Effect of pulse magnetic field on solidification structure and properties of pure copper

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Abstract: The application of pulse magnetic field to metal solidification is an advanced technique which can remarkably refine solidification structure. In this paper, the effect of pulse magnetic field on solidification structure, mechanical properties and conductivity of pure copper was experimentally investigated. The results showed that the solidification structure transformed from coarse columnar crystal to fine globular crystal with increasing pulse voltage. Increasing pulse voltage also improved the tensile strength. However, with the increase of pulse voltage, the elongation and electrical resistivity firstly decreased, then increased when the pulse voltage beyond a critical value. Moreover, in some conditions, pulse magnetic field can simultaneously improve the conductivity and mechanical property of pure copper.

Key words: pure copper; pulse magnetic field; solidification structure; property

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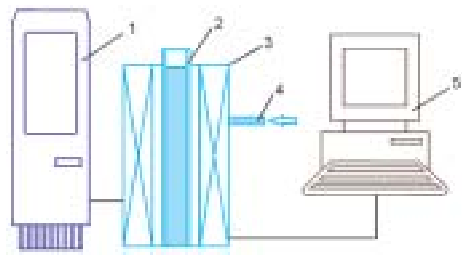
Copper is a critical material for electric cable, whose structure and properties are hard to meet the demands and requirements of practical applications with the rapid development of power industry [1]. How to synchronously improve its conductivity and mechanical properties is an important research field [1]. At present, adding rare-earth [2, 3] and micro-alloying [4, 5] are two main methods to improve solidification structure of copper for obtaining better conductivity and mechanical properties. However, the rare-earth elements cannot significantly improve conductivity and mechanical properties, and cannot synchronously get a better combination of conductivity and mechanical properties [3, 6, 7]. Although micro-alloying can significantly enhance mechanical properties of copper, this approach causes the decrease in conductivity [8]. The application of pulse magnetic field to solidification process of metal is a new advanced technique, which can remarkably refine solidification structure without contamination [9-13]. Therefore, it has potential applications to improve conductivity and mechanical properties of pure copper. In this paper, the effect of pulse magnetic field on solidification structure, mechanical property and conductivity of copper was investigated.

1 Experimental procedure

The pure copper (99.99%) was melted in a medium-frequency induction furnace and superheated to 1 573 K under charcoal cover on its surface. CaB_6 was added for degassing, and then the melt was poured into moulds in size of Φ 30 mm × 180 mm. The experimental apparatus is shown in Fig. 1.



1. Pulse magnetic power supply; 2. Mould; 3. Magnetic field generator; 4. Coolant; 5. Temperature measuring system

Fig. 1 Sketch of experimental apparatus

The samples solidified under different densities of pulse magnetic field were cut along transverse cross-section at the same position, and then they were polished and etched for metallographic examination. The etching reagent was the mixture of $FeCl_3$, HCl and H_2O with ratio of 1:2:20. The cast samples were rolled into wire with diameter of 2 mm. The tensile strength, elongation and resistivity were measured by Chinese National Center of Analysis and Testing for Non-ferrous Melts according to the Chinese National Standards "GB/T228-2002 and GB/T3048-1994".

2 Results and analysis

2.1 Structure

The microstructures of copper with different pulse voltages are

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shown in Fig. 2. Figure 2 (a) is the solidification structure without pulse magnetic field. The solidification structures under different voltages of the pulse magnetic field are presented in Figs. 2(b)-(e). Results indicate that with the increase of voltage, the solidification structure transformed gradually from coarse columnar crystal to fine globular crystal.

Because of the skin effect of high-frequency pulse magnetic field, the induction current is mainly through the sample's outer portion. The skin depth δ can be expressed as:

