Effect of extrusion ratio on microstructure and mechanical properties of Mg-6Sn-3Al-1Zn alloy

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Abstract

The Mg–6Sn–3Al–1Zn (wt%) alloy was prepared by casting and then deformed by hot extrusion at 350 °C with different extrusion ratios (9:1, 13:1, 20:1), extrusion rate was 20 mm min⁻¹. The microstructure of as-extruded alloy was analyzed by XRD and EBSD, the tensile properties were tested by a universal testing machine. The results showed that there underwent processing hardening and recrystallization softening simultaneously during the process thermal deformation. Dynamic recrystallization (DRX) mainly occurred at the grain boundary of the deformed grain, with the extrusion ratio increased, the volume fraction of the dynamic recrystallization grain of alloy increased. When the extrusion ratio was less than or equal to 13:1, the average grain size decreased with the extrusion ratio increased. When the extrusion ratio reached up to 20:1, the average grain size increased. {0001} basal plane texture formed after the alloy extruded, and it paralleled to the extrusion direction, the texture intensity decreased first and then increased as the extrusion ratio increased. With the extrusion ratio increased from 9:1 to 20:1, the tensile properties increased first and then declined. Among all the tested alloys, the alloy with the extrusion ratio of 13:1 exhibited the optimum mechanical properties, the yield strength, tensile strength and elongation of alloy was 320 MPa, 371 MPa and 13.5%, the texture strength of the alloy was 8.26, the average grain size was 1.5 μm.

1. Introduction

Magnesium and its alloys are known as ‘21st century green engineering materials’. Magnesium alloy has the characteristics of low density, high specific strength and specific stiffness, which can achieve lightweight, reduce energy consumption and reduce environmental pollution when used in transportation, aerospace and other fields [1, 2]. In addition, magnesium alloy also has the characteristics of good electromagnetic shielding and environmental protection, widely used in the field of 3 C. Magnesium and its alloys are often used as degradable bone tissue materials in surgery due to the advantages of good biocompatibility, absorbability, degradability, safety and non-toxicity [3]. Magnesium alloy belongs to close-packed hexagonal (HCP) crystal, its deformation modes at room temperature mainly include slip and twinning due to the lack of independent slip system, and so the plastic deformation ability is poor compared to steel and aluminum alloys.

The Mg-3Al-1Zn alloy has been widely used in industry, however, the strength of this alloy very low, the comprehensive properties of Mg-6Sn-3Al-1Zn alloy are better than Mg-3Al-1Zn alloy because of after adding Sn element into magnesium alloy, the coarse columnar crystal is transformed into uniform equiaxial crystal, the grain size of alloy is effectively refined. In addition, the Mg5Sn phase is formed in microstructure, due to the Mg5Sn particle phase have high hardness value, melting point and good thermal stability, which play an effective dispersion strengthening effect role on the Mg matrix. Zhang et al found that adding Sn element to AZ31 alloy can improve the mechanical properties of AZ31 magnesium alloy [4], but, the mechanical properties of Mg-6Sn-3Al-1Zn alloy still very low and needs to be improved further.
Mg-6Sn-3Al-1Zn alloy was cast with commercial pure Mg.

2. Experimental details

2.1. Preparation of specimens

Mg-6Sn-3Al-1Zn alloy was cast with commercial pure Mg (99.99 wt%), Sn (99.99 wt%), Al (99.99 wt%), and Zn (99.99 wt%) elements. The preparation of the specimen underwent five steps, including pretreatment, melting, solid solution treatment, extrusion and annealing. The specific experimental steps were as follows:

