Effect of Annealing Temperature on Microstructure and Properties of 8011 Cold-rolled Sheet

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Abstract. 8011 cold-rolled sheets with a deformation of 78% were annealed at different temperatures. The effect of annealing temperature on the microstructure and mechanical properties of cold-rolled sheets were analyzed using metallographic microscope, SEM, microhardness testing machine and tensile testing. The results show that with the increase of annealing temperature, the degree of recrystallization increased, the distribution of particle size and precipitated phase were more and more uniform, the elongation of 8011 cold-rolled sheets increased gradually while the hardness, tensile strength and yield stress decreased constantly. When annealing at 350°C, the microstructure of 8011 cold-rolled sheets was fine and homogeneous equiaxed grain structure, and the anisotropy index was the lowest. The optimum annealing temperature of 8011 cold-rolled sheets was about 350°C.

1. Introduction

Aluminum and aluminum alloy materials have the advantages of small density, high specific strength, machining and forming easily and high reusability and recyclability, and are widely used in various sectors of industrial production [1]. 8011 aluminum alloy is an aluminum alloy with Fe and Si as the main alloying elements. It is commonly used to make aluminum foils, and their performances are better than pure aluminum foils. Because of its excellent deep drawability and low gearing ratio, 8011 aluminum alloy has been widely used in the drug packaging, sealing packaging of cosmetic bottles, beverage bottles, and aluminum foils for air conditioner [2-4]. In the production of 8011 aluminum foils, after the multi-pass rolling of the cast strips, the original grains are transformed into flat and elongated deformed microstructure after severe plastic deformation, and there are a lot of crystal defects and high dislocation density in the plate, resulting in high hardness, uneven microstructure and residual stresses, which affect the subsequent product processing and service performance [5]. The mechanical properties of 8011 aluminum alloy are closely related to its microstructure, internal precipitation phase and heat treatment process. Improving the microstructure of aluminum sheets is an important means to improve their performances, and annealing treatment is a common method to improve the performances of aluminum alloy. Annealing process can improve material structure and reduce microstructure defects. And it can decrease hardness and improve the cutting machining properties of metal. Diffusion annealing can make the composition of the material uniform and reduce the anisotropy of the material.
Stress relief annealing can reduce the residual stress inside the material and reduce the occurrence of crack tendency [6-10]. Reasonable annealing temperatures and annealing time can improve the microstructure and properties of the sheets, which make the sheets have high strength and good plasticity, which is conducive to subsequent processing. Although there are many researches on annealing of aluminum alloys, there are few reports on 8 series aluminum alloys. Especially, there are few systematic researches and analysis on the effect of annealing on the microstructure and mechanical properties of 8011 aluminum alloy.

Based on production practice, the cold-rolled sheets with a deformation of 78% and a thickness of 1.5mm were annealed at 250°C, 275°C, 300°C, 325°C and 350°C for 2 h. The effect of annealing temperature on metallographic, mechanical properties, precipitated phase and recrystallized structure of cold-rolled sheets were studied by means of mechanical properties test, metallographic structure and tensile fracture morphology observation and SEM. The reasonable annealing temperature was determined, which provided a reference for the formulation of process in actual industrial production.

2. Experimental procedures and test methods

2.1. Materials and chemical compositions

The experimental material was the 8011 aluminum alloy with the chemical compositions listed in Table 1. The 8011 aluminum alloy cold-rolled sheets for the test were from ultrasound cast rolling plate with excellent performances after a five-pass cold rolling [11]. The cold-rolled sheets with the thickness of 1.5 mm and the total deformation of 78% were prepared.

| Element | Content  |
|---------|---------|
| Si      | 0.43-0.56 |
| Fe      | 0.63-0.80 |
| Cu      | <0.01    |
| Mn      | 0.06-0.015 |
| Mg      | <0.01    |
| Zn      | <0.01    |
| Ti      | <0.01    |
| Ni      | <0.01    |
| Al      | Bal.     |

