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Study on the Effect of Aging Treatment on the Microtexture and Mechanical Properties of 6111 Aluminum Alloy

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The effects of aging treatment temperature of 250 °C on microstructure, mechanical properties characteristics of 6111 aluminum alloy sheet were investigated by mechanical testing, scanning electron microscopy, electron backscatter diffraction and other analytical methods. The results show that the aging treatment temperature has a significant effect on the yield strength of cold rolled 6111 aluminum alloy, and appropriate heat treatment can significantly improve the work-hardening properties of rolled 6111 aluminum alloy. The rolled sheet without heat treatment aging shows the highest strength values, with the yield strength reaching 140.2 MPa and the tensile strength 211.2 MPa, while the tensile strength decreases to 119.2 MPa and the yield strength to 35.1 MPa when the heat treatment aging temperature of the cold-rolled sheet is set at 250 °C. In terms of the plastic behavior of the sheet, the elongation reaches a maximum value of 31.3% when aging at 250 °C. The elongation of the cold-rolled aluminum alloy reaches a maximum value of 31.3% when aging at 250 °C. The elongation reached the maximum value of 31.3% at the aging temperature of 250°C.

Keywords: Aging Treatment, 6111 Aluminum Alloy, Mechanical Properties

1 Introduction

Aluminum alloy, as a metal material with both lightweight and high-strength characteristics, has been widely used in high-end industrial fields such as automobile manufacturing and aerospace by virtue of its density, which is about one-third of that of steel, and its excellent mechanical properties[1]. In the process of automobile lightweighting, aluminum alloy effectively reduces the quality of the whole vehicle and improves fuel economy and handling performance by replacing traditional steel in the manufacture of engine blocks, body frames and other key components[2]; and in the field of aerospace, its high specific strength characteristics make it the core material for the load-bearing structure of the aircraft wings, fuselage skins and other bearing structures, which significantly reduces the flight loads while guaranteeing the safety of the structure.

The 6-series aluminum alloys, especially the 6111 aluminum alloy containing Mg_2Si, are widely used in automotive applications due to their good formability, moderate mechanical properties, excellent corrosion resistance and weldability, as well as good oxidation coloring properties. Compared with conventional automotive steels, 6-series aluminum alloys exhibit higher specific strength and specific stiffness through thermo-mechanical treatment, which helps to achieve lighter weight of vehicles [3,4]. This not only significantly improves the range of the vehicle, but also effectively reduces fuel consumption and tailpipe emissions, thus mitigating the pollution of the atmosphere [5,6].

When 6111 aluminum alloy is applied to automotive body cladding parts, high requirements are placed on its strength and formability. Therefore, an in-depth study of the strength and plasticity of the plates is of great significance to realize the lightweighting of the body and to improve the safety and reliability of the vehicle.The properties of 6111 aluminum alloy are affected by a variety of factors, including the state of the material and the aging temperature of the heat treatment. The corrosion resistance changes after solid solution and pre-aging at different temperatures [7]. In addition, the alloy is sensitive to heat treatment temperature, so it is particularly important to study the material properties and work-hardening characteristics under different aging treatment processes to expand its applications [8].

Studies have shown that the corrosion resistance of 6111 aluminum alloy changes after solid solution and pre-aging at different temperatures. With the extension of aging time, its mechanical properties first increase and then decrease, and the higher the aging temperature, the shorter the time to reach the peak. The hardening response of plates treated with pre-ageing after solid solution under artificial ageing is significantly higher than that of natural ageing treatment. In addition, the mechanical properties of in-situ hot roll-formed 6111 aluminum alloy containing ZrB_2 particles were improved after T4 heat treatment, indicating that heat treatment can well repair the defects of roll forming [9,10]. The material is strengthened by nano-precipitation, solid solution aging treatment and other advanced processes to increase the tensile strength to more than 700 MPa, while maintaining excellent fracture toughness and corrosion resistence [11].