(1) Pretreatment. Herein, the alloy used in the experiment was Mg-3Al-6Sn-1Zn. Firstly, the surface of Mg, Al, Zn and Sn bulks were polished with a polishing machine, and then the raw materials of the alloy were weighted by analytical balance according to weight ratio of the alloying elements, the chemical composition of the studied alloy was shown in Table 1. Secondly, the crucible was soaked with dilute hydrochloric acid in order to remove the impurities of inner wall of the crucible. After the impurities were removed, the crucible was dried with a hair dryer, and then the mixture viscous liquid which was mixed by talcum powder and water soluble silicate was coated on the inner wall of the cleaned crucible and mold, the surface of the stirring rod. Thirdly, put the weighed raw materials, refining agents, crucibles, molds, and stirring rods in the mold heating furnace, and keeping the temperature at 200 °C for 2 to 3 h, close the mold heating furnace and keep warm for 20 min, and then turn off the furnace, the melt was second slagging when the magnesium ingot melted, the Al, Zn and Sn bulk added into the crucible sequentially according to the melting point from high to low. Continue heating until all the elements melted, when the temperature of melt reached up to 730 °C, the 36 g refining agent was added into the melt and fully stirred with a stirring rod, then the impurities and residue oxides would be on top of the melt, and could be slagging-off by ladle. Then, continue heating the melt to 750 °C and keep warm for 20 min, and then turn off the furnace, the melt was second slagging when the melt temperature cooled to 730 °C, and then poured the melt into mold which was preheated to 350 °C. Casting should be carried out on a dry site, protective gas was introduced during the pouring process. After cooling for a period, the cylindrical ingot with a diameter of 60 mm and a height of 100 mm was obtained.

| Alloy          | Sn  | Al  | Zn  | Mg  |
|---------------|-----|-----|-----|-----|
| Mg-6Sn-3Al-1Zn| 108 | 54  | 18  | 1620|

Table 1. Chemical composition of the studied alloy.

Through severe plastic deformation, the grain size of magnesium alloys can be refined to micron or sub-micron grade, and the basal texture is weakened; therefore, its mechanical properties are improved [5–7]. The processing methods of magnesium alloys mainly include high-pressure torsion, extrusion, rolling, stirring friction, etc [8–13]. Magnesium alloys have poor plastic deformation ability, extrusion can produce three-dimensional compressive stress state, refine grains and improve forming ability [14]. The alloy is subjected to high pressure during extrusion deformation, which is conducive to eliminating defects such as porosity in the ingot, thus improving formability of the alloy effectively [15]. In addition, owing to extrusion, which has the advantages of low cost; it has become a widely used plastic processing method [16]. Extrusion temperature, extrusion ratio and other process parameters have a great effect on the microstructure and mechanical properties of alloy, especially extrusion ratio during extrusion. Liu et al studied the effect of extrusion ratio on microstructure and mechanical properties of Mg-8Li-3Al-2Zn-0.5Y, and found that the grain is significantly refined with the extrusion ratio increases, and the mechanical properties increase first and then decreases [17]. Taek-Soo Kim found that the tensile strength and elongation of Mg95Zn4.3Y0.7 alloy increases with extrusion ratio increases [18].

In this paper, the effect of extrusion ratios on microstructure and mechanical properties of the Mg-6Sn-3Al-1Zn alloy is researched. The alloy is extruded at 350 °C with different extrusion ratios (9:1, 13:1, 20:1), and the microstructure of extruded alloy is characterized by x-ray diffraction (XRD) and electron back scattering diffraction (EBSD), and the universal testing machine tested the tensile properties of alloy at room temperature.
Solution treatment. The ingot was processed into a cylinder shape with a diameter of 44 mm and a height of 80 mm. Put the ingot into the plate and bury it with toner, and put it into the resistance furnace at 450°C for 8 h, and followed water quenching.

Extrusion. The cylindrical alloy was further machined to \( \varphi 44 \times 40 \) mm and kept warm at 350°C for 90 min before extrusion, selected different extrusion ratios (9:1, 13:1 and 20:1) during extrusion, the extrusion schematic diagram was shown in figure 1, number 1, 2, 3 and 4 represented the extrusion head, as-extruded alloy, mold and extrusion cylinder, respectively.

Annealing. The extruded bar was cut by wire cutting to \( 3 \times 5 \) mm along the extrusion direction for microstructure characterization, the tensile sample was cut by wire cutting into bone shape along the extrusion direction. Put this sample into the ceramic crucible and buried with toner to prevent the alloy oxidation, the sample was annealed by resistance furnace at 350°C for 10 min, and followed water quenching.