2.2. Experimental process and equipments

The annealing treatment of 2 h was carried out at interval of 25°C (from 250°C to 350°C). The annealing equipment was the box type resistance furnace whose type is SX2-4-10. After the annealed samples were ground and polished, their Vickers hardness values were measured using a HV-1000A micro hardness tester. The applied load was 1 N with the dwell time of 10 s. Five results were tested for every samples, and after the maximum and minimum values were discarded, an average of the remaining three values was applied. Metallographic specimens with the dimensions of 10 mm×10 mm were cut by a line cutting machine. The length direction of the sample is parallel to the rolling direction. Electrolytic polishing solution was prepared by per chloric acid and ethanol in a volume ratio of 1:9. The samples were polished at a voltage of 24 V for 1 min. The anode coating agent was connected with 10 ml of fluoroboric acid and 400 ml of water. The working voltage was 24 V, and the lamination time was 3 min. The microstructure of the samples were observed using the OLYMPUS DSX500 metallurgical microscope (OLYMPUS Corporation, Japan). The morphology, size and distribution of the precipitated phase were observed using a Phenom fully automatic scanning electron microscope (Phenom-world BV, Holland). The standard tensile test samples were cut from the strips along the 0°direction (cast-rolling direction, RD), 45°direction and 90°direction (transverse cast-rolling direction, TD) using a line cutting machine. The directions and dimensions of the standard tensile specimens are shown in Fig.1. The mechanical properties of the samples were tested using a MTS 810 universal material testing machine (MTS Systems Corporation, USA) with a strain rate of 2 mm/min at room temperature, and the fracture morphology was observed using a Phenom fully automatic scanning electron microscope.
3. Results and discussions

3.1. Effect of annealing temperature on metallographic structure of 8011 cold-rolled sheet

Figure 2 shows the metallographic of the cold-rolled sheets unannealed and annealed at different temperatures. As can be seen, annealing temperatures have a significant effect on the metallographic structure of cold-rolled sheets. After the multi-pass rolling of cast rolling strips, the metallographic structure was elongated into a fibrous shape under the action of rolling force. Some grains were crushed to form uneven deformed structures. After annealing at 250°C and 275°C, the microstructure of the cold-rolled sheets slightly recovered. Some deformed stored energy was released, but the microstructure is still deformed structure. With the increase of annealing temperatures, the driving force of recrystallization and recovery of deformed microstructure increased. When the annealing temperature is 300 °C, obvious recrystallized structures can be observed, which indicates that the starting recrystallization temperature of cold-rolled sheets is about 300°C. But the grain size distribution was uneven, and there were some grains broken after rolling, as is shown in the circled region of Figure 2(d). The degree of recrystallization increased with the further increase of annealing temperatures and particle size distribution was more and more uniform, and more recrystallized grains appeared. The microstructure was fine and homogeneous equiaxed grain structure annealing at 350°C. This shows that the optimum annealing temperature of the cold-rolled sheets is about 350°C. Because coarse fibre grains had strong directionality, it was difficult to break grains in the subsequent foil rolling process and it was difficult to deform, which will result in uneven microstructure and properties, and make the shape of the sheets difficult to control and lead easily to the phenomena of strip breaks during the foil rolling process [12]. Appropriate grain refinement can avoid the generation of coarse grains, and the grain size has a marked effect on the strength and plasticity of the material [13]. Microstructure of the cold-rolled sheets was fine and homogeneous equiaxed grain structure annealing at 350°C, which is beneficial to the subsequent foil rolling.
3.2. Effect of annealing temperature on precipitates of 8011 cold-rolled sheet

The precipitation phase of 8011 cast rolling plates is a ternary phase in the Al-Fe-Si system. Figure 3 shows the precipitates of the cold-rolled sheets unannealed and annealed at different temperatures. From the pictures, we can see that the distribution, size and morphology of precipitated particles are different after annealing at various temperatures. The distribution of precipitated particles of unannealed cold-
rolled plates shows an uneven distribution. There is a certain enrichment phenomenon presenting block in some areas. When the annealing temperatures are relatively low (250°C and 275°C), the enrichment of precipitated phase has been weakened, but the distribution of the precipitate phase is still uneven, showing a chain. When the annealing temperatures are relatively high (300°C, 325°C and 350°C), the precipitated phase particles are small and spherical, dispersed in the whole aluminum alloy matrix, and their homogeneity is significantly improved.

