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LETTER

Effect of Deformation of Multi-pass Rolling on Microstructure and Properties of C71500 Cupronickel Alloy Tube

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Abstract: Electron backscatter diffraction (EBSD) technique was used to analyze the microstructure of cold-rolled C71500 cupronickel alloy tube. Through the analysis of microhardness, tensile properties, microstructure, texture, and texture content of the cupronickel alloy tube after the second pass cold rolling with different deformations (3.19%, 9.57%, 19.37%, 23.97%, 31.78%), the texture change law of the alloy was obtained. The quantitative relationship between deformation and storage energy was revealed by analyzing the grain size and the change of texture and grain boundary, which could be directly reflected by the proportion of small angle grain boundaries. The optimal deformation of second pass rolling for C71500 alloy was obtained. Results show that the yield strength, tensile strength, and microhardness of cupronickel alloy are increased with increasing the working ratio, while the plasticity is decreased.

Key words: tube; cupronickel alloy; multi-pass rolling; texture; microstructure evolution; deformation mechanism; mechanical properties

Many methods have been proposed to study the texture of copper and cupronickel alloys, for example, the microstructure and properties of Cu alloy tube were analyzed by three-roll planetary rolling process[1], and the crystallographic texture of electrolytic rough bronze was studied after cold drawing deformation and static recrystallization[2]. The difference of recrystallization texture between single crystal and twin crystal of copper can explain the formation mechanism of cubic texture[3]. The residual stress state and texture of copper tube can be analyzed by plug-free drawing technique[4]. The manipulator can change the observation surface to study the inhomogeneity of Cu tube along the circumference and wall thickness directions[5].

This research mainly studied the effect of multi-pass rolling process on the properties of C71500 cupronickel alloy tube. After the first large deformation rolling and annealing, the influence of multi-pass deformation with different working ratios on the texture and grain boundary of C71500 alloy of uniform structure was studied, and the corresponding mechanism was also revealed. The results provided a theoretical basis for the optimal selection of deformation, the thermodynamics of forming special grain boundary, and the subsequent deformation processing design of C71500 alloy tubes.

1 Experiment

The experiment material C71500 alloy consisted of 30.54wt% Ni, 0.93wt% Mn, 0.80wt% Fe, and balance Cu. The alloy was smelted by vacuum induction melting furnace. Then the obtained ingot was hot-rolled and perforated to prepare

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tube blank. After the rolling deformation of 70% by two-roll periodic cold rolling mill, the alloy tube was annealed at 800 °C for 20 min, and then cooled down and used in protective atmosphere. The annealed tubes were rolled with different deformations by the three-roll periodic cold rolling mill to study the influence of deformation on the texture of tubes. The specific rolling procedure is shown in Table 1. When the deformation is less than 15%, the small deformation recovery state is generally taken into consideration; when the deformation is more than 15%, the large deformation recrystallization state is taken into consideration[6-10]. Therefore, the rolling deformation in this research ranged from 0.00% to 31.78%, covering different stages of recovery and recrystallization.

The electron backscatter diffraction (EBSD) observation was conducted on the longitudinal section along the rolling direction (RD) of tube. The electrolyte consisted of 25vol% H_3PO_4, 25vol% C_2H_5OH, and 50vol% H_2O, the polishing voltage was 20 V in direct current (DC), and the polishing time was about 180 s. Scanning electron microscope (SEM) of Gemini SEM300 of Zeiss brand was used to observe the microstructures, and orientation analysis was conducted by Channel 5 data processing software. The microhardness of alloy was measured by Buehler Wilson VH1150 Vickers microhardness tester with the load of indenter of 5 kg for 10 s. The tensile test of alloy was conducted by SUNS UTM5205 electronic universal tester.