In this paper, the influence of temperature on the properties and work-hardening characteristics of 6111 aluminum alloy is studied in depth from the perspective of aging treatment temperature. By fully investigating the changes in mechanical properties and work-hardening characteristics of 6111 aluminum alloy under different heat treatment process conditions, this paper aims to explore the optimal heat treatment aging process to provide certain reference for the industrial production of 6111 aluminum alloy.

2 Experimental Materials and Methods

The test material was selected 6111 aluminum alloy, which was firstly subjected to solid solution treatment at a temperature of 500°C and held for 60 seconds. After that, the use of self-research mill, roll diameter of 180mm, cold rolling of the material, the thickness of 1.02mm 6111 aluminum alloy cold rolled sheet, the specific composition of the table 1. Then, the cold rolled sheet is placed in a heat treatment furnace, at 250 °C insulation for 2 hours, and then water-cooled to room temperature.

For the specimens after the heat treatment aging process, the tensile specimens were cut along the rolling direction (parallel to the marking distance) using an EDM cutting machine bed, and the specimen marking distance was 10 mm in length and 4 mm in width.Subsequently, the tensile properties of these specimens were tested on a universal tensile testing machine. The fracture of the specimens after tensile fracture was then observed by scanning electron microscopy. In addition, two specimens in the rolled state (UT) and aged at 250 °C for 2 hours (HT) were selected to test their microstructures using the electron backscatter diffraction (EBSD) technique.

Tab. 1 Chemical composition of the 6111 aluminum alloy (mass fraction, %)

Element	Mg	Si	Cu	Fe	Mn	Cr	Ti	Al
Mass fraction	0.6	0.5	0.54	0.3	0.24	0.13	0.13	Bal

3 Test results and Analysis

3.1 Grain, Weaving and Orientation Analysis

Grain characteristics have a significant effect on the mechanical properties of materials, such as strength and hardness. This effect stems from the differences in stress distribution and crystal defects caused by different orientation angles.

3.1.1 Grain morphology and size analysis

As shown in Fig. 1, with the increase of aging treatment temperature, the grain size shows a trend of gradual increase, and adjacent grains begin to reorganize. According to the Hall-Petch formula, the increase in grain size predicts that the tensile strength of the material may be reduced in the subsequent tensile test. During cold rolling, the alloy organization undergoes deformation and elongation due to the introduction of large plastic deformation, as shown in Fig. 1 (a). At this time, the grain size decreases, and the percentage of grain equivalent circular diameter less than 20 μm is more than 95%. There is also a large amount of residual stress accumulated within the organization, resulting in a high distortion energy of the plate. And when the cold rolled 6111 alloy after heat treatment aging, as shown in Fig. 1 (b), the grain of the metal material will grow, and the percentage of grain equivalent circular diameter less than 20 μm remains above 93%. This is because the diffusion rate of atoms is accelerated under high-temperature conditions, and the ability to move grain boundaries is enhanced, which provides a larger space for grain growth. At the same time, aging treatment also helps to reduce internal defects, so that the organization is gradually stabilized, thus improving the plasticity of the material. This change keeps the strength of 6111 aluminum alloy sheet at a high level and the plasticity relatively low, a result consistent with the stress-strain curve shown in Fig. 4.

After plastic deformation by cold rolling, the angular grain boundaries formed inside the alloy are all larger than 2°, of which the grain boundaries between 2° and 10° accounted for 59.5 %, and the grain boundaries larger than 10° accounted for 40%, and these grain boundaries are densely distributed inside the grains, which indicates that the dislocation density inside the grains is high. The large angle grain boundaries are mainly distributed around the grain boundaries. When the aging temperature is increased, the recrystallization volume fraction of the grains increases, and the percentage of grain boundaries between 2° and 10° increases to 61.7 %, while the percentage of grain boundaries larger than 10° decreases to 38 %. This is mainly due to the gradual coarsening of the strip grains formed during rolling. The average grain orientation difference is often used to assess the degree of grain recrystallization, and it was observed that the grain orientation difference was lower for large grain bases, which suggests that grain growth and recrystallization occurred after aging at 250 °C for 2 hours. However, not all grains were fully recrystallized, indicating that complete recrystallization of 6111 aluminum alloy was not achieved under this aging condition.

