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Study on anisotropic behavior of 7075 Al alloy after extrusion

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Abstract

For an extrusion process of 7075 Al alloy, the extrusion direction of the initial blank is changed to study the mechanical properties of the formed plates and characterize their microstructure. The as-received bar is extruded 7075 Al alloy. The secondary extrusion deformation is along and perpendicular to the initial extrusion direction. The results show that the anisotropy of mechanical properties of the two samples decreases obviously after secondary deformation. The anisotropy of yield strength and ultimate tensile strength of ED90 sample is lower than that of ED0 sample, but the plastic anisotropy is slightly higher than that of ED0 sample. In addition, the recrystallized grain proportion of ED90 sample is high and the texture strength is low, so the Schmid factor in the three directions is similar. The tensile fracture mode of the two samples belongs to ductile fracture, but the morphology of dimple and the size of cleavage plane are slightly different.

1. Introduction

7xxx aluminum (Al) alloy was widely used in aerospace and transportation industries, due to its excellent properties of low density, high specific strength and specific stiffness. Thus, 7075 Al alloy had great potential as a structural material\cite{1, 2}. High strength Al alloys could reduce the weight of parts and cost of construction applications\cite{3, 4}.

As cast 7075 Al alloy had coarse grains and some casting defects such as shrinkage cavity and porosity. Its mechanical properties were poor, so it could not be directly applied to production practice. These casting defects of 7075 Al alloy must undergo a series of subsequent treatment, including plastic deformation, heat treatment, surface treatment and other means to improve its comprehensive mechanical properties. However, due to the directional flow of metal in the deformation process, the extrude alloy had anisotropy of mechanical properties, which greatly limited the application of extruded 7075 Al alloy. The mechanical behavior of materials after rolling or extrusion deformation was different in different directions, which meant the anisotropy of mechanical properties\cite{2}. Previous researchers have done some research on the anisotropy of the Al alloys\cite{5–11}. Ye et al\cite{11} studied the compression deformation behavior of 6063-T4 Al alloy extruded bar at 0°, 45° and 90° with the axis. It was found that the flow stress of 0° sample was greater than that of 45° and 90° samples. Guo et al\cite{12} mentioned the quasi-static mechanical properties of Al-Zn-Mg-Cu alloy extrusion rod at 0°, 45° and 90° with the extrusion direction, and found a similar law. The 0° specimen showed the highest peak stress. Rahman et al\cite{13} investigatd 6013 and 7075 Al alloy plates. Both plates showed obvious plastic anisotropy in mechanical property test. In a previous research work\cite{14}, the author discussed the anisotropy of T6 extruded 7075 Al alloy bars, and explained the anisotropy of mechanical properties of extruded profiles by analyzing grain morphology, texture type and Schmid factor. During the deformation process, the specific grain morphology and crystal texture are formed in the Al alloy, resulting in obvious anisotropy, which affects the further popularization and application of Al alloy in the field of aerospace\cite{15, 16}.

From the above studies, it was shown that the anisotropy of mechanical properties of extruded Al alloys was common, and many researchers have explained the causes of anisotropy from the micro point of view\cite{17–22}.
Fjeldly et al. [23] carried out uniaxial tensile test and texture analysis on AA7108 Al alloy plate, which showed that the cause of anisotropy was the formation of texture during deformation. Ye et al. [11] attributed the anisotropy of mechanical properties of extruded Al alloys to the formation of {112}〈111〉 and {110}〈111〉 textures during extrusion, resulting in the anisotropy of flow stress in all directions. Y et al. [24] studied the anisotropy of Al-Zn-Mg alloy extrusion plate, and also attributed the anisotropy of mechanical properties to rolling texture.

