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The influence of power spinning and annealing temperature on microstructures and properties of Cu-Sn alloy

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ABSTRACT

Electron back scatter diffraction pattern (EBSD), metallographic microscope (OM) and transmission electron microscope (TEM) are used to analyze the microstructural state of the Cu-Sn alloy before and after power spinning and annealing. The results show that after power spinning, the α phase grains are refined and gradually evolve into small and fine α_{II} and deformed α_{III} crystal grains, with an average grain size of about 2.2 μm. Work hardening results in massive network-like subgrain boundaries distributed in power spinning microstructure. Annealing at 400 °C contributes to the formation of dislocation cells and stacking faults, and high-angle grain boundaries (HABS) start to migrate and slide. After the formation of less defective equiaxed grains at 500 °C, twins continue to grow and widen based through continuous accumulation of stacking faults. Further testing of mechanical properties reveals that power spinning is conducive to the improvement of mechanical properties of Cu-Sn alloy.

1. Introduction

Tin bronze is a type of complex Cu-Sn alloy by introducing a proper amount of P, Fe, Ni and other alloying elements [1]. Due to high ductility, corrosion resistance, fatigue strength, and good cold processing performance, tin bronze is widely used in manufacturing connecting rod bushings, sliding bearings and other parts after plastic processing [2–4]. Power spinning is an advanced modern processing technology to manufacture thin-walled tubular workpieces, which combines the deformation characteristics of forging, drawing, extrusion, and rolling. Due to high production efficiency and low material utilization ratio as well as low forming load, power spinning exhibits significant environmental and economic advantages over traditional plastic processing methods, such as forging and extrusion [5–7]. The Cu-Sn alloy tube workpieces that undergo power spinning can be significantly strengthened, thus exhibiting better anti-fatigue performance and load-bearing capacity. The as-spun tube workpieces are critical parts that connect the small end of engine connecting rods and piston pins, widely used in engine bearings [8]. However, as power spinning utilizes cold deformation to realize the strengthening effect, there are non-uniform microstructural distribution and high stress concentration within the tin bronze parts, frequently causing failures and deformation in Cu-Sn alloy engine bearings. Therefore, post-annealing treatment is required to improve the microstructure uniformity and enhance the mechanical property of as-spun workpieces. Currently, the microstructure evolution of Cu-Sn alloys after power spinning and annealing is less studied, which limits the application of as-spun Cu-Sn alloy workpieces. This study aiming at analyzing the evolution of microstructure and mechanical property of Cu-Sn alloy under power spinning and annealing. Through investigating the transformation and distribution of microstructures (crystal grains, grain boundaries) of Cu-Sn alloy, the deformation mechanism and microstructural evolution of this alloy under power spinning and different annealing conditions are analyzed, which is helpful for broadening the industrial application of as-spun workpieces of Cu-Sn alloy.

2. Experimental Procedures

The composition of the Cu-Sn alloy used in this study is shown in Table 1. The initial tube blanks for power spinning are formed by sheet

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Table 1
Chemical components of Cu-Sn alloy (wt%).

Sn	Al	Zn	Ni	Fe	Pb	P	Cu
6.5	< 0.002	< 0.1	0.087	< 0.01	< 0.01	0.17	Bal

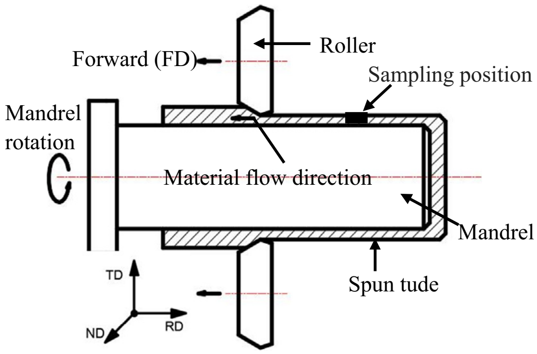

Fig. 1. Schematic diagram of spinning tubular Cu-Sn alloy parts.

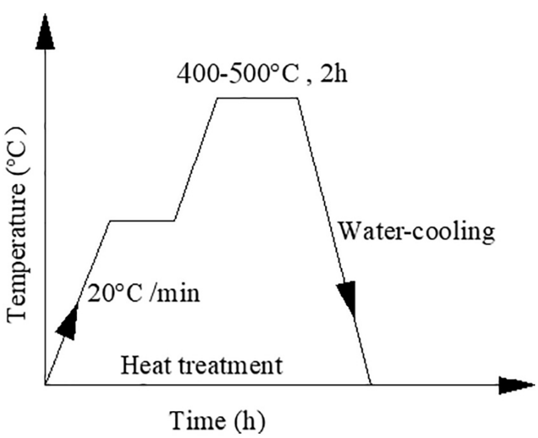

Fig. 2. Flow chart of post-spinning heat treatment of Cu-Sn alloy tube workpiece.

drawing. The schematic diagram of power spinning is shown in Fig. 1. Considering the spinning process and phase transformation of the Cu-Sn alloy, the cold spinning parameters are selected as follows: thinning rate $e = 35\%$, feed ratio $f = 0.8$ mm/r. After power spinning, the specimens are heated to 400 °C–500 °C at a speed of 20 °C/min and kept to the temperature for 2 h. Finally, the specimens are water cooled to retain high temperature microstructures. The details of this process are shown in Fig. 2.