2.2. Microstructure characterization

1) X-ray diffraction (XRD) analysis: The sample grind with 400#, 800#, 1200#, 3000# and 5000# sandpaper respectively, and put it into a beaker that filled with alcohol, and cleaned the sample with an ultrasonic cleaner for 30 min, then dried it with a hair dryer. The phase composition of the sample was analysis by Bruke D8-Advance type XRD. The radiation source was the K\( \alpha \) of Cu target materials, scanning range was 20°–90°, scanning rate was 7° min\(^{-1}\), scanning step was 0.02°, and the operating voltage and current were 40 KV and 40 mA, respectively.

2) Electron back scattering diffraction (EBSD): The samples were grind with 400#, 800#, 1200#, 3000#, 5000# and 7000# sandpaper, respectively. Then polished with 7% perchlorate alcohol solution, adding liquid nitrogen to reduce the temperature of the electrolyte to about −30°C before electrochemical polishing, polished voltage, polished current and time of the sample was 20 V, 0.15 A and 2 min, respectively. After the polishing process was completed, put the sample into the alcohol to prevent corrosion of the sample surface, and then use a hair dryer to dry the surface of the sample. Argon ions polishing was carried out after electrolytic polishing, firstly, set the polishing voltage, angle and time was 3KV, 4° and 1 h, respectively, and then adjusted the polishing angle to 3°, continued polishing for 1 h. After polished, the microstructure of the as-extruded alloy was observed with EBSD, operating voltage was 20KV, scanning step was 0.21 \( \mu \)m, and the texture of the \{0001\} basal plane, \{11−20\} and \{10−10\} cylindrical plane pole figures were tested.
2.3. Mechanical properties tests
The dimensions of the standard tensile specimen (according to Chinese national standard GB/T-2002) are shown in figure 2. The specimen is mounted vertically on the Instron 5982 universal testing machine, the pre-stress was adjusted to 10 N, inputted the diameter and gauge distance of the sample on the computer and then relieved load, tensile rate was 0.2 mm min$^{-1}$. Test three specimens with the same extrusion ratio, taking their average values as the final value of tensile tests.

3. Results

3.1. Phase analysis of alloys
The XRD patterns of the as-extruded alloy with different extrusion ratios are shown in figure 3. The intensity of diffraction peak in XRD patterns reflects the number of diffraction crystal planes, the strongest diffraction peak represents the preferred orientation of the crystal plane [19]. As can be seen from figure 2, the {0002} basal plane texture is formed after extrusion with different extrusion ratios, the basal plane is parallel to the extrusion direction (ED), and the {10–10} cylindrical plane is parallel to transverse direction (TD). The extrusion ratio has no effect on the preferred orientation of the crystal and phase composition. The alloy is composed of $\alpha$-Mg matrix and Mg$_2$Sn phase after extrusion with different extrusion ratios.

3.2. EBSD microstructure analysis of the as-extruded alloys with different extrusion ratios
The microstructure of recrystallization, substructure and deformed grains of as-extruded Mg-6Sn-3Al-1Zn alloy with different extrusion ratios is presented in figure 4. The blue, yellow, and red regions represent recrystallized grains, substructural grains, and deformed grains, respectively. As shown in figure 4(a), when the
extrusion ratio is 9:1, the original grain is significantly elongated along the extrusion direction and forms a fibrous tissue, the average grain size of alloy is large. There are many fine recrystallized grains around the original coarse grain, and the local areas inside the metal accumulate enough high dislocations to form a cellular substructure. When the extrusion ratio of alloy increases to 13:1, the deformation grains of as-extruded alloy are fewer and isoaxial, and the number of recrystallization grains and subcrystalline grains are increased, the grains are small and uniform, which is shown in figure 4(b). When the extrusion ratio of alloy further increases to 20:1, the recrystallization grain growth, the average grain size of alloy increases, the cell-like substructure inside the original grains increases, and the grain boundaries are clear, which is shown in figure 4(c).

The driving force of recrystallization comes from two aspects: extrusion temperature and extrusion ratio, when the extrusion ratio is 13:1, the volume fraction of recrystallization grain reaches the maximum, indicating that the dynamic recrystallization under this driving force has been basically completed. In the extrusion process, the increase of dislocations inside the grains forms dislocation walls. In order to eliminate the internal stress, subgrain boundaries are formed, and the merger of subcrystalline boundaries finally forms subcrystalline. The increase of subgrains indicates that the dislocation density increases with the increases of extrusion ratio.

