Effect of Annealing Temperature on Microstructure, Texture and Earing of 8011 Cold Rolled Sheet

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Abstract. To reduce the work hardening of the 8011 cast-rolled plates after multiple rolling, 8011 cold-rolled plates with a deformation of 78% were annealed at different temperatures. The influence of annealing temperatures exercise upon the microstructure, texture and earing of cold-rolled sheets was analysed by means of ODF texture analysis, EBSD technology and cup drawing test. The results show that the contents of the deformed microstructure, the recrystallized structure and the substructure change sharply annealing at 300℃, but they tend to be stable at 350℃. The starting temperature of recrystallization of 8011 cold-rolled plates is about 300℃. When cold rolled sheets were annealed at low temperatures, there were quantities of grain boundaries whose angle was small. When the annealing temperatures were higher, the small and medium angle grain boundaries of the cold rolled sheets decreased gradually. The general trend was that the small angle grain boundaries first increased and then decreased as the case of annealing temperature rise. The proportion of the small angle grain boundaries reached to the minimum value of 20.2% at 350℃. When annealing temperature is 350 ℃, the lowest earing rate is 2.11%.

Keywords: 8011 aluminum alloy; Cold rolling; Annealing temperature; Microstructure; Texture; Earing.

1. Introduction
Aluminum materials that have recyclability, outstanding plasticity and excellent strength to weight ratio are widely used in many sectors of industrial production [1-4]. 8011 aluminum alloy has low earing ratio and excellent deep drawability, it is commonly used to make aluminum foils, and the performances are better than those who are made by pure aluminum. They have been widely used in the beverage bottles, drug packaging, air conditioner, and on the aluminum foils for sealing packaging of cosmetic bottles [5-9]. After the multi-pass rolling of the cast strips, the original grains of 8011 aluminum foils are transformed into elongated and flat deformed microstructure, a large number of very high dislocation density and crystal defects are introduced [10]. The mechanical properties of 8011 aluminum alloy are closely related to three aspects: microstructure, internal precipitation phase and heat treatment process. The improvement of microstructure is an important measure to improve the performance of aluminum sheets. On the other hand, reasonable heat treatment process can improve material structure and reduce microstructure defects, based on it, the sheets could have good
plasticity and high strength [11-15]. In particular, the anisotropic properties of sheets are closely related to the texture evolution formed during heat treatment.

At present, on the effect of annealing on the microstructure and texture of 8011 aluminum alloy there are rare systematic investigations and analysis, in this work, the evolution of texture, recrystallized microstructure and earing behavior under different certain annealing conditions are studied, the influence that annealing temperature exercise upon microstructure, texture and earing of 8011 cold rolled sheet was studied by ODF texture analysis, EBSD technology and cup drawing test, the research has determined the reasonable annealing temperature and it could provide a reference for the formulation of process in actual industrial production.

2. Experimental procedures and test methods

2.1. Materials
The experimental material is 8011-aluminum alloy, and the chemical compositions are listed in Table 1, the 8011-aluminum alloy cold-rolled sheets with a thickness of 1.5 mm and a total deformation of 78% for the test are from ultrasonic casting plates, which have been cold-rolled for five times and have excellent performance.

| Tab.1 Chemical compositions of the 8011-aluminum alloy (wt-%). |
|------------------|---|---|---|---|---|---|---|---|---|
| Element | Fe | Si | Mn | Cu | Mg | Ni | Ti | Zn | Al |
| Content | 0.64-0.81 | 0.42-0.57 | 0.06-0.02 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | Bal. |

2.2. Experimental process
The cold-rolled sheet with a thickness of 1.5mm and a deformation of 78% was annealed at 250℃, 275℃, 300℃, 325℃ and 350℃ for 2 hours in several. Annealing equipment is box-type resistance furnace, the model is SX2-4-10. Square specimens were cut with a line cutter and the dimension is 12mm×12mm×12mm. The length direction of the samples is set parallel to the rolling direction, use ethanol and perchloric acid in a volume ratio of 9:1 to prepare electrolytic polishing solution. The mechanically polished samples were electrolytically polished for 20-30s at 24 V, then rinsed with alcohol, keep dry. In the end, test the microstructure of the samples on the ZEISS EVO MA10 scanning electron microscope equipped with the EBSD calibration system. The operating parameters were as follows: acceleration voltage of 20 kV, specimen tilt angle of 70°, acquisition speed of 40.21 Hz. Deep drawing property test of 1.4mm thick cold rolled sheets was carried out with BTP-300 cupping test machine. The diameter of cup samples is 55 mm and the moving speed of the punch is 1mm/s.