For the EBSD test, the as-spun specimens are wire cut to 5 × 5 × 1 mm. The specimens should be electropolished because the electronic information used in the EBSD analysis is usually collected from a 50 nm thick layer on the specimen surface. The electropolishing process is carried out in the solution consisting of 70% phosphoric acid and 30% distilled water at a temperature of −15 °C and a voltage of 12 V. The EBSD test is conducted on a Hitachi S-3400 N scanning electron microscope equipped with an HKL-EBSD system. The metallographic observation is performed on a LEICA DM4000 optical microscope. The phases in the specimens are identified by X-ray diffraction (XRD) tests. The tensile tests are conducted on a CMT-5105 at room temperature in order to obtain the yield strength (YS), tensile strength (TS), elongation of as-spun specimens. Each test is repeated 3 times to obtain credible and reproducible results. The hardness of the specimens is measured on a HTV-PHS30 Vickers hardness tester. The transmission electron microscope (TEM) was performed on before and after power spinning and annealing samples using a JEOL 3100 TEM operated at 300 kV. The TEM specimens are prepared as follows: First, the electrical discharge machining (EDM) is used to cut out slices of 0.5 mm thickness; Second, the SiC sandpapers dipped in water are used to grind the slices to 40 μm thick; Finally, the slices are subsequently cut into round patches of 3 mm diameter and thinned by an MTP-1 twin-jetting thinning instrument to form the sliced specimens for TEM observation.

3. Results and Discussion

3.1. Microstructures Before and After Power Spinning and Annealing

Usually, great thinning rate induces large deformation during power spinning, which requires that the processed Cu-Sn alloy has good plasticity and low hardness. Previous studies [9,10] indicates that extruded thick-walled tubular blank of Cu-Sn alloy consists of α single phase microstructure, which features equiaxed recrystallization grains and large amounts of twins, as shown in Fig. 3(a).

After power spinning, the microstructure of tubular parts changes dramatically. The images of diffraction contrast obtained via EBSD test clearly display the changes of crystal grains. As shown in Fig. 3(b), the α-phase grains preferentially deflect and elongate along the RD direction, and become thinner along the ND direction. A large number of newly formed fine α_{II} phase grains are distributed at α_{III} grain boundaries, exhibiting a typical "necklace" structure. The fibrous microstructures are formed along α_{III} grains and nearly distributed in the same one direction. Fig. 3(c) is an enlarged view of as-spun microstructure. Amounts of slip bands appear inside the α_{III} grains after power spinning. Interestingly, although α_{III} phase grains are elongated along the RD direction, slip bands inside deformed crystal grains nearly form a 45° angle with the ND direction. This is because the rollers do not only radially compress the grains in the deformation zone, but squeeze them basically along the feeding direction as well as in a certain angle with the radial direction, resulting in the formation of slip bands within the grains, as shown by the black arrows in the Fig. 3(c). This reveals that slip is the primary factor for the formation of α_{III} phase grains. After power spinning, the tubular workpiece is annealed at 400 °C–500 °C for 2 h. It is found that twins and equiaxed α_{IV} crystal grains dominate the microstructures, as shown in Fig. 4.

Fig. 5 shows metallographic microstructures under different conditions, which is more macroscopic compared to Figs. 3 and 4. It can be seen that the equiaxed grains with amounts of twins are refined evidently after power spinning (Fig. 5a and b). After annealing at 400 °C, the grain sizes are relatively uniform, as shown in Fig. 5(c). After annealing at 500 °C, there is obvious static recrystallization that features coarsening grains and evident twins (Fig. 5d).

Fig. 6 shows the average grain size and length-to-diameter ratio of the Cu-Sn alloy under different conditions. It can be observed that the equiaxed α-phase grains are clearly refined after power spinning, and the grain size of $\alpha_{II} + \alpha_{III}$ crystal grains is approximately 2.2 μm, much smaller than the original 9.6 μm. The significant decrease in the average grain size mainly results from the formation of small-size α_{II} crystal grains from broken and refined crystal grains and fibrous α_{III} grains.