2 Results and discussion

2.1 Grain

Fig. 1a shows the structure of the original annealed alloy with uniform grains. After deformation of 3.19%, the grain size becomes small, and the grains have slight deformation along the rolling direction. At the same time, many fine grain strips appear in the position of severe deformation. When the deformation increases to 9.57%, the fibrous deformed structure can be observed parallel to the rolling direction. A mass of deformed dislocations is twining to form capillary discontinuous free grain boundaries, namely subgrain boundaries. The large grain is prone to deformation due to the small number of grain boundaries per unit area. Therefore, it can be concluded that the small-size grain is prone to

Table 1 Rolling procedure parameters of C71500 alloy tube

Specimen	Pre-treatment of cold rolling	Diameter/ mm	Thickness/ mm	Diameter reduction/%	Thickness reduction/%	Working ratio/%
1	70% cold rolling+800 °C/20 min+air cooling	61.40	5.58	0.00	0.00	0.00
2		60.02	5.50	1.43	2.25	3.19
3		60.00	5.03	9.86	2.28	9.57
4		57.40	4.68	16.13	6.51	19.37
5		57.00	4.46	20.07	7.17	23.97
6		56.90	4.09	26.70	7.33	31.78

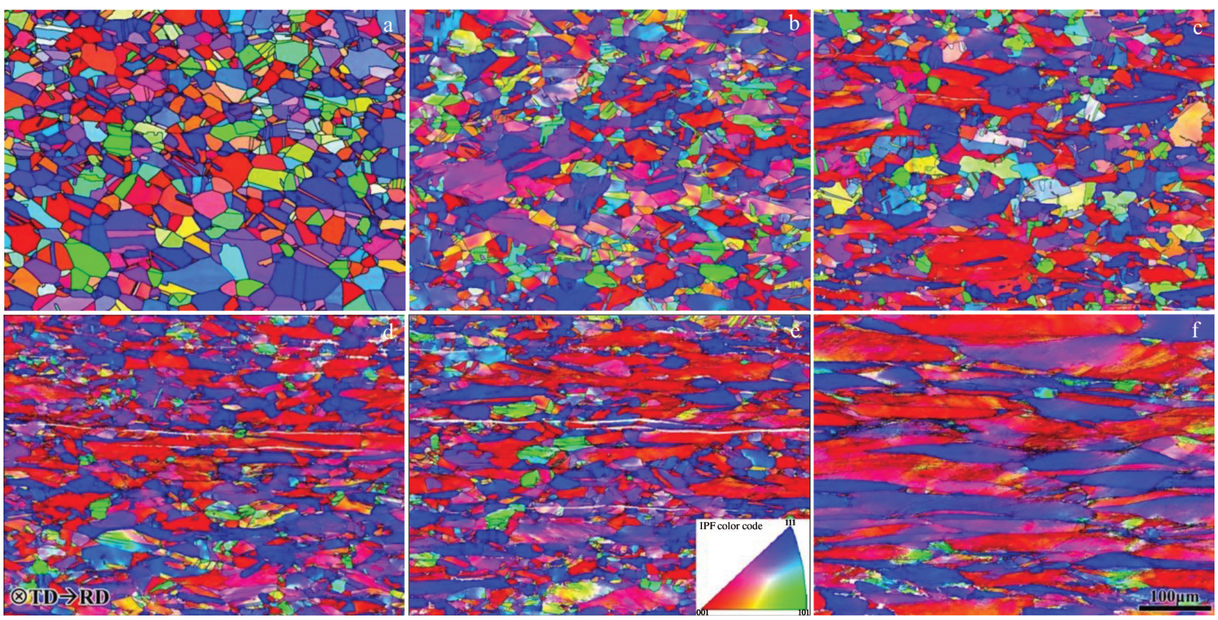

Fig.1 Inverse pole figures (IPFs) of C71500 alloy tubes after different deformations: (a) 0.00%, (b) 3.19%, (c) 9.57%, (d) 19.37%, (e) 23.97%, and (f) 31.78% (TD: transverse direction)

