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Influence Mechanism of Texture Evolution on Residual Stress under Thermal-Ultrasonic Treatment

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Abstract

Thermal-ultrasonic coupling residual stress release experiment of C19400 copper alloy strip was carried out with self-made experimental device under different ultrasonic amplitudes. The texture evolution and residual stress relaxation of the strip were systematically studied. The results show that, with the increasing ultrasonic amplitude, the strength of cubic texture decreased, while the strength of Brass texture increased. Low-angle grain boundaries were mainly formed in brass texture owing to its high Taylor factor. The slip and interaction of dislocations lead to the grain rotation and the change in texture type, which was the main reason for the relaxation of residual stress.

Keywords: Residual stress; Texture; Grain rotation

Abbreviations: ND: Normal Direction; VSR: Vibration Stress Relaxation; TUSR: Thermal-Ultrasonic Coupling Stress Relief; EBSD: Electron Backscattering Diffraction; HAGBs: High-Angle Grain Boundaries; LAGBs: Low-Angle Grain Boundaries; GND: Geometrically Necessary Dislocation; IPF: Inverse Pole Figure; ODF: Orientation Distribution Function

Introduction

C19400 copper alloy strips are widely used in electronic components such as semiconductor lead frames and connectors due to their high electrical conductivity, high thermal conductivity and medium strength. Uneven stress in the processing process often leads to residual stress in the strips. The strips will warp and deform in industrial applications, which cannot meet the packaging requirements. In addition, the effect of texture on the residual stress and properties of thin strip cannot be neglected. Wei et al. [1] proposed that the <111> hard orientation had the effect of concentrating the residual compressive stress in Cu-Ni-Si cold-rolled sheet, while the effect of the <211> medium orientation was not obvious. Zohrevand et al. [2] found that ultrasonic treatment effectively reduced the internal stress of the duplex structure. The <111> and <110> deformed texture gradually decreased, but the <100> texture was strengthened. Wang et al. [3] found that the vibration process can weaken the (0002) preferred orientation of cold-rolled AZ31 magnesium alloy, and the residual stress decreased. The same result was found in a cold-rolled Al-Mg-Si-Cu alloy [4]. The texture of (111) almost disappeared, which was affected by vibratory force parallel to normal direction (ND).

Annealing and vibration stress relaxation (VSR) methods are used to eliminate residual stress of materials traditionally. However, using these methods may decrease the strength of materials and cannot satisfy the requirements of high-end thin strips. A new thermal-ultrasonic coupling stress relief (TUSR) method suitable for thin strips was proposed in our previous work [5]. The residual stress reduction of TUSR was efficient, the residual stress in both directions reduced and the effect was more significant with the increasing amplitude. However, the mechanism of residual stress relaxation related to evolution of texture is still unclear. In this work, electron backscattering diffraction (EBSD) was used for analysis the texture evolution of C19400 alloy strips during TUSR treatment. And the influence mechanism of texture evolution on the residual stress was investigated, so as to improve the efficiency of residual stress relaxation.

Experimental Procedures

The materials used in the experiment was H state C19400 copper alloy strips, with a width of 50mm and a thickness of 0.2mm. The experiment was conducted on a self-developed multifield coupling residual stress relaxation equipment. A tensile force of 350N was applied and the strip moved at a linear speed of 2 m/min during the experiment. The heating furnace provided a temperature field of 200℃. The loading amplitude on the strip was changed to 20 and 35 μm, respectively. The natural frequency of the material was selected as the excitation frequency. In addition, EBSD tests of the samples were conducted on JSM-7800F backscattering scanning electron microscope. EBSD data was processed by Channel 5 software.

