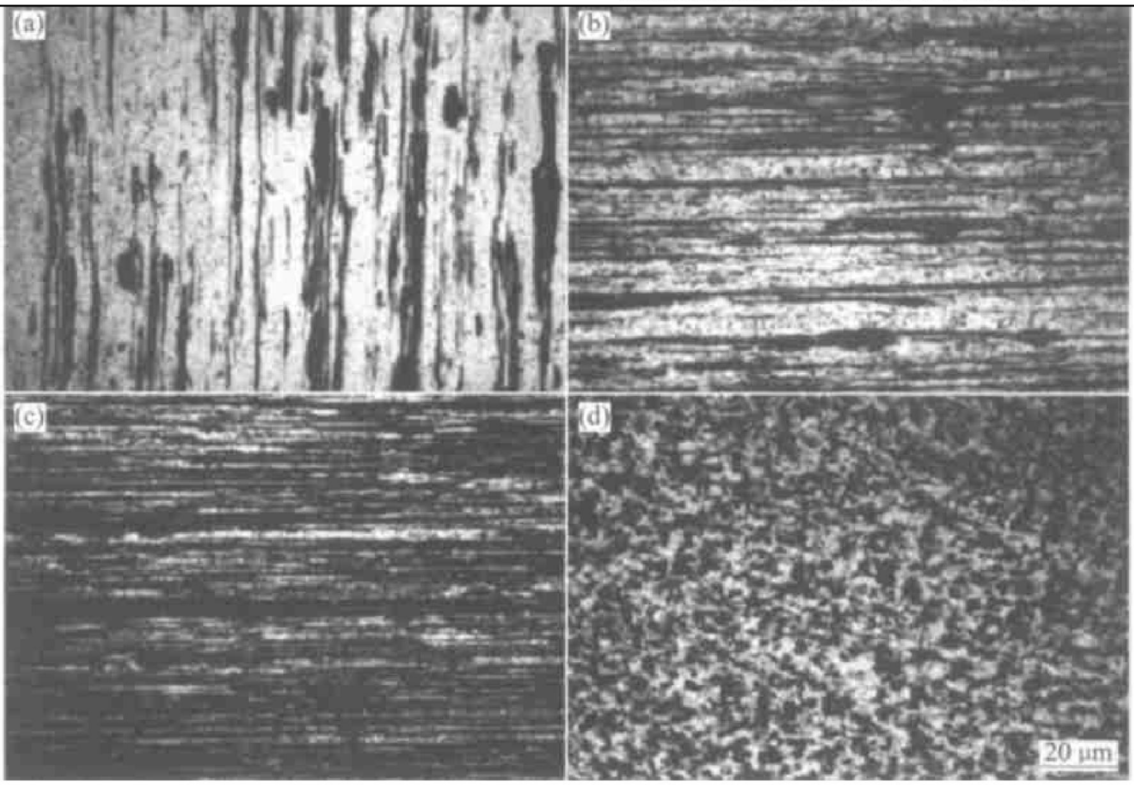

Fig. 1 Optical microstructures of longitudinal ((a), (b), (c)) and transverse ((d)) sections of Cu-16Fe-2Cr in-situ composites at different drawing strains

(a) —$\eta = 1.67$; (b) —$\eta = 2.52$; (c) —$\eta = 5.42$; (d) —$\eta = 3.79$

During drawing, the Cu matrix deform plastically first because of its lower flow stress, and then the stresses are transferred to the Fe phase or Fe(Cr) phase by the surrounding Cu. The flow stress of pour Cu without work hardening is too low to drive the Fe phase or Fe(Cr) phase deform plastically. However, the flow stress of the Cu matrix is increased by work hardening as a result of the heavy deformation. The Fe phase or Fe(Cr) phase is then forced to deform cooperatively with the Cu matrix by deforming on its slip planes {110}. Because of higher strength of Fe(Cr) phase than that of Fe phase, the refinement of filaments in Cu-16Fe-2Cr is relatively difficult, consistent with the somewhat coarse filaments in Cu-16Fe-2Cr at same drawing strains. At $\eta = 5.42$, the average width of Fe filaments and Fe(Cr) filaments are 182 nm and 262 nm, respectively.

