Higher tensile strength and higher conductivity in-situ deformation composite of Copper-steel

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Conductive wire with higher tensile strength was produced by in-situ deformation of copper-steel alloy. The alloy contains 11.5 wt % of low carbon steel and was cast to ingot in a vacuum inductive melting furnace. The ingot was forged to rod which then underwent multi-cold-drawing into fine electrical wire. The maximum tensile strength of the wire is 862 MPa with an electrical conductivity of 42.33 % IACS when the cold-drawing strain (η) is 6.31.

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1. Introduction

With the fast development of electronic information technology, it requires material with higher tensile strength and higher conductivity. Copper-matrix composites (CMC) have been studied by more and more researchers. Some elements such as Ag, Cd, As were alloyed with pure copper in the sixties of the 20th century. These kinds of wires were usually of conductivity >90% IACS and lower tensile strength. The tensile strength of copper-matrix composite was significantly enforced by deformation combining with alloy strengthening phases in the last seventies. Afterwards, researches focused on adding elements to lower cost and protecting environment.

In the present paper, the manufacturing process of copper-matrix composite is investigated. The tensile strength and conductivity as a function of strain during cold wire drawing are studied.

2. Test materials and experimental methods

The raw materials used in this work were T2 copper and mild steel wire with 0.20%C. The T2 copper is the "tough pitch" copper which contains less than 0.04% of oxygen, wildly used in applications requiring maximum electrical conductivity. The mild steel possesses good plasticity and higher strength than pure iron. The percentage of mild steel in the total alloy weight was 11.5%. The chemical composition of T2 copper is shown in Table 1.

Table. 1. Chemical compositions of T2 copper / (wt %).

Cu	Bi	As	Pb	Fe	S	Others
99.92	<0.001	<0.002	<0.002	<0.005	<0.004	0.1

The copper and low carbon steel wire was put together in a vacuum inductive melting furnace. They were melted and homogenized with magnetic force, and then cast to a cylindrical ingot followed by cooling to room temperature in the vacuum furnace.

The cylindrical ingot was forged to rod of 23 mm in diameter and then underwent multi-cold-drawing.

In order to investigate effects of plastic deformation and intermediate annealing treatment on tensile strength and conductivity, cold drawings of the composite wire were performed in two modes: one was multi-cold-drawing without intermediate annealing and the other was multi-cold-drawing with an intermediate annealing at 670℃ for 1 hour. In both cases, the final wire diameter after cold drawing was 0.98 mm. The amount of plastic strain the wires underwent after cold drawing is expressed by cold-drawing strain η ($\eta=\ln(A_0/A_f)$, where A_0 and A_f are the initial and final cross-sectional areas respectively)

Changes in microscopic structure of the drawn wires were examined by optical microscope and scanning electron microscope (SEM), and the phase composition of the copper-steel composite was determined by X-ray diffractometer. The ultimate tensile strength of the composite wire at room temperature was measured by an 880 Material Test System. The cross head speed was 1.5 mm/min through out the test. The electrical conductivity of the composite wire was measured by electric double bridges.

3. Results and discussion

Microstructure of the alloy ingot after forging is shown in Fig. 1. It can be seen from Fig. 1 that the composite alloy is microstructurally characterized by the dark grey constituent distributing in the grey matrix.

To identify the phase composition of the composite wire, a sample of 13 mm in diameter was cut from the drawn wire and was solid-solution treated for the X-ray examination. Fig. 2 is the X-ray diffraction diagram of the sample, which shows that there are Cu and α-Fe phases in the composite rod.