Extrusion deformation was one of the commonly deformation technologies in industrial production. The anisotropy of mechanical properties of formed plates was an important aspect to measure the quality of this deformation process. The anisotropy of formed plates greatly restricted its application range. Therefore, it was urgent to propose a means to improve the common deformation process, so as to weaken the anisotropy of parts. In this paper, 7075Al alloy bar was extruded in different directions according to a specific extrusion process, and the effects of different initial grain morphology on the mechanical properties of the formed samples were studied to guide the production practice. The purpose is to find a method to weaken the anisotropy of mechanical properties after deformation.

2. Experimental methods

2.1. Materials

The raw material is extruded 7075 Al alloy, and its composition is shown in Table 1.

Table 1. Chemical composition of the 7075 Al alloy (wt%).

| Element | Zn | Mg | Cu | Mn | Fe | Si | Cr | Ti | Al  |
|---------|----|----|----|----|----|----|----|----|-----|
| Content | 5.97 | 2.07 | 1.58 | 0.27 | 0.32 | 0.11 | 0.14 | 0.028 | Bal. |

In order to study the effect of initial grain shape and texture type on the mechanical properties after extrusion, two types of as-received samples (79 mm × 79 mm × 90 mm) are used for the extrusion process: (1) the extrusion direction coincide with the extrusion direction of the original bar (ED0); (2) The extrusion direction is perpendicular to the extrusion direction of the original bar (ED90). Firstly, the two kinds of billets are and the die are preheated. The preheating temperature of the samples is 470 °C and the preheating time is 1h. The preheating temperature of the die is 450 °C, and the preheating time is 5h. Then, it was formed on a press with a full load of 630t at a pressing speed of 10 mm s⁻¹, and air cooling was carried out after forming.

Figures 1(a), (b) shows the sampling position of the extruded blank and the die structure. After the extrusion process, T6 (480 × 3h + 130 × 24h) heat treatment was carried out to stabilize the performance of the sample. The microstructure characterization sample (10 mm × 10 mm × 10 mm) was cut from the extruded samples.
The sampling position could be seen from figure 1(c). Dog bone specimens are cut at 0°, 45° and 90° to the extrusion direction for quasi-static mechanical properties test, as shown in figure 1(d).

2.2. Quasi static uniaxial tensile test

The quasi-static uniaxial tensile test is carried out on a tensile testing machine with a full load of 100kN Instron 3382 (Instron Inc., Canton, MA, USA). The strain value is measured by an extensometer with a gauge distance of 25 mm, and the strain rate is $1 \times 10^{-3}$. The samples for each parameter are tested three times and then averaged. After the test, the fracture characteristics were observed by scanning electron microscope (SEM, SU5000, Hitachi, Tokyo, Japan). In order to specifically measure the anisotropy of materials, we introduce the in-plane anisotropy index (IPA) [25, 26], which is commonly used to evaluate the anisotropy of materials. The specific formula is as follows:

$$IPA = \frac{2X_{\text{max}} - X_{\text{mid}} - X_{\text{min}}}{2X_{\text{max}}} \times 100\%$$

where $X_{\text{max}}$, $X_{\text{mid}}$ and $X_{\text{min}}$ represent the maximum, middle and minimum values of mechanical properties respectively. Therefore, the greater the IPA, the stronger the anisotropy energy of the material.
2.3. Microstructure characterization

The samples characterized by optical microscope (OM, DM2500M, Leica Microsystem, Wetzlar, Germany) should be polished (from #800 to #7000). The corrosive agent is Keller reagent (HF: HNO₃: HCl: HO₂ = 1:1.5:2.5:95), which is corroded for 20s. After grinding and polishing, the samples characterized by Electron Backscattered Diffraction (EBSD) need to electrolyze the samples with perchloric acid (20ml) and alcohol (180ml) for 20s at −18°C, and the electrolytic voltage was 20V for electropolishing. The EBSD data processing software is orientation imaging microcopy (OIM, EDAX Inc., Mahwah, NJ, USA).