Fig. 2 shows the TEM bright field image of Cu-16Fe-2Cr in situ composites ($\eta = 2.52$) after annealing at 450 ℃ for 3 h, Fe(Cr) precipitate phases were found in Cu matrix. The precipitation of impurities and alloying elements during intermediate annealing would increase the electrical conductivity due to the reduced impurity scattering[13]. The electrical conductivity of Cu-16Fe-2Cr in-situ composites ($\eta = 2.52$) before and after the annealing are 51.5%IACS and 55.8%IACS, respectively.

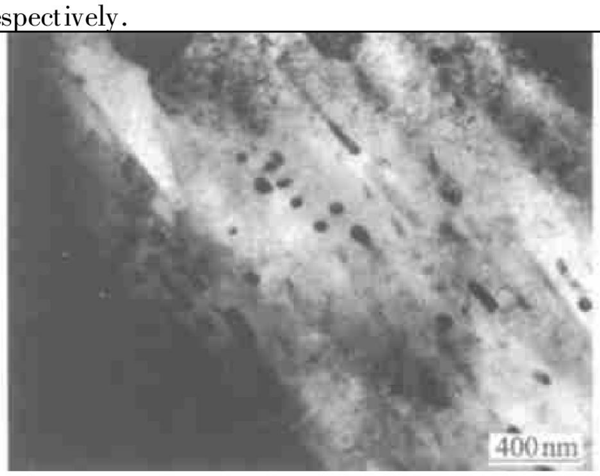

Fig. 2 TEM bright field image of Cu-16Fe-2Cr in-situ composites ($\eta = 2.52$) after annealing at 450 ℃

3.2 Strength and electrical conductivity

Fig. 3 shows the effect of drawing strain (η) on the ultimate tensile strength of Cu-18Fe and Cu-16Fe-2Cr, it can be seen that the results for Cu-18Fe and Cu-16Fe-2Cr are quite similar. The increase of strength of Cu-16Fe-2Cr due to higher strength of Fe(Cr) filaments than that of Fe filaments is counteracted by the somewhat coarse filaments in Cu-16Fe-2Cr at the same drawing strains.

The effect of drawing strain (η) on the electrical conductivity of Cu-18Fe and Cu-16Fe-2Cr is shown in Fig. 4. The electrical conductivity of Cu-16Fe-2Cr is higher than that of Cu-18Fe at the same drawing strains. The addition of Cr to Cu-Fe system is known to limit the liquid solubility of iron in copper, making it to have better electrical conductivity.

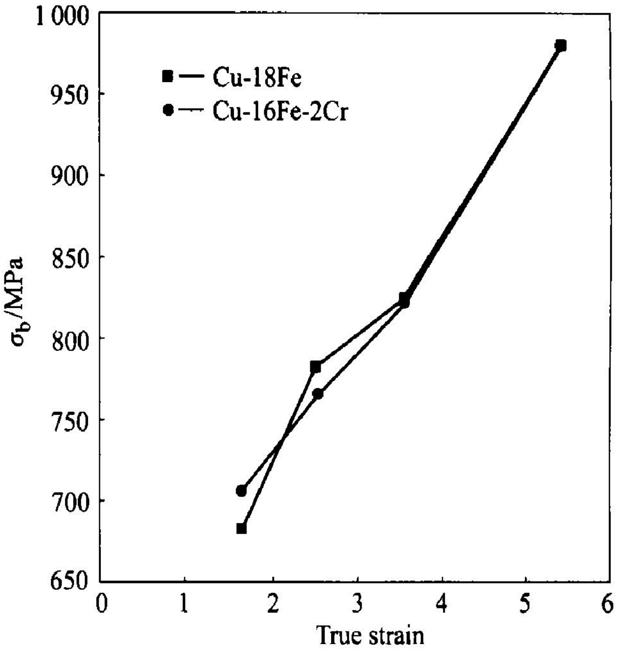

Fig. 3 Effect of drawing strain on ultimate tensile strength of Cu-18Fe and Cu-16Fe-2Cr

