Short Communication

Improving bending property of copper foil by the combination of double-rolling and cross rolling

Jingkun Li\textsuperscript{a}, Xueping Ren\textsuperscript{a,}\textsuperscript{*,} Zi Ling \textsuperscript{b}, Haibo Wang\textsuperscript{a}

\textsuperscript{a} School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing, 100083, China
\textsuperscript{b} Chinese Academy of Agricultural Mechanization Sciences, Beijing, 100083, China

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\textbf{ABSTRACT}

Copper foils with excellent bending property were fabricated by double-rolling followed by cross rolling. The deformation characteristics of the two advanced rolling processes introduce high density of grain boundaries and dislocations in copper foils. Due to high densities of grain boundaries, dislocations and strong single texture, bending cracks are fine and dispersive, a 101.0% improvement of the bending fatigue life compared to copper foils fabricated by conventional rolling process. After bending fracture, concentrated dislocation and fine dispersive cracks can be observed.

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1. Introduction

Rolled copper foils have attracted much attention in the past decade due to advantages of excellent ductility, corrosion resistance, favorable electrical conductivity and outstanding bending property [1–4]. Excellent bending resistance is one of the important properties of the copper foils, which is also the key factor to achieve a wide application [5]. However, optimization of these copper foils is challenging resulting from their limited bending fatigue life.

Studies on bending property showed that finer grain size and strong single texture contribute to improving bending properties [6–8]. To utilize such beneficial microstructures, double-rolling was used to prepare copper foils with improved bending property [9]. Meanwhile, cross rolling is an effective process to obtain a finer grain size compared to the conventional rolling [10]. In addition, a strong texture could be introduced in the cross-rolled face-center cubic (f.c.c.) metals along the \(\alpha\)-fiber orientation in the cross rolling of aluminum, identified by Huh et al. [11] and Wang et al. [12]. Therefore, to refine grain size and control texture generation, theoretically, double rolling and cross rolling can be combined. To date, double rolling were mainly composed by one pass rolling, and the improved bending fatigue life was limited in 16.2% [9]. However, a double rolling followed by cross rolling process has not been reported.

The present work aims to investigate the propensity of bending property improvement in copper foil, which was fabricated using double rolling followed by cross rolling. The research performed in this study provides a new insight into the effect of rolling process on microstructure, texture and bending property in copper foil systematically. Besides the significance of fundamentals, the work also contributes to...
practical application of copper foils that are gaining growing importance in flexible printed circuit board (FPCB) and lithium ion battery industries.

2. Experimental

The material used was commercial purity copper (99.99 wt%) belts. The length and width of the belt is 300 mm and 50 mm, respectively. The thickness is 0.15 mm. The as-received copper belts were annealed in an Ar atmosphere at 500 °C/10 min. After the annealing heat treatment, the copper belts were ground using silicon carbide sandpapers from #1000 to #2000. One pass double-rolling process shown in reference [13] was performed on a four-high mill without rolling oil. The rolling direction is defined as RD, and the transverse direction is defined as TD. The copper foil produced by one pass double-rolling is defined as double-rolled copper foil. After one pass double-rolling, some copper foils were rolled along RD for second pass, defined as Sample 1; others were rolled along TD for second pass, defined as Sample 2. The thickness reduction of each pass was 50%. The thickness of Samples 1 and 2 was 37.5 μm.

The bending fatigue tests were carried using a folding endurance tester with bending radius of 1 mm. The samples were machine into 80 mm × 16 mm. Then the samples were cyclic bended for 135° until fracture. The tensile force was 2.5 N. Three samples were tested for each direction of the copper foil samples. After the fatigue test, the copper material near the fracture surfaces was punched to be discs with a 3 mm diameter, and twin jet electro polished in a solution with HClO4 10 mL + C2H5OH 90 mL solution at −30 °C. The applied Voltage potential was 50 V, and then transmission electron microscope (TEM) observations were performed by using FEI Talos F200-field emission TEM operated at 200 kV.

The longitudinal section microstructure and fracture surfaces were observed by a Phenom G2 Pro scanning electronic microscopy (SEM). Microstructure of bright and matt surfaces was observed by an Imager.M2M optical microscope (OM) for double-rolled copper foil. Microstructure, texture and dislocation density of Samples 1 and 2 were characterized by a JEOL JSM-7800F field emission SEM equipped with EBSD analysis, operated at an acceleration voltage of 20 kV. Oxford Instruments Nordlys Nano EBSD system equipped with Channel 5 software were used for analyzing microstructure, texture, dislocation density and Taylor factor.
Fig. 2 – Microstructure of copper foils: (a) longitudinal section, (b) bright surface, (c) matt surface of double-rolled copper foil; (d) longitudinal section, (e) bright surface, (f) matt surface of Sample 1; (g) longitudinal section, (h) bright surface, (i) matt surface of Sample 2.