reservation. With the further increase of deformation, more fibrous structures and less equiaxed grains can be observed. When the deformation reaches 31.78%, the uniform equiaxed grains basically disappear. With increasing the deformation, the length to width ratio of fibrous deformed structure is increased gradually, i. e., the length of deformed structure is increased and the width is decreased gradually. Therefore, the equiaxed grains change to the cellular block grains. The grains are broken during this process and the broken areas are separated by dislocation walls. With increasing the deformation, the grains along <101> direction gradually move to <001> and <111> directions. When the deformation reaches 31.78%, the basic grains along <101> direction disappear.

A small deformation can produce a certain number of non-coherent twin boundaries. According to Chen et al[11], this kind of grain boundary is the fundamental reason for the optimization of grain boundary characteristic distribution. The non-coherent twin boundary has higher free energy than coherent twin boundary does, and it can easily migrate and interact with others to produce new special grain boundaries. It can be seen from Fig.1 that when the rolling deformation is 9.57%, there are a certain number of deformation bands in the material, indicating that the lattice has some distortion and the optimal deformation of C71500 alloy is achieved.

2.2 Texture characteristics

Orientation distribution function (ODF) was used to quantitatively analyze the texture of the alloy, as shown in Fig. 2. The maximum and the minimum density value of texture is 4.02 and 0.14, respectively. The texture is mainly the typical annealed texture of face centered cubic, such as R-Cube{001}<110>, R-Brass{111}<110>, and RZ{111}<112> textures. As shown in Fig.2b, after deformation of 3.19%, the texture orientation strength is increased, the maximum and the minimum density of texture is increased to 4.32 and 0.13, respectively, and the R-Cube{001} <110> texture becomes stronger. At the same time, the strength of Brass{110}<112> texture and R-Brass{111}<110> texture obviously decreases, resulting in the weakening of annealing texture orientation. When the deformation reaches 9.57%, the R-Cube{001}<110> texture turns to the Cube{100} <100> texture, the R-Brass {111}<110> texture becomes stronger, and the RZ{111}<110> texture can be observed. When the deformation reaches