3. Results and discussions

3.1. Effect of annealing temperatures on microstructure of 8011 cold-rolled sheet
Fig.1 shows the microstructure of cold rolled plates measured by the EBSD at different annealing temperatures. From the orientation map, after annealing at different temperatures, the microstructure of the 8011 cold-rolled sheets changed greatly. Fig.1(a) shows the microstructure of the unannealed plates. Under the effect of the rolling force, the structure is elongated into fibers. The microstructure is uneven, and some grains have been broken. Under the action of the rolling force, the microstructure was elongated into a fibrous form, becoming uneven, and some crystal grains were broken. There are a lot of fine grains near the elongated grains and maintain a certain orientation relationship. Fig.1(b) shows the rolled plates microstructure after annealing at 250℃. We can see that the structure had a slight recovery and the grains grew slightly. And recrystallization was in the primary inoculation stage, microstructure was still the previous deformed structure. After annealing at 275℃, the degree of the microstructure's recovery increased and the grains grew further, and the elongated grains were clear
and were observed easily. After annealing at 300 °C, the crystal grains grew significantly, but the particle size distribution was not uniform. There are obvious recrystallized microstructures and a lot of deformed structures. After annealing at 325 °C, the grains kept growing and the recrystallization was further strengthened. After annealing at 350 °C, the recrystallization process was basically completed, and the grains are homogeneous equiaxed grain structures. When the connected grains with smaller orientation difference increase with the annealing temperatures, one of the grains will rotate at a certain angle. When the angle of rotation makes the angle of orientation difference between the two adjacent grains roughly coincide with each other, the two grains will be merged into a new grain [16]. The grain boundaries of the newly generated grains continuously move and merge during the annealing process, eventually forming a new equiaxed grain.

After annealing at 325 °C and 350 °C, there are still some small grains distributed on the grain boundaries of the large grains in the microstructure of the cold-rolled sheets, and the phenomenon of cluster aggregation exists in some areas. In the process of grains growth, the growth of these small grains was inhibited by the large grains around, and so they did not have the preferential growth conditions. In addition, there are many substructures in the deformed matrix. Some substructures are still difficult to disappear after annealing at high temperatures, so they exist in recrystallized grains in the form of subgrain boundary.

![Fig. 1. The microstructure of the cold-rolled sheets unannealed and annealed at different temperatures: (a) Unannealed, (b) 250 °C, (c) 275 °C, (d) 300 °C, (e) 325 °C, (f) 350 °C.](image-url)
Fig. 2 shows the deformed microstructure content, recrystallized microstructure content and substructure content of the cold-rolled sheets after different annealing temperatures. It can be seen from the figure that with the annealing temperature increasing, the content of deformed microstructure first increases slowly, then decreases rapidly and finally becomes stable. The recrystallized microstructure decreased slightly with the increase of annealing temperatures and increases rapidly at 300°C. As the annealing temperature rise, the content of substructures decreased slightly, rising sharply at 300°C, and then decreased as the case of annealing temperature rise.

![Graph showing microstructure content changes](image)

Fig. 2 The microstructure content of the cold-rolled sheets unannealed and annealed at different temperatures

In unannealed cold rolled plates, the content of the deformed microstructure accounted for the majority, about 90%, containing less recrystallized microstructure, accounting for about 8%, and few substructures, about 2%. After annealing at 250°C, the content of the deformed microstructure increased slightly to 93.2%, the substructure content was basically unchanged, 1.8%, and the content of the recrystallized microstructure decreased slightly, to 5%. After annealing at 275°C, the content of the deformed microstructure increased to 95%, the substructure content decreased to 1%, and the content of the recrystallized microstructure decreased to 4%. After annealing at 300°C, the content of the deformed microstructure decreased sharply to 24%, the substructure content increased to a greater degree, increasing to 27%, and the change of the content of the recrystallized microstructure was also very significant, increasing to 49%. After annealing at 325°C, the content of the deformed microstructure continued to decrease to 4%, the substructure content began to decrease to 14%, and the content of the recrystallized microstructure increased sharply to 82%. After annealing at 350°C, there was no obvious change in the content of the deformed microstructure, the substructure content continued to decrease to only 0.5%, and the recrystallized microstructure content continued to increase to 96%.