Result and Discussion

Misorientation and taylor factor

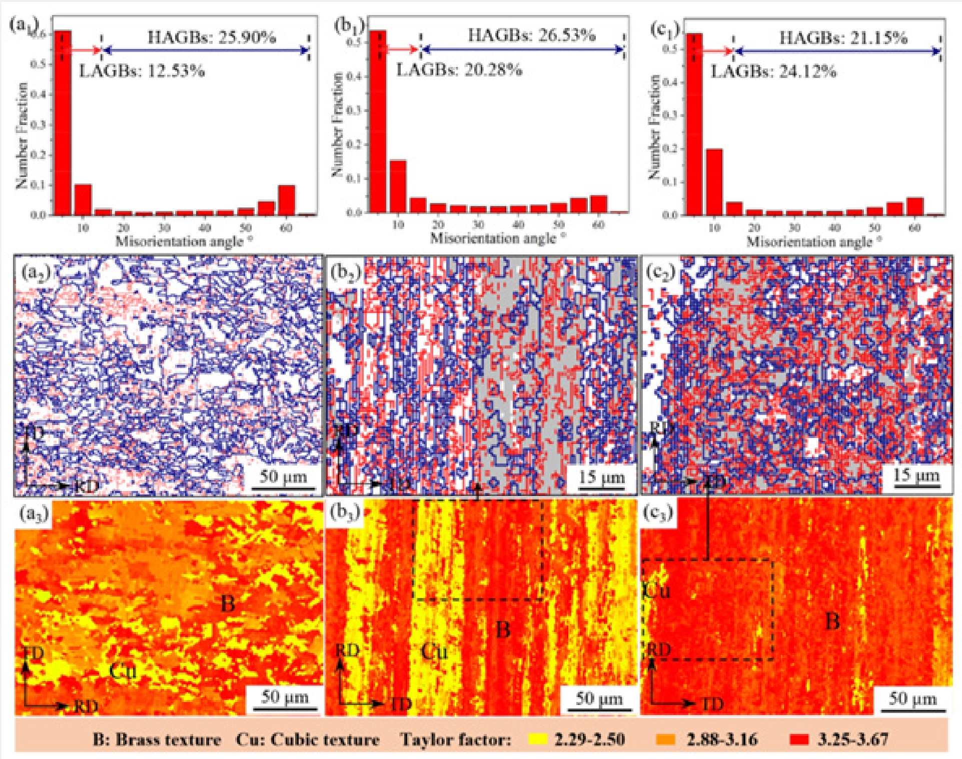

Figure 1: Misorientation angle distribution (a1-c1) and orientation maps (a2-c2) and Taylor factor maps (a3-c3) of original sample and samples under different amplitudes.

Figure 1 shows the misorientation angle distribution and Taylor factor map of different samples. Low-angle grain boundaries (LAGBs, misorientation angle 5°~15°) and high-angle grain boundaries (HAGBs, misorientation angle >15°) were depicted in red and blue, respectively. Brass texture was indicated separately in gray. From the statistical results in figure 1 (a1-c1), it can be seen that the proportion of LAGBs increased obviously after TUSR treatment with different ultrasonic amplitudes. Figure 1 (a3-c3) are the Taylor factor maps of samples. The Taylor factor M is a geometric factor used in analysis of plastic deformation in polycrystals [6]. The researchers used the Taylor factor to define "hard grain" and "soft grains" [7]. The Taylor factor of cubic texture was lower (2.29-2.50) and that of brass texture was higher (3.25-3.67).

It was found that the points with high GND (geometrically necessary dislocation) preferentially gather in the grains with high Taylor factor ("hard" grains) in the plastic deformation samples [6,7]. Because the grains with high Taylor factor need more stress to apply uniform geometry change and more work in the deformation process, which leads to the generation of dislocation on different slip surfaces and higher GND density, so the dislocation density is higher. The concentration at low misorientation values is related to the stored dislocation [8]. The application of TUSR led to micro plastic deformation in the material. The dislocation dipoles with small distance interacted and offset, and the dislocation morphology evolved into the low-energy dislocation cells and dislocation walls, and finally evolved into a large number of LAGBs. The newly formed dislocation

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boundary further evolved to HAGBs, resulting in grain refinement. In addition, Brass texture has high deformation energy storage [9]. Residual stress is classified as elastic stress, this shows that part of the lattice can be evolved from the position with larger distortion and higher residual stress to the position with smaller distortion and lower residual stress, so the residual stress is released. The dynamic evolution process of dislocation was also the process of energy storage and release. After treatment, LAGBs were formed in Brass texture, which indicated that stress relaxed in grains with high energy storage.