3. Results and discussion

Fig. 1 shows the comparisons of bending fatigue life between the copper foil fabricated by one pass double-rolling, Sample 1, Sample 2 and conventional rolled copper foils [5] with an equivalent deformation degree. Table 1 shows the specific bending number of the related copper foils. After the second pass rolling, bending properties were generally improved for all directions (RD, TD and 45° direction). However, the largest increased range of bending fatigue life is only 21.4% for Sample 1 and the value in some bending directions is even lower compared with conventional rolled copper foil. On the contrary, the maximum increased range of Sample 2 reaches 101.0% and the value in all the bending directions are higher compared with that of conventional rolled copper foil. Cleavage steps can be observed in the whole fracture surface of Sample 1 (45° direction). However, it can only be observed in central of Sample 2 (RD). While some cleavage river patterns were formed approaching the surfaces of the copper foil.

Fig. 2 shows the microstructure of copper foil fabricated by one pass double-rolling, Sample 1 and Sample 2. In the longitudinal section images, a gradient microstructure [9] can be observed (Fig. 2a, d and g). However, the gradient of samples is different, which shows increasing and decreasing for Sample 1 and Sample 2, respectively. In the bright surface of one pass double-rolled copper foil and Sample 1, grains were elongated along RD; this tendency becomes weaken in matt surface due to the semi-free deformation [13]. However,
in terms of both surfaces of Sample 2, no obvious elongated grains can be observed.

Fig. 3 shows ODF maps of bright and matt surfaces for Sample 1 and Sample 2, respectively. The morphology observations show a moderate brass texture (110)<001> in both bright and matt surfaces of Sample 1 (Fig. 3a and b). It is mainly related to the action of multi-slip systems in face-center cubic (f.c.c.) crystal, resulting in dislocation slipping [14]. Weak cube texture (001)<100> and rotate cube texture (100)<011> can be observed in bright surface (Fig. 3c) and a strong copper texture (112)<111> formed in matt surface (Fig. 3d) of Sample 2. The different texture is believed to be induced by the shear stress difference between bright and matt surfaces during rolling process [14].

To understand mechanism of bending property improvement, the strengthening effect requires to be discussed. The strengthening effect of grain boundary can be expressed using Hall-Petch relation as: \( \sigma_{H-P} = k \cdot d^{-1/2} \) [15–17], where \( k \) represents Hall-Petch constant (\( k = 0.18 \) MPa m\(^{1/2} \)) for copper [18], \( d \) is grain size which can be determined using Fig. 3 [19,20]. While strengthening effect of dislocation can be expressed as: \( \sigma_d = M b \alpha / G \) [19,21]. The dislocation densities of copper foils are 2.17 \( \times 10^{14} \) (bright surface, Sample 1), 1.89 \( \times 10^{14} \) (matt surface, Sample 1), 1.76 \( \times 10^{14} \) (bright surface, Sample 2) and 2.13 \( \times 10^{14} \) m\(^{-2} \) (matt surface, Sample 2) measured by EBSD technique. On the one hand, since grain size \( d \) of Sample 2 is smaller than that of Sample 1, grain boundary strengthening effect of Sample 2 is stronger than that of Sample 1. On the other hand, the dislocation densities of Sample 1 and Sample 2 are in a same order of magnitude. Thus the strengthening effect of dislocation is similar for Sample 1 and Sample 2. Combining the strengthening effects of grain boundary and dislocation, the strengthening effect of Sample 2 is stronger than that of Sample 1. In addition, dense grain boundaries in longitudinal section of Sample 2 can inhibit the crack propagation [6,7].

Fig. 4 shows TEM images and surface cracks of copper foils after bending. It is generally believed that the fracture is caused by concentration of microcracks [5], and the dislocations emitted by crack tips can consume energy of crack [22]. For Sample 1, dislocations distribute dispersedly (Fig. 4a), which have limited effect on preventing the spread of cracks, resulting in coarse and concentrated cracks on the surface (Fig. 4b). While for Sample 2, dislocations are concentrated and mainly move along the same crystal direction (Fig. 4c), resulting in fine and dispersive cracks on the surface, which have a positive effect on improving bending fatigue life (Fig. 4d). Owing to the strong single copper texture in matt surface of Sample 2 (Fig. 3d), the misorientation between neighboring grains is small, resulting in weak stress concentration effect on grain boundaries during the bending test [23]. Such type of microstructure could also contribute to improving the bending fatigue life.

4. Conclusions

(1) A novel double rolling followed by cross rolling process was proposed to fabricate copper foils with more excellent bending property. The bending fatigue life was increased
from 103 to 207 times, namely 101.0%, compared to the conventional rolled copper foil.

(2) Grain boundary and dislocation strengthening play dominant roles in improving the bending property as well as single strong copper texture that could decrease stress concentration in grain boundaries.

(3) The fractured copper foil after bending contained concentrated dislocations, with fine and dispersive cracks on the surface. Consequently, crack propagation and concentration could be prevented, resulting in the observed excellent bending property.

Fig. 4 – TEM images (a) (c) and surface cracks (b) (d) of Samples 1 and 2 after bending fracture, respectively.

REFERENCES


Conflicts of interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmrt.2020.02.004.