It can be seen that the microstructure content of the cold rolled plates, the content of the deformed microstructure, the content of the recrystallized structure and the content of the substructure all change sharply annealing at 300°C, but they tend to be stable at 350°C. Therefore, it can be deduced that the initial temperature of recrystallization of 8011 cold-rolled plates is around 300°C, and the better annealing temperature is about 350°C.
Fig. 3 The misorientation distribution of cold-rolled sheets unannealed and annealed at different temperatures: (a) Unannealed, (b) 250°C, (c) 275°C, (d) 300°C, (e) 325°C, (f) 350°C.

Fig. 3 shows the misorientation distribution of cold-rolled plates under different annealing temperatures. There were many low-angle grain boundaries at different temperatures. When the
Annealing temperature is higher, the grain boundaries of medium and low angle of cold-rolled sheets decreased gradually. The general trend is that the low angle grain boundaries increase first and then decrease with the increase of annealing temperature. The proportion of low angle grain boundaries of cold rolled sheets is 49.3% without annealing, the proportion is 58.5% annealing at 250 °C, and it continues to rise at 275 °C, reaching the maximum value of 61.2%, starting to decrease to 45.9% at 300 °C, and continue to decrease to 29.3% at 325 °C, and to reach to the minimum value of 20.2% at 350 °C. After rolling, a large amount of deformed microstructure and deformation texture were formed on the aluminum sheets, and a large number of high-density dislocations were formed inside the sheets, resulting in the increase of low angle grain boundaries. After the cold rolling plates were annealed at high temperatures, the deformation energy was released, which made microstructure recovery and grains grow up, and dislocation energy reduced, and the high intensity annealing microstructure appeared. During the annealing process, a small number of low-angle grain boundaries changed to high-angle grain boundaries, which resulted in a large increase of high-angle grain boundaries. Low-angle grain boundaries can be modelled as dislocation arrays, and these dislocation structures play a vital role in determining the energy, dynamics and other properties of grain boundaries [17]. And the low-angle grain boundary plays a very significant role in the strengthening [18], which is in accordance with the characteristics that the yield strength and tensile strength of aluminum plate gradually decrease as the case of annealing temperature rise.

3.2. Effect of annealing temperature on texture and earing of 8011 cold-rolled sheet

3.2.1. Effect of annealing temperature on microtexture of 8011 cold-rolled plate. There are a lot of Brass texture, Copper texture and S texture in aluminium sheets after cold rolling. Deformation texture with high density will affect the subsequent processing and forming of aluminium sheets and cause higher earing rate for deep drawing aluminium sheets. Reasonable annealing process can reduce the deformation texture of aluminium sheet, when the amount of deformation texture and recrystallization texture reaches a certain balance, the aluminum sheet will have better deep drawing properties.

Fig. 4 shows the ODF after Testing and Analysis. From the pictures, we can see that there are obvious deformation textures such as B \{011\} < 211 > texture, C \{112\} < 111 > texture and S \{123\} < 634 > texture for cold-rolled sheets without annealing treatment. The recrystallization texture of Cube \{001\} < 100> begins to appear when annealing temperature is 300 °C, indicating that the initial recrystallization temperature of 8011 cold-rolled sheet with 78% deformation is about 300 °C. As the annealing temperature rise, the number of recrystallized textures continues to increase and the number of deformed textures continues to decrease. The recrystallization texture and deformation texture reach a good balance when annealing temperature is 350 °C.
3.2.2. Effect of annealing temperature on yield ratio of 8011 cold-rolled sheet. The yield ratio (known as the Y/T ratio) is an important parameter to measure the stamping formability of materials. Generally speaking, the lower the yield ratio of the material is, the stronger its plastic deformation ability is, and the better its stamping performance is [19-20]. In stamping process, the smaller the yield ratio of material, the smaller the stamping force and the corresponding plane shear stress are. Reducing the yield ratio of material can improve the quality of stamping products, reduce the defective rate and improve the stability of forming process. Fig. 5 shows the change of yield ratio of cold-rolled aluminum sheets under different annealing temperatures.