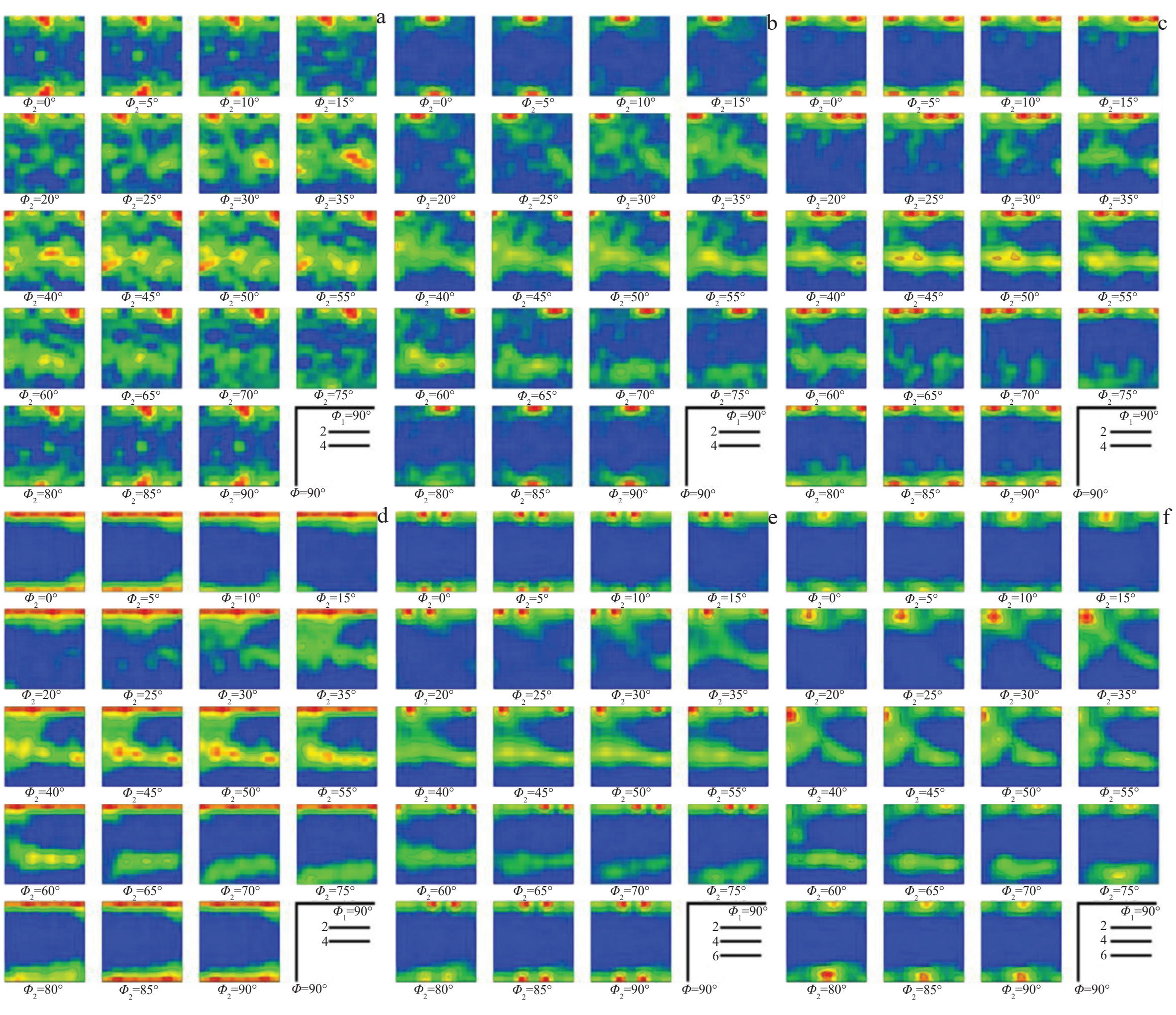

Fig.2 Texture orientation distributions of C71500 alloy tubes of different deformations: (a) 0.00%, (b) 3.19%, (c) 9.57%, (d) 19.37%, (e) 23.97%, and (f) 31.78%

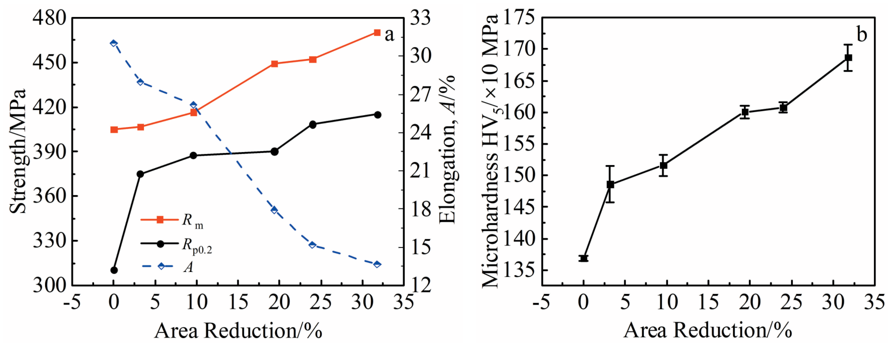

Fig.3 Mechanical properties of C71500 alloy tubes with different deformations: (a) yield strength $R_{p0.2}$, tensile strength R_m, and elongation A; (b) microhardness, HV_5

19.37%, the texture of Cube{100}<100>, R-Cube{001}<110>, and normal direction (ND) -Cube{001} <310> can all be observed, indicating that the grain direction turns to {100} crystal surface, and there are a small number of R-Brass{111} <110> and RZ{111}<110> textures. When the deformation continuously increases to 23.97%, the grains mainly consist of R-Cube{001}<110> texture and a small number of R-Brass {111} <110> and RZ{111} <112> textures. When the deformation reaches 31.78%, R-Cube{001} <110> and RZ {111}<110> textures are strengthened, whereas the R-Brass {111}<110> texture disappears and is gradually transformed into Rolled{112} <110> texture. With increasing the deformation, the orientation of texture becomes more obvious, and the maximum density of texture is increased from 3.48 to 6.32.