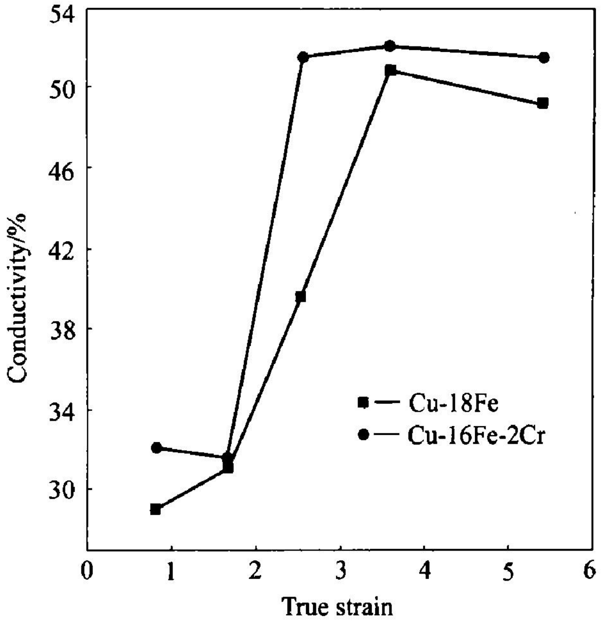

Fig. 4 Effect of drawing strain on electrical conductivity of Cu-18Fe and Cu-16Fe-2Cr

Fig. 5 shows the effect of annealing at different temperatures on the ultimate tensile strength of Cu-18Fe and Cu-16Fe-2Cr ($\eta = 3.79$). The ultimate tensile strength of Cu-16Fe-2Cr is always higher than that of Cu-18Fe after the same annealing below about 500 ℃. After annealing at 700 ℃, the ultimate tensile strength of them are roughly equal. The addition of Cr to Cu-Fe system can increase

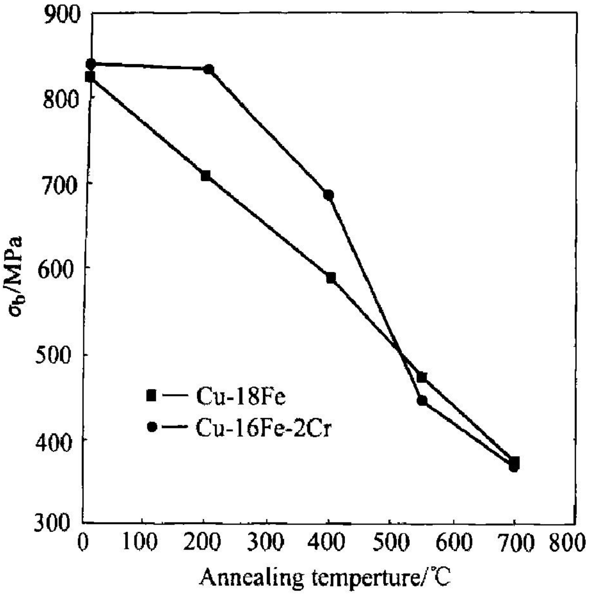

Fig. 5 Effect of annealing on ultimate tensile strength of Cu-18Fe and Cu-16Fe-2Cr

mechanical stability of the filaments in the composites.