As can be seen from the Fig.5, with the increase of annealing temperature, the yield ratio of cold-rolled plates decreases first and then becomes stable. The yield ratio of aluminum sheets decreases from 0.95 to 0.88 when the annealing temperature is below 275°C, and the change is not large. After annealing at 300°C, the yield ratio decreases significantly to 0.44, by 53.68%. When annealing...
temperatures are greater than 300 ℃, the yield ratio decreases little with the increase of annealing temperature and remains at about 0.42.

3.2.3. Effect of annealing temperature on earing of 8011 cold-rolled sheet. The mechanical properties of aluminum plates are different after the multi-pass rolling, leading to uneven distribution of stress at different directions in stamping process and there are uneven bumps on the upper end of the samples, which are also called the earing. The occurrence of earing is not conducive to the industrial production of deep-drawn containers [21]. Excessively high earing needs to be removed, which increases production process and cost, and reduces production efficiency, reducing the earing rate is an important step to improve the drawability of the 8011-aluminum sheet.

For cold rolled sheets, the stronger deformation texture such as copper texture, brass texture and S texture produce earing in the direction of 45°direction. Strong recrystallization texture, such as cube texture, can lead to earing at 0°and 90°directions. After cup drawing tests, the peak height and valley height of earing were measured and the average value was calculated. For a quantitative assessment of earing, the mean earing value $e$ is determined, which is defined as:

$$ e = \frac{\bar{h}_p - \bar{h}_v}{\bar{h}_v} \times 100 $$

Where the values $\bar{h}_p$ and $\bar{h}_v$ correspond respectively to the average of all earing and all slots for a given cup profile.

Fig. 6 shows the earing ratio of cold-rolled sheets at different annealing temperatures. From the figure, we can see that the unannealed cold rolled sheets have a high earing rate of 8.33% in the direction of 45°, which shows that there is strong deformation texture in cold rolled sheets. Earing rate gradually decreased as the case of annealing temperature rise. The earing rate dropped from 6.18% to 3.73% when the annealing temperature is 300 ℃, down by about 39.64%. When annealing temperature is 350 ℃, the lowest earing rate is 2.11%. Compared with the cold rolled sheets without annealing, the earing rate is obviously reduced. After the cold-rolled sheets are annealed at different temperatures, the structure shows different degrees of recovery and recrystallization. When annealing temperatures are low, the degree of structure recovery is very low, the recrystallized structure does not appear, and the earing rate decreases slightly. When the annealing temperature is high, the degree of recovery of the structure becomes larger, and recrystallization structure appears, forming recrystallization texture. Fig. 7 shows the earing of cup-punching samples of the cold-rolled sheets after annealing at different temperatures. It can be seen from the figure that when annealing at 325 ℃ and 350 ℃, the edge of the small end face of the cup punching samples is flat, and the edge along the punching direction fluctuates little.
4. Conclusions

Based on the above results and discussion, the conclusions can be drawn as following.

1) The contents of the deformed microstructure, the recrystallized structure and the substructure change sharply annealing at 300°C, but they tend to be stable at 350°C. The starting temperature of recrystallization of 8011 cold-rolled plates is about 300°C.

2) When cold-rolled sheets were annealed at low temperature, there were many small-angle grain boundaries. When the annealing temperatures were higher, the small and medium angle grain boundaries of the cold-rolled sheets decreased gradually. The general trend was that as the case of annealing temperature rise, the small-angle grain boundaries first increased and then decreased. The proportion of the small-angle grain boundaries reached to the minimum value of 20.2% at 350°C.

3) After annealing at 300°C, the yield ratio decreases significantly to 0.44, by 53.68%. When annealing temperature is 350°C, the lowest earing rate is 2.11% and the edge of the small end face of the cup punching samples is flat.

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