Texture evolution

Figure 2 shows inverse pole figure (IPF) in ND which is ultrasonic loading direction, and orientation distribution function (ODF) maps of samples. The internal grain size of the samples decreased after TUSR treatment and the grain morphology changed into a long strip along the rolling direction. The texture types of original C19400 alloy include {100} <001> cubic texture (red region), {110} <112> brass texture (green region) and {123} <634> S texture (purple region). After TUSR treatment, with the increased amplitude, cubic texture almost disappeared, while Brass texture increased greatly, and the strength of S texture also increased.

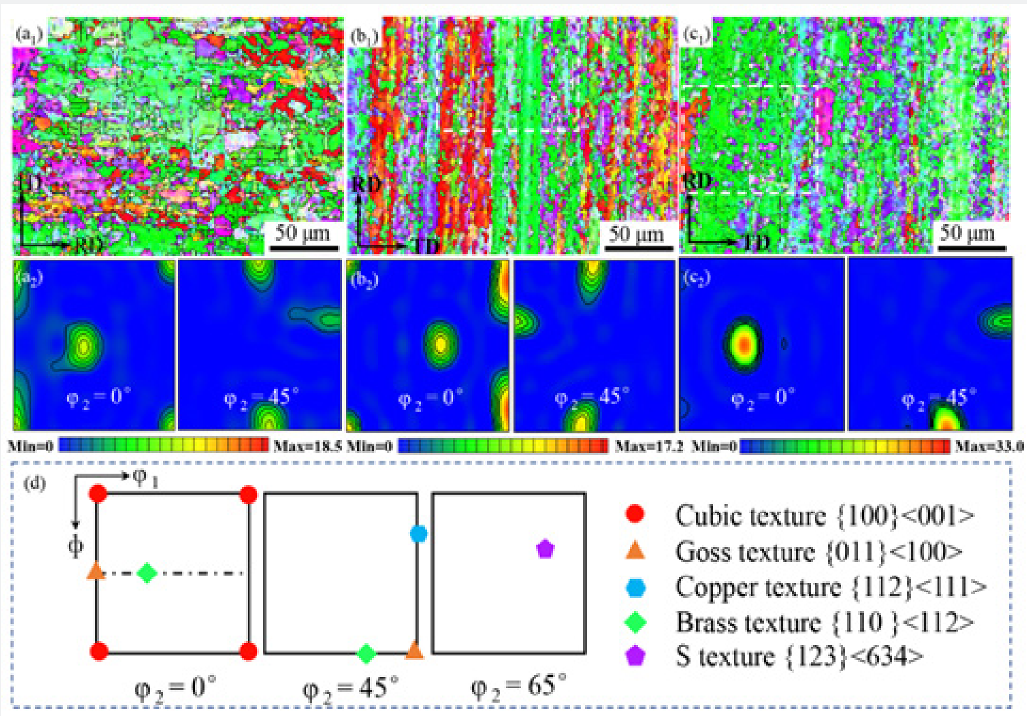

Figure 2: IPF in ND (a1-c1) and orientation distribution function maps of original sample and samples under different amplitudes (a2-c2). (d) Schematic illustration of the ideal texture components for copper alloy.