Figure 6 illustrates the grain sizes statistical diagram of Mg-6Sn-3Al-1Zn alloy after extrusion with different extrusion ratios. With the increases of the extrusion ratio, the average grain size of the alloy decreases first and then increases, and when the extrusion ratio is 9:1, the grain size less than 40 μm accounted for higher than 95%, the average grain size is 15.4 μm, as shown in figure 6(a). When the extrusion ratio increases to 13:1, most of grain sizes range from 0 μm to 4 μm, the grain size is evenly distributed, and the average grain size is reduced to 1.5 μm, as shown in figure 6(b). When the extrusion ratio is 20:1, the range of grain size is concentrated on less than 5 μm, and the average grain size is 2.2 μm, as showed in figure 6(c).
3.3. Texture analysis of alloys

Figure 7 shows the pole figure of {0001} basal plane, {11–20} and {10-10} cylindrical planes of Mg-6Sn-3Al-1Zn alloys with different extrusion ratios. {0001} basal texture formed and texture types do not change after hot extruding. Xo refers to the transverse direction (TD direction), and the direction which perpendicular to Xo refers to the extrusion direction (ED direction). After extrusion, the polar density points of the {0001} polar diagram are distributed along the TD direction, that is, most of the <0001> normal direction of the {0001} basal plane perpendicular to the extrusion direction. Which indicates that most of the grains rotated in the extruding process, making the {0001} basal plane parallel to the extrusion direction, which is consistent with the results that obtained by the XRD diffraction pattern. When the extrusion ratio increases from 9:1 to 13:1, the texture intensity reduces from 11.30 to 8.26 owing to the dynamic recrystallization, while the extrusion ratio further increases to 20:1, the volume fraction of recrystallization grain decreases and the texture strength increases to 15.54.

3.4. Grain boundary analysis of alloys

Figure 8 shows the grain boundary types of Mg-6Sn-3Al-1Zn alloys with different extrusion ratios. Black grain boundaries are large angle grain boundaries (HAGBs) with an orientation difference greater than 10°, and the green grain boundaries are small angle grain boundaries (LAGBs) with an orientation difference less than 10°[20]. Dislocations rearrange and form LAGBs at the grain boundary migration regions, the transition energy from LAGBs to HAGBs mainly comes from the dislocation energy, which is determined by the number of dislocations between adjacent grains, therefore, the grain boundary energy of LAGBs increases with the increase of the dislocation density. When the extrusion ratio of alloy is 9:1, a large number of LAGBs distributed near the grain boundaries of the deformed grains, and the density of LAGBs is very high, which is shown in figure 8(a). When the extrusion ratio increases to 13:1 and 20:1, respectively, the LAGBs in the alloy are mainly distributed at the original grain boundary of the unrecrystallized grain, and the LAGBs density decreases sharply, is shown in figures 8(b) and (c), indicating that the number of recrystallization grain increases. With the increases of the extrusion ratio, the degree of grain fragmentation increases leads to dislocation accumulation, resulting in the low-angle grain boundaries decreasing, in addition, the high-angle grain boundaries increase and the average grain size decreases as the dynamic recrystallization in progress. In addition, the pinning effect of Mg2Sn phase in
the alloy hinders the dislocations movement and grain boundaries migration, thereby reducing the stacking fault energy and refining the grains. The grain refinement greatly reduces the distance between grain boundaries, and makes the dislocations easier to reach the grain boundaries and accumulates at the grain boundaries during extrusion, finally the dislocations annihilated at the grain boundary, which lead to the boundaries angle increases and becomes high-angle grain boundaries. Figure 9 shows the twin boundary types of Mg-6Sn-3Al-1Zn alloys with different extrusion ratio. The red boundary represents \{10–12\} tensile twin boundaries, and the blue boundary represents \{10–11\} compression twin boundaries. The volume fraction of the twin grain boundaries of the \{10–12\} tensile twinning and the \{10–11\} compression twinning of Mg-6Sn-3Al-1Zn alloy with extruded at different extrusion ratios is shown in table 2. The volume fraction of \{10–12\} tensile twin grain boundary increases first and then decreases with the extrusion ratio increases, when the extrusion ratio is 9:1, 13:1 and 20:1, the volume fraction of \{10–12\} tensile twin boundary is 0.0123%, 0.43% and 0.276%, respectively. The volume fraction of \{10–11\} compression twinning decreases first and then increases with the extrusion ratio increases, when the extrusion ratio is 9:1, 13:1 and 20:1, the volume fraction of the \{10–11\} compression twin boundaries are 0.0676%, 0.0202% and 0.3749%, respectively. Twin crystals play a very important role in the strengthening of the alloy, the number of twin crystals increases will lead to the tensile strength of the alloy increases.