Irregular block and long strip precipitates often have sharp edges and corners. It is easy to cause stress concentration at the tip, which is not conducive to the plastic deformation of the matrix. The spheroidal precipitations with symmetrical and smooth boundary are smaller than those of the matrix, which is beneficial to the uniform plastic deformation of the matrix. Therefore, annealing at 350°C of rolled plates is conducive to subsequent processing.

![Figure 3. The precipitation phase of the cold-rolled sheets unannealed and annealed at different temperatures](image)

3.3. Effect of annealing temperature on mechanical properties of 8011 cold-rolled sheet

The hardness test results of the annealed samples of cold-rolled plates after grinding and polishing are listed in Table 2.
Table 2. The hardness of cold-rolled plates at different annealing temperatures (HV)

| Temperature | effective test 1 | effective test 2 | effective test 3 | average value |
|-------------|------------------|------------------|------------------|---------------|
| 25°C        | 63.2             | 65.9             | 66.9             | 65.3          |
| 250°C       | 55.3             | 54.1             | 53.0             | 54.1          |
| 275°C       | 48.4             | 50.4             | 49.4             | 49.4          |
| 300°C       | 31.7             | 30.7             | 31.5             | 31.3          |
| 325°C       | 30.4             | 28.8             | 31.8             | 30.3          |
| 350°C       | 29.5             | 29.7             | 29.9             | 29.7          |

The working hardening of aluminium plates after cold rolling was serious and the average hardness reached 65.3 HV, the results are shown in Table 2. The reason for the phenomenon is that the grains were crushed and elongated under the action of rolling force, and there existed severe lattice distortion, then there were a large number of crystal defects such as vacancies or dislocations, which resulted in higher hardness of the aluminium plates. As can be seen, when the annealing temperature increased from 250°C to 275°C and from 275°C to 300°C, the hardness values had different degrees of decline, which reflects that the recovery and recrystallization degree of aluminium sheets were different under different temperatures. After annealing treatment at 300°C, the hardness value dropped to 31.3 HV, down by about 52%. After annealing treatment at 350°C, the hardness value dropped to 29.7 HV, down by about 54.5%. According to the temperature at which the hardness value decreases to 50% is defined as the recrystallization temperature of the material [14], it is further determined that the initial recrystallization temperature of the 8011 cold-rolled plate is about 300°C. When the annealing temperature increased from 300°C to 350°C, the hardness value of cold-rolled sheets changed little and remained at about 30 HV.

![Figure 4](image-url)

Figure 4. The mechanical properties of the cold-rolled sheets unannealed and annealed at different temperatures
Figure 4 shows the mechanical properties of the cold-rolled sheets unannealed and annealed at different temperatures. From the figures, we can see that the tensile strength and yield strength of aluminium sheets decreased gradually with the increase of annealing temperatures, but the decreasing degree was obviously different in different annealing temperature range. The tensile strength and yield strength dropped sharply at the annealing temperature from 250°C to 300°C. The tensile strength decreased from 215.73 MPa to 110.21 MPa, reducing by about 48.9%, and the yield strength decreased from 204.46 MPa to 46.67 MPa, reducing by about 77.2% in the RD direction. When the annealing temperature is from 300°C to 350°C, the tensile strength changed little, basically maintaining at 105 to 110 MPa, and the tensile strength was almost changeless, basically maintaining at 44 to 47 MPa. The elongation of aluminium plates increased with the increase of annealing temperatures. The elongation increased significantly from 250°C to 300°C, up from 6.1% of the cold-rolled sheets unannealed to 30.66%, increasing by 402.6%, while the elongation of aluminium sheets changed little and maintained at 30% to 37% at the annealing temperature from 300°C to 350°C.