Comparative analysis of the Kernel average misorientation (KAM) values of the grains of different orientations of the samples in different states reveals that, regardless of whether recrystallization of the grains occurs or not, the KAM values of the grains decreased significantly after the aging heat treatment. This means that aging at 250 °C for 2 hours effectively releases the stresses stored inside the grains, which in turn improves the plasticity of the material. At the same time, the grains gradually grew with the aging time.

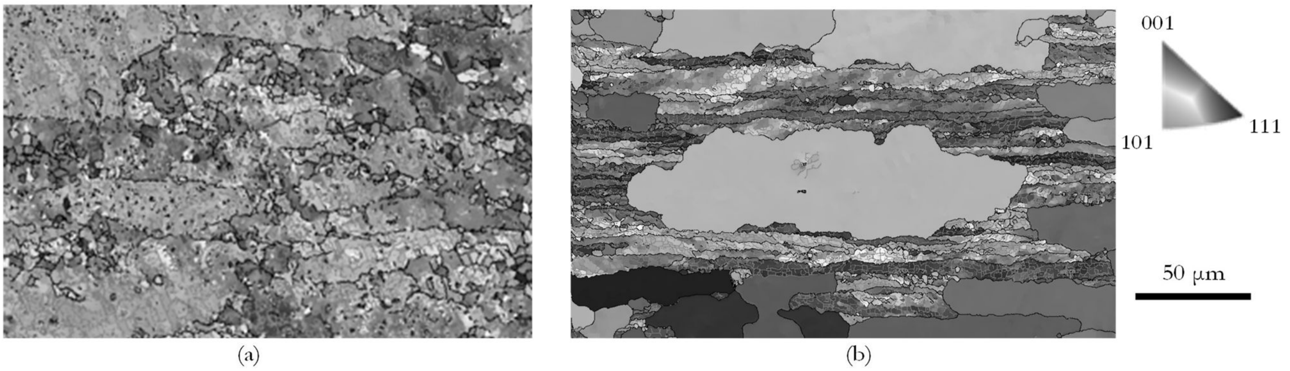

Fig. 1 *Reverse polarity diagram with grain boundaries; (a) Cold rolling; (b) 250 ℃ aging after cold rolling*

3.1.2 Organizational Orientation Analysis

Fig. 2 (a)-(f) demonstrate the polar plots and antipodal plots of the unageing treated samples after rolling. After plastic deformation, it can be seen from the polar plots of the coordinate system of the sample shown in Fig. 2 (b) that the crystals in the sample appeared to be selectively oriented in the {110} direction in the range of about 10.5°. Meanwhile, by observing the antipodal plot of the crystal coordinate system in Fig. 2 (d), it can be observed that the {110} grain orientation tends to be parallel to the rolling direction (RD). This observation further confirms that the grains have undergone severe twisting deformation.