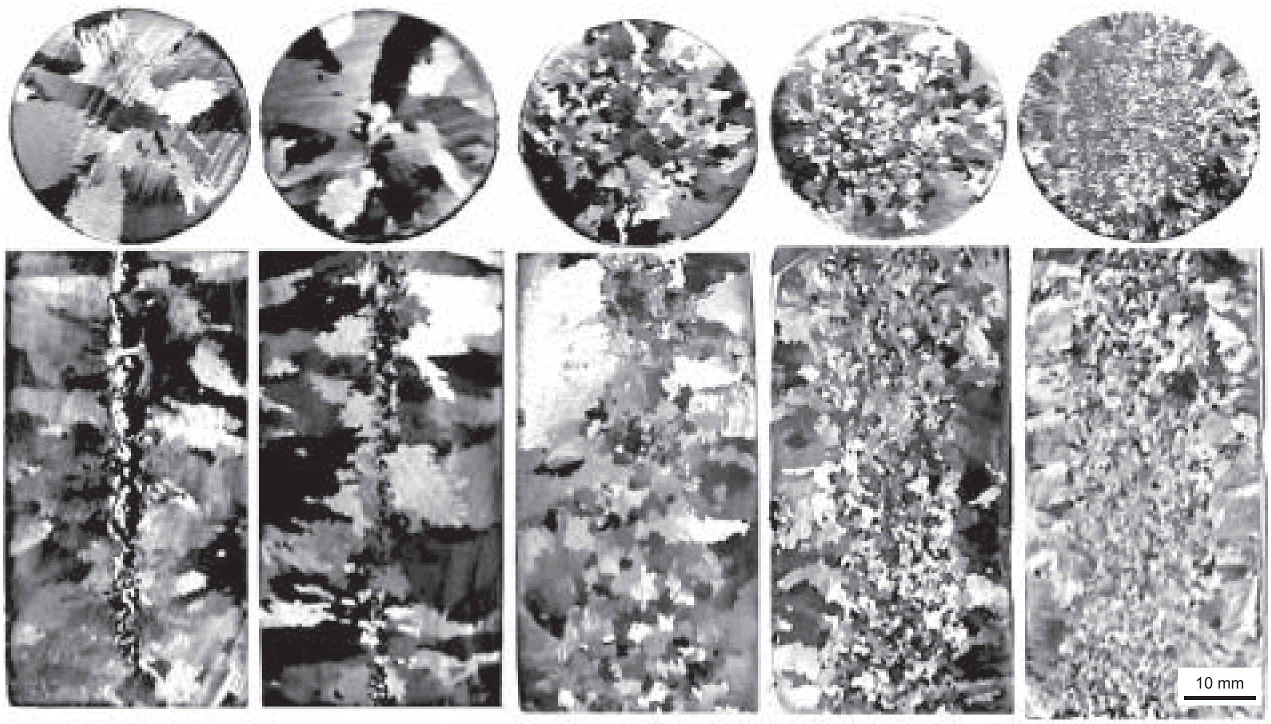
$$\delta = (\pi\sigma\mu f)^{-\frac{1}{2}} \quad (1)$$

Where μ is the magnetic permeability, σ the electric conductivity and f the frequency of the pulse magnetic field. According to the experiment parameters, the calculated skin depth is about 3 mm. This pulse magnetic field and induction current can give rise to Lorentz force along the radial direction:

$$f = J \times B \quad (2)$$

Where, J is induction current density and B the pulse magnetic field strength.

When liquid metal was poured into the mould, the nucleation firstly occurs near the mould wall. The nuclei are broken up into more small fragments from the mold wall and dissociated into the melt due to convection caused by pulse magnetic pressure. This course lasts until formation of the solidification shell near the mould wall, which substantially increases the number of nuclei and suppresses the formation of columnar crystal. Figure 2 shows that the size of columnar crystal in casting samples gradually decreases with increase of the pulse voltage. This indicates that the nucleus density increases with the increase of the Lorentz force.



(a) 0 V (b) 1 000 V (c) 2 000 V (d) 3 000 V (e) 4 800 V

Fig. 2 Effect of pulse magnetic field on solidification structure of pure copper

2.2 Mechanical properties

Figures 3 and 4 show the effect of pulse magnetic field on the tensile strength and elongation of pure copper, respectively. The findings reveal that with increase of the pulse voltage, the tensile strength increases monotonously, but the elongation firstly decreases, and then increases when the voltage surpasses some critical value.

The refinement of solidification structure makes grain boundary increase significantly, which helps to block dislocation movement. On the other hand, increase in grain boundary also promotes the lattice distortion. Both factors contribute to the enhancement of tensile strength. The elongation level of pure copper firstly decreases with the increasing of voltage of pulse magnetic field. However, the elongation turned into an increasing