3. Results and discussion

3.1. Quasi static uniaxial tensile properties

In order to study the anisotropy of 7075 Al alloy after extrusion and further analyze the influence of different extrusion directions on the mechanical properties of the alloy, the quasi-static mechanical properties of the extrusion patterns in two deformation directions are tested, and the test results were displayed in figure 2. It can be seen that the yield strength (YS), ultimate tensile strength (UTS) and elongation after fracture (EL) of ED0 samples along the extrusion direction (0°) and 45° with the extrusion direction (45°) are higher than those of ED90 samples. The yield strength, tensile strength and plasticity of ED90 specimen perpendicular to the extrusion direction (90°) are better than those of ED0 sample.

Figure 3 presents the IPA under different parameters. Compared with the deformed sample, the as-received sample had high anisotropy. The results showed that the anisotropy of the material can be effectively reduced after this extrusion deformation. The anisotropy of YS and UTS are the highest in the as-received samples and the lowest in the ED90 samples. For the EL, the anisotropy of as-received samples is still the largest, but the

| Specimens   | Direction | YS (MPa) | IPAYS | UTS (MPa) | IPAUTS | EL (%) | IPA (%) |
|-------------|-----------|----------|-------|-----------|--------|--------|---------|
| As-received | 0°        | 592.1(1.2)| 15.6  | 636.1(2.2)| 11.5   | 15.1(1.3)|        |
|             | 45°       | 491.3(0.7)|       | 559.2(1.0)| 11.5   | 22.0(0.6)| 40.9    |
|             | 90°       | 508.2(1.9)|       | 566.6(1.2)| 11.2   | 16.0(1.2)| 10.7    |
| ED0         | 0°        | 566.7(2.1)| 7.1   | 620.9(0.8)| 16.0   | 16.8(0.5)|        |
|             | 45°       | 512.9(1.5)|       | 569.1(0.7)| 6.5    | 14.0(1.1)|        |
|             | 90°       | 539.9(0.4)|       | 591.6(1.4)| 14.0   | 15.2(2.0)|        |
| ED90        | 0°        | 527.8(1.2)| 2.3   | 587.7(2.1)| 1.5    | 15.8(0.5)| 14.8    |
|             | 45°       | 528.7(1.2)|       | 598.1(0.7)| 18.2   | 14.8    |         |
|             | 90°       | 540.9(1.5)|       |     |        |         |         |
anisotropy of ED0 samples was the smallest. Table 2 shows the quasi-static mechanical properties of the as-received, ED0 and ED90 samples. The IPA of YS, UTS and EL of the as-received samples were 15.6%, 11.5% and 40.9% respectively. After deformation, the IPA of YS anisotropy index of ED90 sample is 2.3%, which is reduced by 85.3%. The IPA of UTS is 1.5%, which is reduced by 87.0%. The anisotropy of EL of ED0 sample is only 10.7%, which is reduced by 73.8%. It can be seen that this extrusion process can greatly weaken the anisotropy of 7075 Al alloy.

3.2. Microstructure
3.2.1. Metallographic Structure
As we all known, the anisotropy of mechanical properties of Al alloy is related to microstructure, so it is necessary to characterize the microstructure. Figure 4 is the microstructure and metallographic diagrams of as-received, ED0 and ED90 samples, respectively. The red arrows represent the extrusion direction of ED0 sample and ED90
sample. The initial microstructure is fibrous grains along the extrusion direction, and the grain size is large. The extrusion direction of ED0 sample is the same as the elongation direction of grain of the as-received sample. The long axis direction of fibrous grain is stressed to flatten the grain. Therefore, the grain of ED0 sample had a smaller aspect ratio. The extrusion direction of ED90 sample is perpendicular to the stretching direction of the original grain. After deformation, the grain shape of ED90 sample is still fibrous stretching, but the grain shape is not parallel to the extrusion direction, at an included angle of nearly 45° with the extrusion direction. And the
grain becomes slenderer and the aspect ratio increased. This special grain morphology may be an important reason for the anisotropy of Al alloy after deformation. The anisotropy of mechanical properties of samples along and perpendicular to the grain elongation direction is more significant.