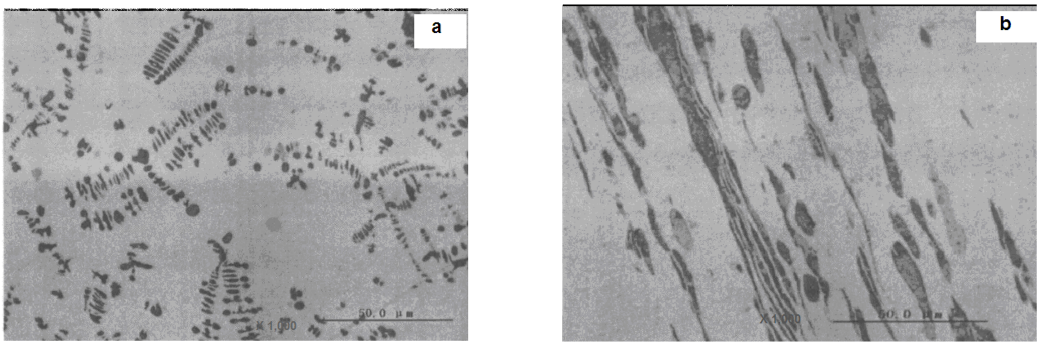

Fig. 1. Optical micrographs of the composite after forging, (a) Cross-section, (b) Longitudinal-section.

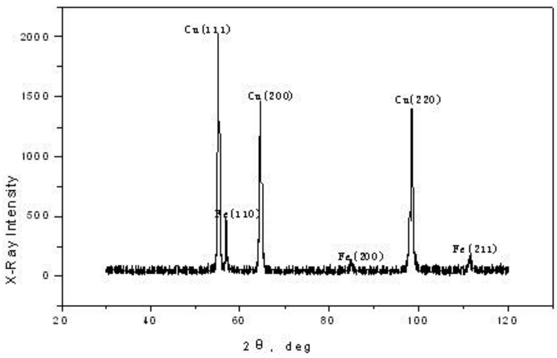

Fig. 2. X-Ray diffraction profile of the composite alloy.

As the composite rod is composed of only two phases and the raw materials used in making the composite were copper in primary and mild steel in supplement, it can be determined from the X-ray analysis that the dark grey constituent in Fig. 1 is α-Fe and the grey matrix Cu.

It can also be seen from Fig. 1 that though α-Fe is elongated in the direction of forging, dendritic α-Fe is still obvious in the cross-section direction of the forged rod.

The elongated α-Fe becomes thinner and thinner as drawing continues, and the space between linear α-Fe becomes shorter and shorter, as shown in Fig. 3.