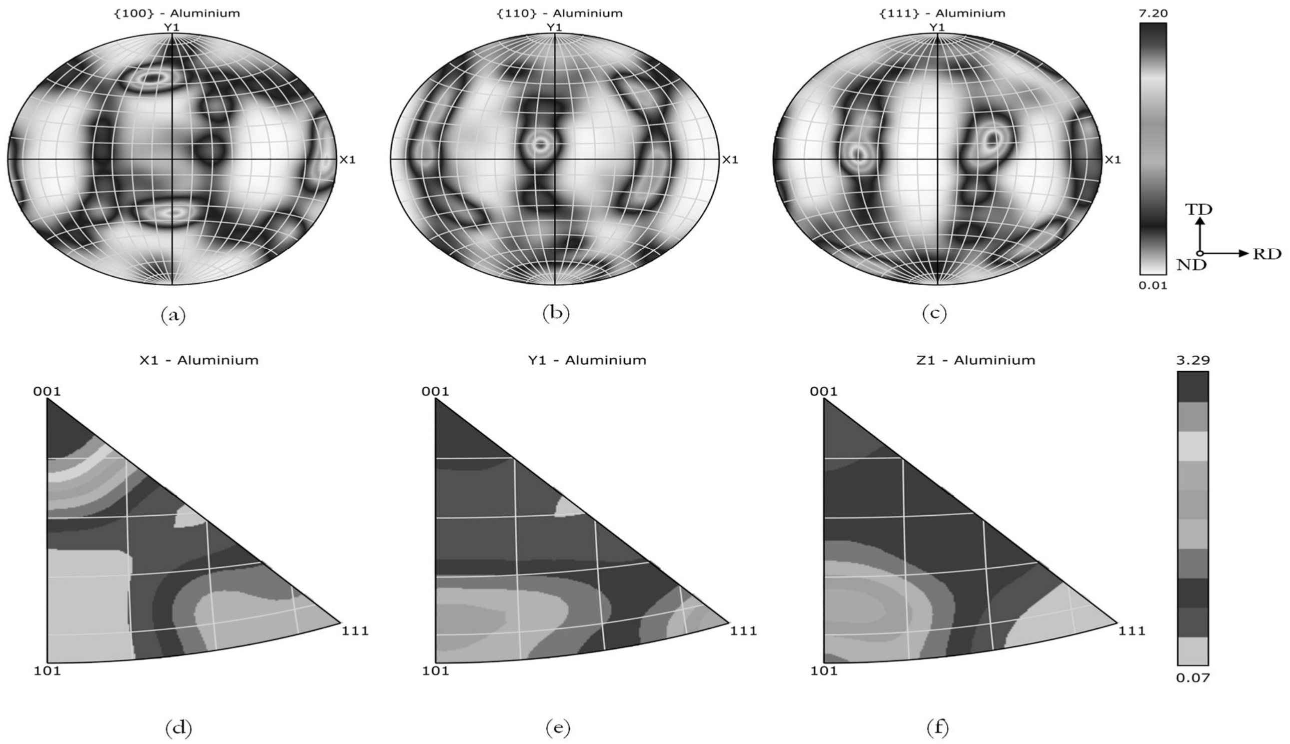

Fig. 2 *Polar plots and antipodal plots of the workpiece after cold rolling; (a-c) polar plots in the {100}{110}{111} direction of the sample coordinate system; (d-f) antipodal plots in the {100}{110}{111} direction of the crystal coordinate system*

Fig. 3 (a)-(f) demonstrate the polar and antipolar diagrams of the 250 °C aging-treated samples. After the aging heat treatment, the crystal orientation in the sample starts to show a decentralized distribution as shown by the polar plot of the coordinate system of the sample in Fig. 3 (b). Moreover, by observing the antipodal plot of the crystal coordinate system in Fig. 3 (d), it can be seen that {110} the tendency of the crystal orientation to tend to be parallel to the rolling direction (RD) also began to weaken. This further indicates that the twisting deformation of the grains is released.