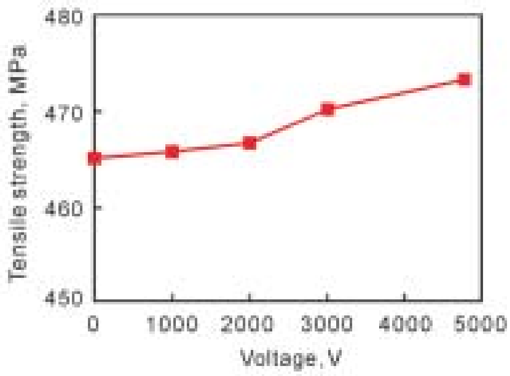


Fig. 3 Effect of pulse magnetic field on tensile strength of pure copper

mode when the voltage is above 3 000 V. The reason for this phenomenon is that deformation is related to dislocation movement. Finer grains make the grain boundaries increase, which will block dislocation movement. Therefore, the deformation ability decreases. But when the grain size further decreases, deformation will be dispersed to more grains, and homogeneous deformation avoids local stress concentration in the sample with finer grain. This action becomes dominant in the sample with refined grains, which leads to increase of the elongation.

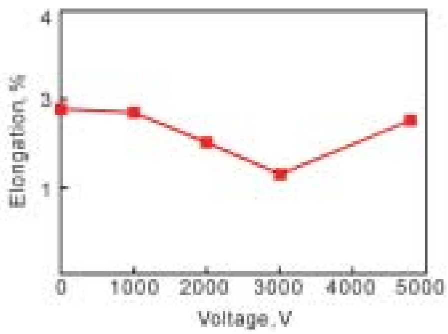


Fig. 4 Effect of pulse magnetic field on the elongation of pure copper

2.3 Conductivity

Figure 5 shows the effect of pulse magnetic field on conductivity of pure copper. It can be seen that the electrical resistivity firstly decreases, and then increases with the increasing of pulse voltage. When the voltage is above 4 800 V, the electrical resistivity is more than that of the samples without pulse magnetic field. This suggests that beyond a critical value, the pulse magnetic field cannot make the electrical resistivity decrease any more.

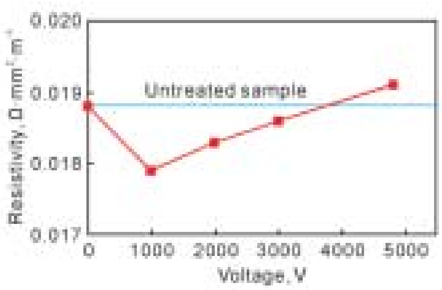


Fig. 5 Effect of pulse magnetic field on resistivity of pure copper

According to electrical conduction theory of metal, charge carriers are free electrons. If metal is ideal crystal, the electronic motions do not suffer from encumbrance, and no electrons scattering. The Lattice vibration (phonon), defects (vacancy, interstitial atom, dislocation and grain boundary) and inclusions are the factors destroying lattice periodicity, which are reasons for creating electrical resistibility of metal crystal. According to the Matthiessen Rule, the resistivity of crystal is the sum of resistivity of these factors, which is expressed as:

$$\rho = \rho' + \rho'' + \rho(T) \qquad (3)$$

Where, $\rho(T)$ is the resistivity caused by lattice vibration (which is related with temperature), ρ' , ρ'' are the resistibility caused by defects and inclusions, respectively.

All measurement temperatures of the samples are constant when they are measured. Therefore, resistivity difference of the samples should be caused only by defects and inclusions.

Analysis results suggest that there should be two opposite factors affecting the resistivity of pure copper. Pulse magnetic field may decrease the resistivity of every grain because it makes crystal orientation favor electric conduction of pure copper. This factor is dominant when the grain is larger, thus the resistivity of pure copper decreases. On the other hand, the grain boundaries increase electrical resistivity. The grain boundary gradually becomes the dominant factor with the increase of grain density. These two factors determined the effect of pulse magnetic field on resistivity of pure copper as shown in Fig.5. But the electrical resistivity of pure copper with pulse voltage in the range of 1 000 V to 3 000 V is lower than that of the samples without pulse magnetic field (Fig.5). Only when the pulse voltage is beyond 4 000 V, the resistivity becomes higher than that of the samples without pulse magnetic field.

3 Conclusions

(1) The pulse magnetic field can significantly refine the solidification structure of copper. The solidification structure transforms from coarse columnar crystal to fine globular crystal with increasing pulse voltage. Increasing pulse voltage improves the tensile strength. However, with the increase of pulse voltage, the elongation and electrical resistivity firstly decreases, then increases when the pulse voltage surpasses a critical value.

(2) In some conditions, the pulse magnetic field can synchronously improve the conductivity and mechanical property of pure copper.

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