3.2.2. EBSD Analysis

Figures 5 and 6 reveal an inverse pole figure (IPF) of the microstructure of as-received, ED0 and ED90 samples. Black solid lines represent high angle grain boundaries (HGBS, < 15°), and white solid lines represent low angle grain boundaries (LGBS, 2°–15°). The average grain size of the as-received samples is 98.28 μm. After thermal deformation, the large grains were broken and the dynamic recrystallization occurred, forming some new fine grains distributed around the large grains [16]. Figure 6(c) is a grain size diagram of ED0 and ED90 samples. The average grain size of ED sample is 64.48 μm and that of ED90 sample is 49.11 μm. The size and proportion of large grains in ED0 sample are also much higher than that in ED90 sample. The average grain size of ED90 sample was smaller, so it could be judged that the grain refinement effect of ED90 sample after thermal deformation is better than that of ED0 sample.

In order to study the reason for the decrease of anisotropy after deformation, the proportion of recrystallized grains of deformed samples is quantified. The position distribution of recrystallized grains and deformed grains of ED0 and ED90 samples as shown in figure 7. After extrusion deformation, large grains are broken to form small recrystallized grains, which grow slightly in the subsequent heat treatment process. However, due to different loading directions, the stress directions of fibrous original grains are different, resulting in different recrystallization ratios of deformed samples. We define recrystallized grains with grain size less than 10 μm and deformed grains with grain size greater than 10 μm. The recrystallized grains and deformed grains of as-received samples account for 15.4% and 84.6% respectively. The recrystallized grains and deformed grains of ED0 samples account for 23.6% and 76.4% respectively. The recrystallized grains and deformed grains of ED90 samples account for 37.3% and 67.5% respectively. After extrusion deformation, the recrystallization ratio of the two samples increased significantly. It can be clearly seen that the proportion of recrystallized grains in ED90 sample is greater than that in ED0 sample, and the of recrystallized grains have a great influence on the

Figure 8. (001) plane pole figure (a, c) and [ED] inverse pole figure of: (a, b) ED0 sample and (c, d) ED90 sample.
anisotropy of the sample. The anisotropy of recrystallized grains is weaker than that of deformed grains, so the anisotropy of ED90 sample with large proportion of recrystallized grains was weaker than that of ED0 sample.

The weakening effect of recrystallized grains on the anisotropy of material properties can be reflected in the research of other researchers [27]. The texture of all grains, deformed grains and recrystallized grains of ED0 and ED90 samples are analyzed.

Figure 8 displays the pole figure (PF) of the base plane (001) and the inverse pole figure (IPF) along the ED direction. Texture is one of the important reasons affecting the anisotropy of 7075 Al alloy. Obviously, there are differences in texture type and texture strength between ED0 and ED90 samples. The texture strength of ED0 sample is 10.914, but that of ED90 sample is only 7.348. Therefore, the YS and UTS of ED0 sample along the 0° direction are higher than that of ED90 sample, which confirms the macro mechanical properties of the sample from the micro point of view.

The PF and the IPF along the ED direction of the (001) base plane of the deformed grains as shown in figure 9. The texture strength of deformed grains is much greater than that of all grains. The texture strength of deformed grains of ED0 sample is 12.681 and that of ED90 sample is 9.756. The texture strength of deformed grains is the main reason affecting the anisotropy of parts.

Figure 10 demonstrates the PF and the IPF along the ED direction of the (001) base plane of the recrystallized grains. The texture strength of recrystallized grains is much less than that of all grains. The texture strength of recrystallized grains of ED0 sample is 2.813 and that of ED90 sample is 3.755. The texture strength of recrystallized grains greatly affects the total texture strength.