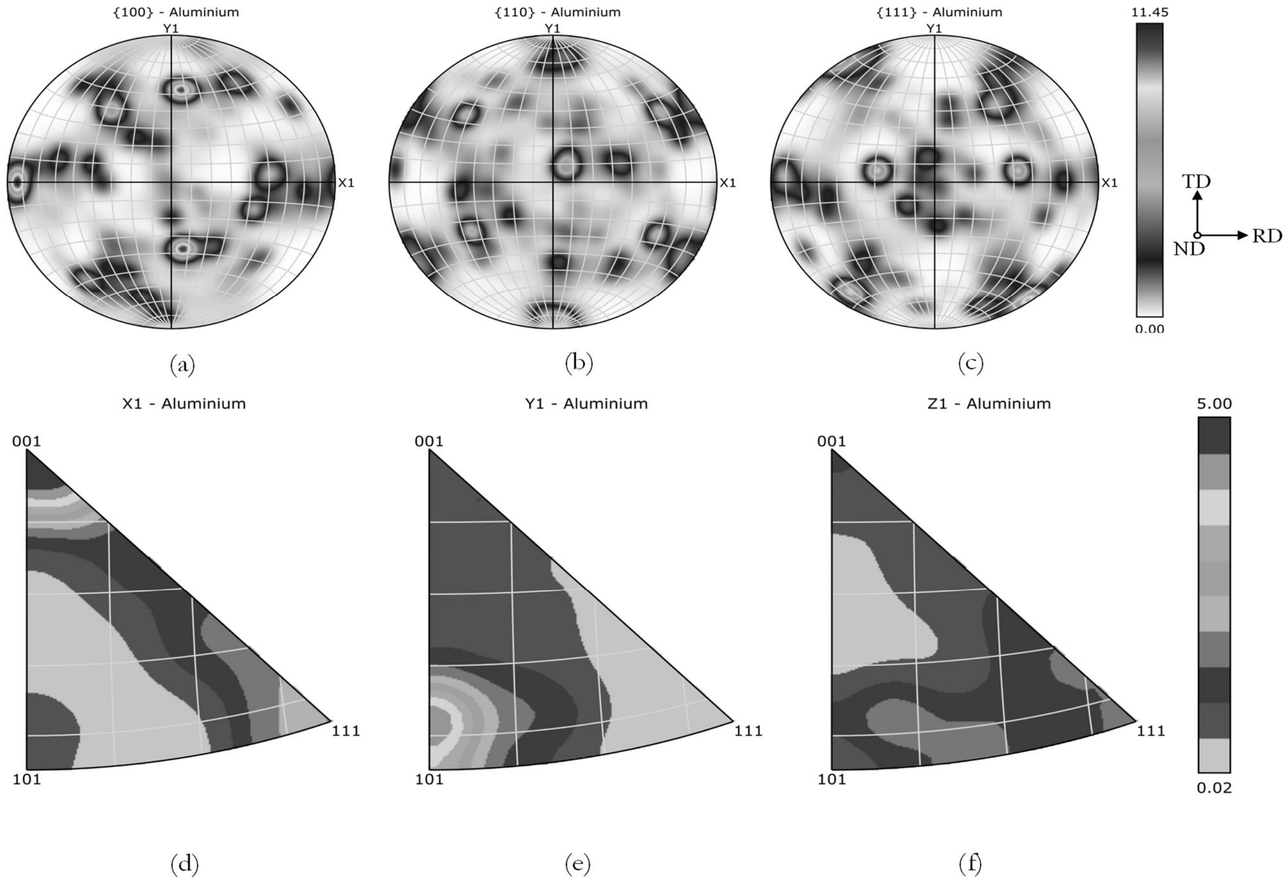

Fig. 3 *Polar plots and antipodal plots of the workpieces treated by aging at 250 °C after cold rolling; (a-c) polar plots in the {100}{110}{111} direction of the sample coordinate system; (d-f) antipodal plots in the {100}{110}{111} direction of the crystal coordinate system*

3.2 Tensile Performance Analysis

Fig. 4 demonstrates the tensile properties of 6111 aluminum alloy plates after heat treatment aging temperature treatment. The tensile strength and plasticity of the plates at room temperature show opposite trends, with the rolled plates exhibiting the greatest yield and tensile strengths. The strength gradually decreases with increasing aging temperature, while the plasticity increases. Rolled plates aged without heat treatment have the highest strength values, with a yield strength of 140.2 MPa and a tensile strength of 211.2 MPa. In cold rolled 6111 alloy plates that have not undergone heat treatment aging, Its tensile strength decreases to 119.2 MPa, and its yield strength is 35.1 Mpa.the presence of these defects and residual stresses results in plates with higher strength and lower plasticity. However, after aging treatment, the defects and residual stresses inside the plates were released and eliminated to a certain extent, which improved the plasticity of the plates, but correspondingly reduced their strength [12].