4 CONCLUSIONS

1) At lower strains ($\eta < 2.52$), most of the Fe (Cr) phases in Cu-16Fe-2Cr have been elongated into filaments while some of them still remain granular because of their higher hardness. The filament is strengthened by the addition of Cr atoms. The refinement of filaments in Cu-16Fe-2Cr is relatively difficult, consistent with the somewhat coarse filaments in Cu-16Fe-2Cr at the same drawing strains.

2) The electrical conductivity of Cu-16Fe-2Cr is higher than that of Cu-18Fe at the same drawing strains. The precipitation of impurities and alloying elements in Cu-16Fe-2Cr during intermediate annealing would increase the conductivity due to the reduced impurity scattering.

3) The increase of strength of Cu-16Fe-2Cr due to higher strength of Fe(Cr) filaments than that of Fe filaments in Cu-18Fe is counteracted by the somewhat coarse filaments in Cu-16Fe-2Cr at the same drawing strains.

4) The ultimate tensile strength of Cu-16Fe-2Cr is higher than that of Cu-18Fe after same annealing (< 500 ℃). The addition of Cr to Cu-Fe system can increase mechanical stability of the filaments in the composites.

REFERENCES

[1] Verhoeven J D, Chumbley L S, Laabs F C, et al. Measurement of filament spacing in deformation processed Cu-Nb alloys[J]. Acta Metal Mater, 1991, 39(11): 2825-2834.

[2] Trybus C L, Spitzig W A. Characterization of the strength and microstructural evolution of a heavily cold rolling Cu-20% Nb composite[J]. Acta Metall, 1989, 37(7): 1971-1981.

[3] Spitzig W A. Strengthening in heavily deformation processed Cu-20% Nb composite[J]. Acta Metall Mater, 1991, 39(6): 1085-1090.

[4] Spitzig W A, Krotz P D. Comparison of the strength and microstructure of Cu-20% Ta and Cu-20% Nb in-situ composites[J]. Acta Metall, 1988, 36(7): 1709-1715.

[5] SUN Shou-jin. Structures and residual stresses of Cr filaments in Cu-15Cr in-situ composites[J]. Metallurgical and Materials Transactions A, 2001, 32A(5): 1225-1232.

[6] Jin Y, Adachi K, Takeuchi T, et al. Correlation between the cold-working and aging treatments in a Cu-15Wt Pct Cr in-situ composite[J]. Metallurgical and Materials Transactions A, 1998, 29A: 2195-2203.

[7] Ellis T W, Kim S T, Verhoeven J D. Deformation-processed copper-chromium alloys: role of age hardening [J]. J Mater Eng Perform, 1995, 4: 581-586.

[8] Jerman G A, Anderson I E, Verhoeven J D. Strength and electrical conductivity of deformation processed Cu-15% Fe alloys produced by powder metallurgy techniques [J]. Metall Trans A, 1993, 24A: 35-42.

[9] Biselli C, Morris D G. Microstructure and strength of Cu-Fe in-situ composites after very high drawing strains [J]. Acta Mater, 1996, 44(2): 493-504.

[10] Sakai Y, Schneider-Muntau H J. Ultra-high strength, high conductivity Cu-Ag alloy wires[J]. Acta Mater, 1997, 45: 1017-1023.

[11] Hong S I, Hill M A. Microstructural stability and mechanical response of Cu-Ag microcomposite wires[J]. Acta Mater, 1998, 46(12): 4111-4122.

[12] Go Y S, Spitzig W A. Strengthening in deformation-processed Cu-20% Fe composites[J]. J Mater Sci, 1991, 26(1): 163-171.

[13] Verhoeven J D, Chueh S C, Gibson E D. Strength and conductivity of in-situ Cu-Fe alloys[J]. J Mater Sci, 1989, 24(5): 1749-1752.

[14] Raabe D, Miyake K, Takahara H. Processing, microstructure, and properties of ternary high-strength Cu-Cr-Ag in-situ composites[J]. Mater Sci Eng, 2000, A291(1): 186-197.

(Edited by LONG Huai-zhong)