The texture strength of the sample is determined by the texture of recrystallized grains and the texture strength of deformed grains. Increasing the proportion of deformed grains is an important method to reduce the total texture strength. The anisotropy of the mechanical properties of the samples depends largely on the texture strength of the samples. Therefore, the strength of the anisotropy of the mechanical properties of the samples can be inferred from the proportion of recrystallized grains of the two samples.

![Figure 9](image-url)
Figure 11 is a Schmid factor diagram of ED0 and ED90 samples. Schmid factor reflects the difficulty of starting the slip system of the sample during deformation [28, 29]. The larger the Schmid coefficient is, the easier the slip system of the sample is to start, and the lower the yield strength is. On the contrary, the smaller the...
Schmid factor, the higher the yield strength of the sample. The average Schmid factors of ED0 sample along the 0°, 45° and 90° are 0.41, 0.46 and 0.45 respectively. The Schmid factors in the three directions are quite different, so the anisotropy of yield strength and ultimate tensile strength is also large. The average Schmid factors of ED90 along the 0° direction, 45° direction and 90° direction are 0.45, 0.43 and 0.44 respectively. The difference of the three Schmid factors is small, so the anisotropy of YS and UTS is lower than that of ED0 sample.

3.2.3. Fracture morphologies

Figure 12 presents the tensile fracture of ED0 sample in three directions (0°, 45° and 90°). Figures 12(a)–(c) is the SEM diagram of low magnification of fracture, and figures 12(d)–(f) is the SEM diagram of high magnification. There are cleavage planes and dimples in the fractures which belong to ductile fracture. The dimple of 0° sample is large and deep, and the cleavage plane is also large. The dimple size of 45° specimen is small, but the proportion of dimple is large. Therefore, the plasticity of 0° specimen and 45° specimen are similar and better [30]. The fracture of 90° sample is mostly cleavage plane, and the number of dimples is small and shallow, so the plasticity is poor in the three directions. However, the fracture mode of the samples in the three directions belongs to ductile fracture.

The tensile fracture of ED90 sample in three directions (0°, 45° and 90°) as shown in figure 13. Figures 13(a)–(c) is the SEM diagram of low magnification of fracture, and figures 13(d)–(f) is the SEM diagram of high magnification. The fracture morphology of the samples in the three directions is similar, but they all belong to
ductile fracture. The fracture of 0° sample has a large area of cleavage plane and a small number of dimples, and the size of dimples is small and shallow, showing relatively poor plasticity. The fracture of 45° sample has dimples, cleavage plane and secondary cracks, and the proportion of dimples in the fracture is also relatively high. The fracture shape of 90° sample is similar to that of the other two directions. The fracture characteristics of ductile fracture are obvious, and the size of dimple is large and deep, representing good plasticity.

4. Conclusion

Through the secondary extrusion deformation of extruded 7075 Al alloy in different directions, the mechanical properties and microstructure of the formed plates are studied, and the effects of different extrusion directions on the anisotropy of the formed plates are revealed. The main conclusions are as follows:

1. The anisotropy of mechanical properties of extruded 7075 Al alloy decreased significantly after secondary deformation. The anisotropy of YS and UTS of ED0 sample is lower than that of ED90 sample, and the plastic anisotropy of ED90 sample is lower than that of ED0 sample.

2. The YS and UTS of ED0 specimen are the highest along 0, followed by 90°. The plasticity of ED0 sample along ED and 45° is similar, but that of 90° is poor. The and UTS of ED90 specimen along three directions are similar, but the plasticity of 90° is better than 0° and 45°.

3. After secondary deformation, the recrystallization ratio of ED90 sample is higher than that of ED0 sample, and the texture strength is lower than that of ED0 sample. The increase of recrystallization ratio can effectively reduce the anisotropy of mechanical properties. There are dimples and cleavage planes in the quasi-static tensile fracture of the two samples, which belongs to ductile fracture.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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