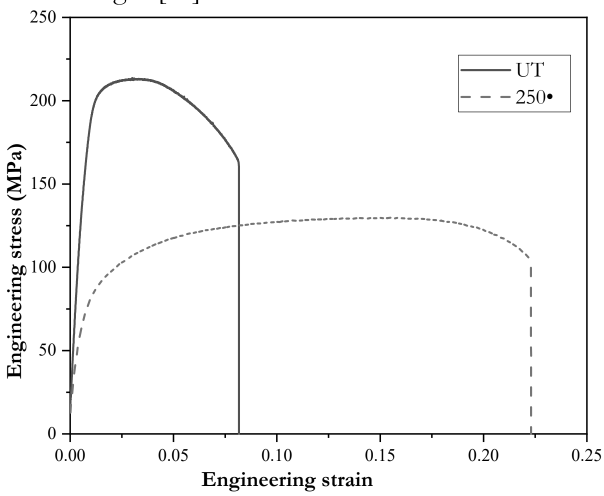

Fig. 4 *The Room Temperature Engineering Stress-Strain Curves After Aging Treatment at Various Temperatures*

3.2.1 Analysis of microstructure and fracture behavior of tensile fracture surface

Fig. 5 shows the tensile fracture micro-morphology of 6111 aluminum alloy cold rolled sheet treated with different aging treatment temperatures. It is observed that the sample aged at 250 °C has the largest and deepest number of fracture ligament fossae, which is a clear indication that the plasticity of the sheet is optimal at this time. In contrast, the fracture ligament foci of the samples without aging treatment appeared to be small and shallow. This is due to the fact that the increase in aging temperature induces a coarsening of the grain size in the tissue, which increases the elongation of the plate and correspondingly decreases its strength, an observation that is consistent with the actual test results.

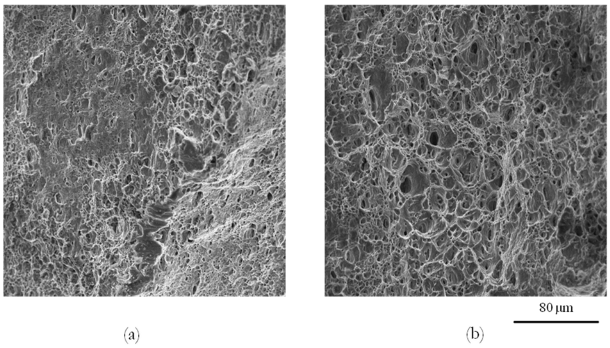

Fig. 5 *Tensile fracture morphology; (a)After 250 ℃ aging temperature treatment after cold pressing; (b)Cold rolling at room temperature*

The number of tough nests and their morphology in the fracture profile is a key basis for evaluating the performance of 6111Al alloy under the aging regime. Generally speaking, the high number and depth of ligamentous fossae in the tensile fracture imply that the material has excellent plasticity accompanied by low strength; on the contrary, when the number of ligamentous fossae is low and shallow, the material shows low toughness and has high strength.

Meanwhile, during the tensile process, the formation of tough nests originates from the rapid plastic deformation of the material, which leads to the stress concentration of dislocations in the tissue during the slip process. At the same time, the micropores inside the material organization will preferentially become nucleation points. During the stretching experiments, the repulsive force on dislocation movement decreases, allowing a small number of dislocations to enter the micropores and thus activate the dislocation source. As the stretching process continues, new dislocations are continuously generated and enter the micropores, which promotes the growth of micropores. Eventually, a large number of micropores converge at the fracture location, forming a visible tough nest.