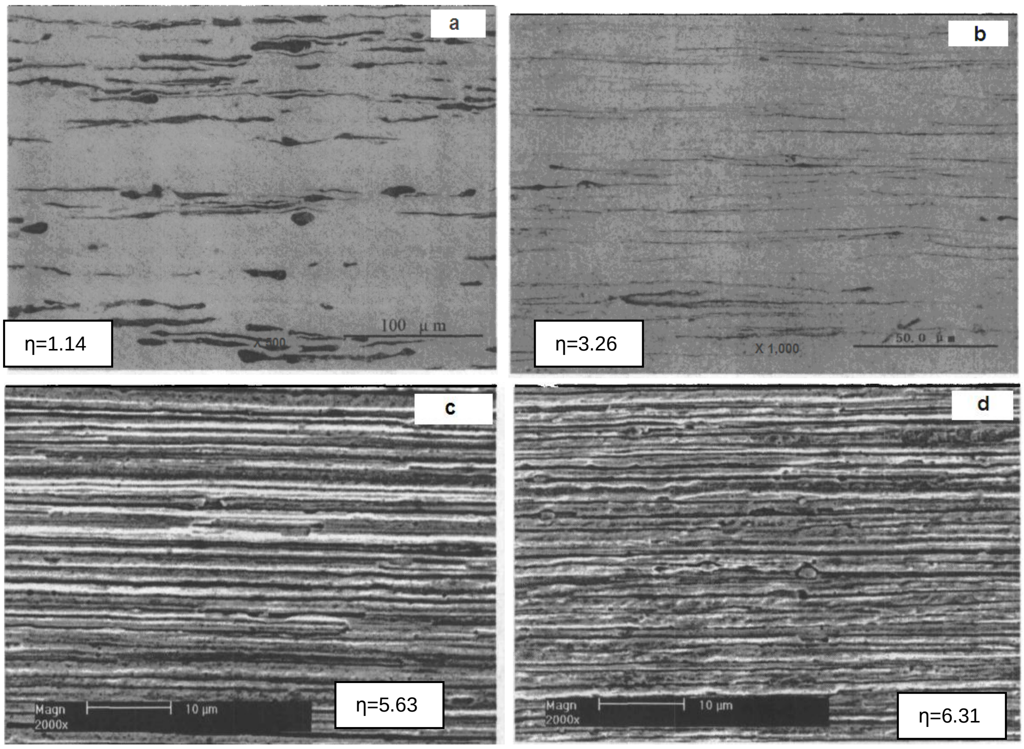

Fig. 3. Micrograph changes of composite as drawing strain increases, (a) and (b) under optical microscope, (c) and (d) under SEM.

To clearly understand the strengthening effects of steel fiber, the composite material was drawn to as thin as 0.98 mm in diameter in different drawing processes. The tensile strengths of composite material are shown in Table 2. It can be seen from Table 2 that the composite wire has the maximum tensile strength of 862.22 MPa when drawn without intermediate annealing. The tensile strength of the composite material is attributed to hard-working of the matrix and second fibrous strengthening phase. The smaller of the spacing between the steel fibers, the greater of the tensile strength of the composite wire1 according to the Hall-Petch relationship.

Table. 2. Tensile strength of 0.98mm diameter composite materials produced by different processes.

Processes	No intermediate annealing	Intermediate annealed when η=3.26	Intermediate annealed when η=4.31	Intermediate annealed when η=4.88
Tensile strength(Mpa)	862.22	852.1	823.76	755.62

Intermediate annealing at 670 ℃ for 1h, while improving deformation performance, removes hard working from cold drawing, and results in tensile strength decrease, as shown in Table 2.

Commercial electrical copper wire 0.98 mm in diameter was also measured for tensile strength and the result is 338.78 MPa. The difference in tensile strength for these two kinds of wires is obvious, although they were not in the same condition. It was also noted that Ge et al2 reported that the tensile strength of a composite wire of copper with pure iron fiber produced by the same method as used in the present study is 630 Mpa. It is believed that the steel fibers in the copper matrix have stronger effect in strengthening the composite than iron fibers do.

The conductivity of the composite material 0.98 mm in diameter produced by different processes is shown in Table 3. The composite wire which has the highest tensile strength via directly drawn process has the lowest conductivity. In other words, the conductivity of the composite wires can be improved by intermediate annealing at 670℃×1h. Verhoevenl3 and Heringhaus4 demonstrated that the decrement in resistivity of heavily drawn wire when heat treated with annealing is due mainly to second filament phase coarsening which reduces interface scattering.

Table 3. Conductivities of composite material 0.98mm in diameter produced in different processes.

Processes	No intermediate annealing	Intermediate annealed when η=3.26	Intermediate annealed when η=4.31	Intermediate annealed when η=4.88
%IACS	42.33	52.39	53.06	57.86

4. Conclusions

Composite wire with copper matrix strengthened with steel fiber can be produced by heavy drawing of copper-steel alloy. Cold drawing without intermediate heat treatment can obtain the maximum tensile strength. Intermediate heat treatment can improve the conductivity of the composite wire while decreases strength, and can be used to adjust strength and conductivity for practical applications.

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References

[1] S. I. Hongs, M. A. Hillb, Acta Materialia. **46**, 4111 (1998).
[2] Ji-Ping Ge, Zai-Qi Yao, Chinese Journal of Nonferrous Metals. **14**, 568 (2004).
[3] J. D. Verhoeven, H. L. Downing, L. S. Chumbley, E. D. Gibson, J. Appl. Phys. **65**, 1293 (1989).
[4] Frank Heringhaus, Hans-Jörg Schneider-Muntau, Günter Gottstein, Mater. Sci. and Eng. **A347**, 9 (2003).

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