Figure 7. Pole diagram of Mg-6Sn-3Al-1Zn alloy with different extrusion ratios (a) 9:1; (b) 13:1; (c) 20:1.

The inverse pole figures (IPF) and misorientation angle distribution diagrams of the as-extrude Mg-6Sn-3Al-1Zn alloys with different extrusion ratios are shown in figure 10. From figures 10(a), (b) and (c), when the extrusion ratio is 9:1 and 13:1, the volume fraction of necklace-like microstructure increases with the extrusion ratio increases, magnesium alloys occur significant continuous dynamic recrystallization (CDRX), a large number of fine recrystallized grains formed at the original grain boundaries and subcrystalline boundaries. When the extrusion ratio continues rise to 20:1, generated new orientation that is not conducive to sustained deformation, and occurring local shear deformation, resulting in the recrystallization grains of the magnesium
alloy rotate into different grain orientations, this phenomenon is known as rotational dynamic recrystallization (RDRX). When the extrusion ratio is 9:1, volume fraction of low-angle grain boundary as higher as 70%, as showed in figure 10(d). When the extrusion ratio increases to 13:1, the volume fraction of LAGBs decreases sharply to 24%, as shown in figure 10(e), when the extrusion ratio further increases to 20:1, the volume fraction of LAGBs increases to 34%, as shown in figure 10(f). It can be seen from misorientation angle distribution diagrams, {10–12} tensile twinning and {10–11} compression twinning appears at 86.1° and 56°, respectively, related studies have reported that these twins have a special orientation relationship with the parent crystal ({10–12} twin 86.1° and {10–11} twin 56°) [21, 22]. With the increases of the extrusion ratio, the {10–12} tensile twin boundaries increase first and then decreases, and the {10–11} compression twin boundaries decrease first and then increase.

3.5. Mechanical properties

The stress-strain curve, elongation, tensile strength and yield strength of Mg-6Sn-3Al-1Zn alloy after extruded with different extrusion ratios are shown in figure 11. The tensile strength and yield strength of the extruded alloy increases first and then decreases with the increases of extrusion ratio. When the extrusion ratio is 9:1, 13:1 and 20:1, the tensile strength is 337 MPa, 371 MPa and 348 MPa, respectively, the yield strength is 294 MPa, 320 MPa and 280 MPa, respectively. The elongation increases with the increases of the extrusion ratio, when the extrusion ratio is 9:1, 13:1 and 20:1, the elongation rate is 7.4%, 13.5% and 17.4%, respectively. After the alloy is extruded with the extrusion ratio of 13:1, the comprehensive mechanical properties of the alloy are optimal.

4. Discussion

4.1. Effect of different extrusion ratios on grain size of Mg-6Sn-3Al-1Zn alloy

The extrusion temperature is 350 °C, which is higher than recrystallization temperature of the magnesium alloy, so the extrusion process of the magnesium alloy belongs to thermoplastic deformation. During the...
thermoplastic deformation, some regions of the magnesium alloy will accumulate enough high distortion energy to occur dynamic recrystallization that grows by merging or annexing subcrystalline. The alloy occurred two opposite processes simultaneously during thermoplastic processing, one is plastic deformation based on dislocation movement, and the other is dynamic recrystallization based on nucleation and growth. After the alloy is extruded, some grains undergo dynamic recrystallization to form small isometric grains, and the other grains are stretched into threadiness and parallel to the extrusion direction. When the extrusion ratio is 9:1, the distortion energy stored in the metal is small since the little degree of plastic deformation, and the dynamic recrystallization can only occur in the region with large deformation degree. Therefore, the alloy is mainly composed of deformed grains and recrystallized grains. When the extrusion ratio increased to 13:1, the deformation degree increases, and sufficient dislocations accumulated in alloy, which is conducive to recrystallization nucleation, and new isometric crystals will be formed, the grains are small and distribute in microstructure uniformly, so the volume fraction of recrystallization grains increase. When the extrusion ratio increases to 20:1, the distortion energy further increased, which will prompt the recrystallization grain to grow