The rolled tube, plate, and wire of copper alloys are different. The results of appearance of RZ{111}<112> texture during the deformation process are similar to those of TP2 alloy tube during rolling process[12]. In the rolling process, the initial grains can be directly rotated 90° around the <110> axis to obtain Rd-Cube{100}<001>, Copper{112}<111>, RZ{111} <112>, and Goss{110}<001> textures. It can be concluded that the texture of C71500 alloy tube is mainly dominated by the transformation among R-Cube{001}<110>, R-Brass{111} <110>, RZ{111}<112>, and Rolled{112}<110> textures.

2.3 Mechanical property

Fig.3 shows the changing rule of mechanical properties of C71500 alloy tubes with different deformations. It can be seen from Fig.3a that with increasing the working ratio, the yield strength ($R_{p0.2}$), tensile strength (R_m), and microhardness (HV_5) all show an upward trend, while the plasticity (elongation, A) of the C71500 alloy tubes shows a downward trend. Microhardness (HV_5) can reflect the change rule of $R_{p0.2}$. When the rolling deformation is 3.19%, the yield strength of cupronickel alloy increases by 64.71 MPa, while the tensile strength increases by 1.49 MPa, compared with the properties of the original alloy. When the deformation reaches 31.78%, the yield strength of cupronickel alloy increases by 104.77 MPa, while the tensile strength only increases by 65.29 MPa, and the elongation decreases from 31.02% to 13.64%, compared with the properties of the original alloy. The change trend of microhardness is consistent with that of the yield strength, thereby reflecting changing rule of yield strength. During the deformation process, the C71500 alloy is gradually hardened, the grain is refined gradually, and the grains change to the ones along the direction of <111>, forming the sub-crystalline structure which hinders the movement of dislocation, improves the strength, and reduces the plasticity of the alloy.

3 Conclusions

1) The optimal rolling deformation for C71500 alloy tube is 9.57%.

2) The texture of C71500 alloy tube is mainly dominated by the transformation among R-Cube{001}<110>, R-Brass{111} <110>, RZ{111}<112>, and Rolled{112}<110> textures.

3) The yield strength, tensile strength, and microhardness of C71500 alloy are increased with increasing the working ratio, while the plasticity of the alloy is decreased. The change rule of microhardness of the alloy can well reflect that of the yield strength of the alloy.

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多道次轧制不同变形量对铜镍合金管材组织和性能的影响

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摘　要：采用电子背散射衍射（EBSD）技术对冷轧后铜镍合金管材的组织进行分析。通过对第二道次冷轧不同变形量（3.19%、9.57%、19.37%、23.97%、31.78%）的C71500铜镍合金在管材轧制后的显微硬度、抗拉伸性能、微观组织、织构及其含量变化的研究，揭示该合金织构的变化规律。通过对铜镍合金管材晶界、织构的变化及晶粒尺寸进行分析，揭示了变形量与变形储存能的量化关系，这种关系可以通过小角度晶界的比例更直观地体现出来。随着加工率的增加，铜镍合金的屈服强度、抗拉伸强度和维氏显微硬度均呈现上升的趋势，而合金的塑性则呈现下降的趋势。研究结果为合理选择变形量以及形成特殊晶界的热力学提供依据，同时为后续铜镍合金管材的变形加工提供理论依据。

关键词：管材；铜镍合金；多道次轧制；织构；组织演变；变形机理；力学性能

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