According to the measured mechanical properties, the anisotropy index (IPA) was calculated by the following equation:

\[
IPA = \frac{2X_{\text{max}} - X_{\text{mid}} - X_{\text{min}}}{2X_{\text{max}}}
\]

Where \(X_{\text{max}}\) is the maximum of tensile strength, yield strength or elongation, \(X_{\text{mid}}\) is the middle value of tensile strength, yield strength or elongation, and \(X_{\text{min}}\) is the maximum of tensile strength, yield strength or elongation. The numerical value of IPA is used to show the difference of mechanical properties in different directions of plates and to characterize the anisotropy of materials. The results are shown in Table 3.

**Table 3. The anisotropy index of plate at different annealing temperatures**

| Temperature /°C | IPA(tensile strength)/% | IPA(yield strength)/% | IPA(elongation)/% |
|-----------------|-------------------------|-----------------------|-------------------|
| 25              | 3.4                     | 3.7                   | 21.48             |
| 250             | 3.8                     | 4.46                  | 18.06             |
| 275             | 10.93                   | 15.87                 | 11.51             |
| 300             | 5.79                    | 10.38                 | 10.77             |
| 325             | 5.95                    | 6.88                  | 11.15             |
| 350             | 0.38                    | 0.23                  | 3.42              |

The results show that IPA (\(\sigma_b\)) and IPA (\(\sigma_t\)) increased firstly and then decreased with increasing annealing temperatures. When the annealing temperature was 275°C, IPA (\(\sigma_b\)) and IPA (\(\sigma_t\)) are 10.93% and 15.87%, respectively and the anisotropy of cold-rolled sheets was the most significant. When the annealing temperature was 350°C, the anisotropy index of cold-rolled sheets is very low, IPA (\(\sigma_b\)) and IPA (\(\sigma_t\)) are 0.38% and 0.23% respectively. IPA (\(\delta\)) first decreased, then rised and then decreased with the increase of annealing temperatures. When the cold-rolled sheets was unannealed, the highest IPA (\(\delta\)) was 21.48%, and the lowest reached 3.42% after annealing at 350°C. Therefore, after annealing at 350°C, the anisotropy index of the cold-rolled sheets was the lowest, and their mechanical properties are the most balanced.

The cold-rolled sheets underwent different degrees of recovery and recrystallization during different annealing temperatures, and the deformation energy storage had different degrees of release [15]. When annealing temperatures are low, the microstructure recovery and grain growth are relatively weak. With the increase of annealing temperatures, atoms diffusion is promoted, and more deformation energy storage is released, and the driving force of recrystallization increases, thus improving the nucleation rate [16]. Annealing can reduce the density of crystal defects dominated by dislocation in the process of cold rolling and improve the degree of recrystallization of the cold rolling deformed microstructure, which leads to the reduction of the strength and the increase of the elongation of the plates.
Figure 5 shows the fractography of the tensile samples of the cold-rolled sheets unannealed and annealed at different temperatures. From the figures, we can see that fracture in all the states shows dimple fracture characteristics, which is full of dimples of different sizes. The shape of the dimples is mainly elongated oval or round. Tensile fracture mode belongs to typical ductile fracture. The unannealed cold-rolled sheets have shallow dimples, which indirectly indicates its low elongation. With the increase of annealing temperatures, the depth of dimples had different degrees of increase. When the annealing temperature was 350°C, there is obvious necking phenomenon at tensile fracture and size distribution of dimples is uniform, which also shows that the cold-rolled sheets annealing at the temperature have higher elongation and the annealing treatment improves the plasticity of the material.

![Figure 5. The fractography of the tensile sample of the cold-rolled sheets unannealed and annealed at different temperatures](image)

4. Conclusion
According to the above results and discussions, the following conclusions can be drawn.

1. When the annealing temperature was 300°C, obvious recrystallized structures can be observed. But the grain size distribution was uneven. The degree of recrystallization increased with the further increase of annealing temperatures and particle size distribution was more and more uniform, and more recrystallized grains appeared. The microstructure was fine and homogeneous equated grain structure annealing at 350°C. When the annealing temperatures are relatively high, the precipitated phase particles are small and spherical, dispersed evenly in the whole aluminium alloy matrix. The optimum annealing temperature of 8011 cold-rolled sheets was about 350°C.