FCC metals often have Brass and S textures after cold rolling when metals with low stacking fault energy. The recrystallization texture of FCC metals is often cubic texture. These were consistent with the leading texture types observed in the original sample. When the amplitude increased to 35 μm, cubic texture weakened. This was because, for cubic texture, (001) preferred orientation was parallel to the direction of vibration stress, so the vibration stress had the greatest influence on exciting (001) preferred orientation near ND. Moreover, <110> {111} slip is considered as the unique deformation mechanism of FCC metals at present [10]. It was thought that the S texture was less affected, because there was only one slip system, so the process of dislocation climbing and sliding was not easy to occur. There were eight slip systems in cubic texture. Under the external force, the slip systems were easy to start, which led to the complete process of dislocation climbing, sliding and cross-sliding. In addition, the applied direction of ultrasonic stress is perpendicular to the preferred orientation direction of cubic texture, and with the increase of ultrasonic amplitude, the dislocation reaction can proceed more violently, resulting in the destruction of preferred orientation, which explained why cubic texture disappears in one aspect.

Grain rotation

Previous research showed that the relaxation process in the nonequilibrium grain boundary was accompanied by misorientation and grain rotation [11,12]. In addition, dislocation

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slip played an important role in grain rotation [13]. In the process of TUSR, micro plastic deformation occurred, and the nonequilibrium structure of grain boundary was the main condition for grain rotation in the TUSR process. The high residual stress of the original sample was due to the high internal stress at the grain boundary. And the lattice dislocation formed an unbalanced dislocation group. There were few LAGBs in the original sample. Lots of lattice dislocations were absorbed by the grain boundaries in nonequilibrium state. After the TUSR process, the grains rotated due to the rearrangement of these trapped dislocations. Then these dislocations left the boundary, resulting in the formation of LAGBs, and the unbalanced structure relaxed. The grain boundary orientation changed, resulting in the reduction of excess energy stored in grain boundaries and the relaxation of residual stress. Therefore, grain rotation can be regarded as an indicator of the relaxation of polycrystalline materials.

Take a single cube as an example, according to the formula of angle between two planes, the angles between the Cubic {001}, Brass {110} and S {123} preferred orientation planes were calculated respectively, as shown in figure 3. The angle between the crystal plan family of Brass {110} and cubic {001} can only be 45° or 90°. The angles between some plans of cubic and S texture were 36.69° (such as $(001)-(123)$, $(00\bar{1})-(12\bar{3})$, etc.) and 74.51° (such as $(100)-(123)$, $(\bar{1}00)-(123)$, etc.). The angles between some plans of Brass and S texture were 19.11°(such as $(011)-(123)$, $(0\bar{1}\bar{1})-(123)$, etc.), 55.46° (such as $(110)-(123)$, $(\bar{1}\bar{1}0)-(123)$, etc.) and 74.51° (such as $(01\bar{1})-(123)$, $(0\bar{1}1)-(123)$, etc.).

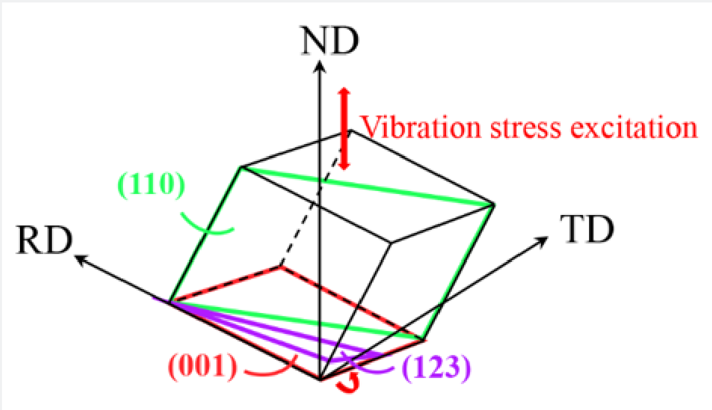

Figure 3: Schematic representation of preferred orientation plane of different texture.