4 Discussion

The grain refinement and deformation in the rolling process is the basis for enhancing the subsequent processing properties of the material. The elongation and fracture of grain boundaries prompts the original grain to refine and change its shape, forming a new grain structure, which provides a good organizational basis for the subsequent aging treatment. Aging treatment further promotes changes in grain morphology, such as elongation or compression, and grain growth. This phenomenon can be attributed to the acceleration of the atomic diffusion rate at high temperatures and the enhancement of the ability to move grain boundaries, which provides a larger space for grain growth and thus affects the macroscopic properties of the material.

Aging treatment not only changes the grain morphology, but also significantly affects the type and distribution of grain boundaries. After cold rolling plastic deformation, a large number of small-angle grain boundaries were formed within the alloy, which were densely distributed within the grains, reflecting the high dislocation density. In contrast, large-angle grain boundaries are mainly distributed around the grain boundaries. After the aging treatment, some of the grains recrystallized, resulting in a change in the grain orientation difference, with the grain orientation difference at the base of the large grains decreasing, while the orientation between grains became more randomized. This phenomenon indicates that the aging treatment optimizes the distribution of grain boundaries while promoting grain recrystallization, which in turn affects the mechanical properties of the material.

Regarding the plasticity of the plates, the 250 °C aging heat treatment significantly increased the elongation of the plates to 31.3%. This increase can be attributed to the release and elimination of internal defects and residual stresses in the plate during the aging treatment, thus improving the plasticity of the plate. However, at the same time, the strength of the plates decreased. This result is in accordance with the general rule in material science that there is often a trade-off between plasticity and strength.

The observation of the micro-morphology of the tensile fracture further verified the effect of aging treatment on the properties of 6111 aluminum alloy. The fracture of the unaged sample shows small and shallow toughness pockets, indicating poor plasticity, while the fracture of the aged sample shows a large number of equiaxial and deep toughness pockets, indicating a significant increase in plasticity. The formation of tough nests is related to the dislocation motion and microporous nucleation inside the material, and the aging treatment promotes the formation and growth of tough nests by optimizing the grain structure and reducing the internal defects, thus improving the plasticity of the material.

The effects of different aging treatment temperatures on the morphology of tough nests also show a certain pattern. With the increase of heat treatment temperature, the toughness fossa gradually deepens, which reflects the grain coarsening phenomenon caused by the temperature increase. The coarsening of the grain not only improves the elongation of the plate, but also reduces its strength, which is consistent with the actual test results. Therefore, the microstructure and mechanical properties of 6111 aluminum alloy can be further optimized by reasonably regulating the aging treatment temperature and time to meet the demands of different application scenarios.

In summary, rolling and aging treatment are effective means to regulate the microstructure and enhance the material properties of 6111 aluminum alloy. Through in-depth analysis of the functioning mechanism of the two and their effects on the material properties, it can provide useful reference and guidance for the research and development and application of aluminum alloy materials.

5 Conclusions

In this paper, the effect of aging treatment at 250 °C on microstructure, mechanical properties and work-hardening characteristics of 6111 aluminum alloy plate was investigated by mechanical testing, scanning electron microscopy and electron backscattering diffraction. The results show that:

- The aging treatment temperature significantly affects the yield strength of cold rolled 6111 aluminum alloy. The yield strength and tensile strength of the rolled sheet without aging treatment were as high as 140.2 MPa and 211.2 MPa, respectively, while after aging treatment at 250 °C, these two strength indexes were reduced to 119.2 MPa and 35.1 MPa, respectively, which indicated that the aging treatment had a significant modulation on the strengthening mechanism of the aluminum alloy.
- Appropriate heat treatment significantly enhanced the work-hardening properties of rolled 6111 aluminum alloy, optimized the microstructure, and possibly enhanced the deformation resistance of the material by refining the grains or promoting the formation of precipitates.
- In terms of plasticity, the plates under aging treatment at 250 °C exhibited the best elongation of 31.3%, indicating that this aging temperature is conducive to the enhancement of the plastic deformation capacity of the aluminum alloy.

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