2. With the increase of annealing temperatures, the hardness, tensile strength and yield strength of 8011 cold-rolled sheets decreased gradually, but the elongation of sheets and the depth of dimples of tensile fracture increased gradually. When annealing at 350°C, the anisotropy index of 8011 cold-rolled sheets was the lowest, which indicates that their mechanical properties are the most balanced, and there was an obvious necking phenomenon at tensile fracture and size distribution of dimples was uniform.
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References
[1] Miller W S, Zhuang L, Bottema J, et al. Recent development in aluminium alloys for the automotive industry. Materials Science & Engineering A, 2000, 280 (1), p37 - 49.
[2] Ryu J H, Lee Y S, Dong N L. The effect of precipitation on the evolution of recrystallization textures in an AA 8011 aluminum alloy sheet. Materials Science & Engineering A, 2002, 336(1–2), p225 - 232.
[3] Luiggi A. N J. Precipitation Study in a Commercial 8011 Alloy. Materials Science Forum, 1996, 217 - 222, p883 - 888.
[4] Xing Z P, Kang S B, Kim H W. Softening behavior of 8011 alloy produced by accumulative roll bonding process. Scripta Materialia, 2001, 45 (5), p597 - 604.
[5] Ding H, Shen N, Shin Y C. Predictive modeling of grain refinement during multi-pass cold rolling. Journal of Materials Processing Tech, 2012, 212 (5), p1003 - 1013.
[6] Zhao F X, Xu X C, Liu H Q, et al. Effect of annealing treatment on the microstructure and mechanical properties of ultrafine-grained aluminum. Materials & Design, 2014, 53 (1), p262 - 268.
[7] Yong-Fu W U, Liu X H, Xie J X. Effect of annealing temperature on texture and properties of copper cladding aluminum flat bar fabricated by continuous casting and subsequent rolling technology. Chinese Journal of Nonferrous Metals, 2014, 24 (1), p188-196 (in Chinese).
[8] Wang J, Xu J, Pan F. Effect of annealing on microstructure and properties of Er modified 5052 alloy. Results in Physics, 2018.
[9] Kumar R, Gupta A, Kumar A, et al. Microstructure and texture development during deformation and recrystallization in strip cast AA8011 aluminum alloy. Journal of Alloys & Compounds, 2018, p742.
[10] Wang X, Guo M, Luo J, et al. Effect of intermediate annealing time on microstructure, texture and mechanical properties of Al-Mg-Si-Cu alloy. Materials Characterization, 2018, p142.
[11] Shi C, Shen K. Twin-roll Casting 8011 Aluminium Alloy Strips Under Ultrasonic Energy Field. International Journal of Lightweight Materials & Manufacture, 2018.
[12] Keles O, Dundar M. Aluminum foil: Its typical quality problems and their causes. Journal of Materials Processing Tech, 2007, 186 (1), p125 - 137.
[13] Burger G B, Gupta A K, Jeffrey P W, et al. Microstructural control of aluminum sheet used in automotive applications. Materials Characterization, 1995, 35 (1), p23 - 39.
[14] Wu H, Wen S P, Wu X L, et al. A study of precipitation strengthening and recrystallization behavior in dilute Al–Er–Hf–Zr alloys. Materials Science & Engineering A, 2015, 639 (4), p307 - 313.
[15] Wang Y, Cao L Y, Jun-Peng L I, et al. Effect of Intermediate Annealing on Microstructure and Property of 5182 Aluminum Alloy Sheet for Automobile. Journal of Materials Engineering, 2016, 44 (9), p76 – 81.
[16] Humphreys, F. J., and M. Hatherly. Recovery After Deformation, Recrystallization and Related Annealing Phenomena, 3rd. John Fedor, 2017, p199 - 204.