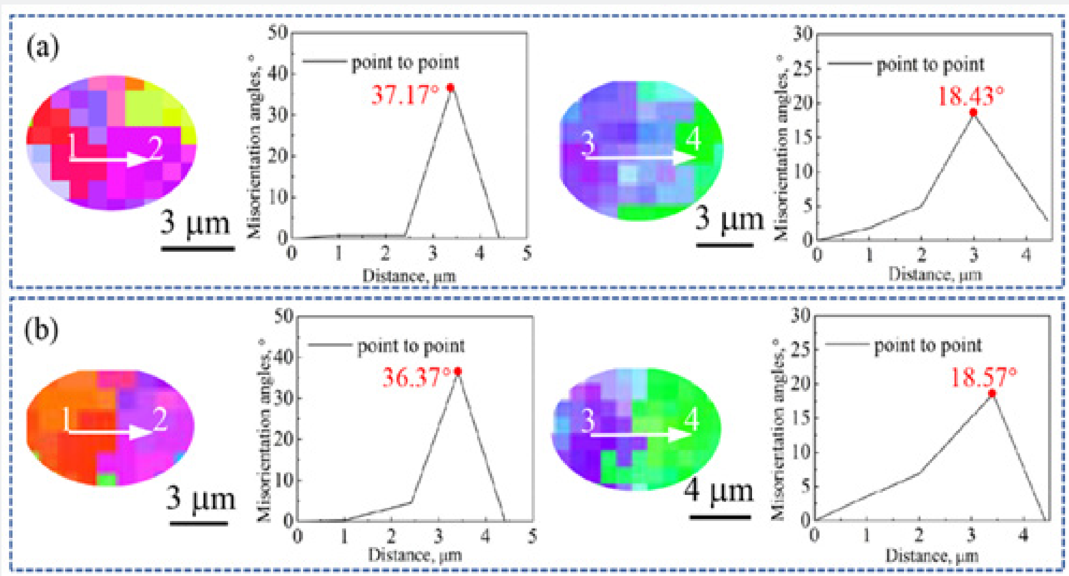

Figure 4: Partial IPF maps of samples under different amplitudes and misorientation measurements along line 1-2 and 3-4. (a) amplitude is 20 μm, (b) amplitude is 35 μm.

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Based on the calculation results, we speculated that it was difficult for grains to rotate from cubic to Brass texture owing to the large angles between their preferred orientation planes. However, the cubic texture transformed into S texture by rotating a small angle first, and then transformed into Brass texture by further rotating a small angle. The evidence of this situation can be found in EBSD results as figure 4 shows. Selecting the grains in the "substructure zone" between cubic to S texture (1→2) and S to Brass (3→4) texture to enlarge. The measured misorientation angles between cubic and S texture in different samples were 37.17° and 36.37°; that of S and Brass texture were 18.43° and 18.57°. It can be seen that the result was close to the calculated result, the texture type can change though grain rotation. This explained the disappearance of cubic texture in another aspect.

In summary, due to the start of slip systems in Cubic texture, dislocation slip and grain rotation, the Cubic texture changes into Brass texture. In this process, dislocations leave the grain boundary which is in a non-equilibrium state and contains a large number of lattice dislocations. The high residual stress at the grain boundary is released due to the high internal stress released. In the further TUSR process, micro plastic deformation occurred, and the dislocations preferentially gathered at the Brass texture with high Taylor factor. Due to the rearrangement of these unbalanced dislocations, the stress relaxes and the LAGBs are formed, which are further transformed into HAGBs, resulting in grain refinement. Therefore, the evolution of texture leads to the release of residual stress.

Conclusion

Based on the TUSR method of C19400 copper alloy strips with the amplitude of 20 μm and 35 μm, the effect of texture evolution on residual stress release was studied. The following conclusions were drawn:

a) For TUSR treatment, when the amplitude was 35 μm, the cubic texture almost disappeared, but the Brass texture increased greatly.

b) After TUSR treatment, LAGBs were mainly formed in Brass texture owing to its high Taylor factor, and residual stress was released in these grains having high energy storage.

c) The texture type changed from cubic to S texture and S to Brass though grain rotation, which resulted in the relaxation of residual stress.

Author Statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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