![Figure 9. Twin boundary types of Mg-6Sn-3Al-Zn alloys with different extrusion ratios (a) 9:1; (b) 13:1; (c) 20:1.](image)

| Extrusion ratio | 9:1 | 13:1 | 20:1 |
|----------------|-----|------|------|
| Type of twin grain boundary | The \(\{10\text{-}12\}\) tensile twin grain boundary | 0.0123% | 0.43% | 0.276% |
| | The \(\{10\text{-}11\}\) compress twin grain boundary | 0.0767% | 0.0202% | 0.0989% |
| | Total | 0.089% | 0.4502% | 0.3749% |
up again and lead to the average grain size of alloy increase. When the plastic deformation degree increases, the dislocations are entangled with each other to form a cell-like substructure, so the proportion of subcrystallines gradually increases with the increases of the extrusion ratio. The extrusion ratio also has an impact on the grain boundaries, when the extrusion ratio is 9:1, the volume fraction of recrystallization grains are few, the dislocation density is larger, and the dislocation is accumulated at the grain boundary of the deformed grain, so there are many low-angle boundary at the grain boundary. When the extrusion ratio rises to 13:1, the degree of dynamic recrystallization becomes larger, and the dynamic recrystallization grows through the merger or annexation of subcrystallines, and preferentially occurs at the grain boundaries with large dislocation density and irregular arrangement, so the proportion of low-angle boundaries are reduced rapidly and convert to high angle boundaries. When the extrusion ratio continues rise to 20:1, due to work hardening effect exceeds the recrystallization softening effect, therefore the dislocation increases, and the proportion of the low-angle grain boundary increases. The volume fraction of twin grain boundaries is very low with different conditions of extrusion ratio, and so the alloy not considered with win grain boundaries effects.

4.2. Effects of different extrusion ratios on the texture of Mg-6Sn-3Al-1Zn alloy

The {0001} basal plane texture is easily formed in magnesium alloy during extrusion, the basal plane is preferentially parallel to the extrusion direction, and the texture intensity decreases first and then increases with the increases of the extrusion ratio. Texture intensity decreases when the extrusion ratio is 13:1 owing to the
volume fraction of the dynamic recrystallization grains increases, and a phenomenon of texture weakening appears. When the extrusion ratio increases to 20:1, the volume fraction of dynamic recrystallization grains decreases, which leads to the texture intensity increase.

4.3. Effects of different extrusion ratios on mechanical properties of Mg-6Sn-3Al-1Zn alloy

Hall–Petch relation demonstrates that grain refinement is an effective method for improving yield strength. When the extrusion ratio is 13:1, the average grain size of alloy is the smallest and the yield strength is also the highest, but when the extrusion ratio increases to 20:1, the average grain size of alloy increases, which reduces the grain refinement effect, so the yield strength reduces. The elongation of alloy increases with the increases of extrusion ratio, when the extrusion ratio increases from 9:1 to 13:1, grain refinement not only makes the yield strength increases, but also the elongation of the alloy increase, when the extrusion ratio is 20:1, the grain size grows slightly and the elongation increases further.

5. Conclusions

(1) Extrusion ratio had a great impact on the grain, texture, orientation difference and mechanical properties of extruded alloys. With the increased of the extrusion ratio, the texture intensity and average grain size of the alloy decreased first and then increased, the yield strength and tensile strength increased first and then decreased, while the elongation increased monotonically.

(2) The basal texture intense was the weakest when the extrusion ratio was 13:1, which was 8.6, and the average grain size of the alloy was the smallest, which was 1.5 μm, and its comprehensive mechanical properties were the best, with a yield strength of 320 MPa, a tensile strength of 371 MPa, and an elongation of 13.5%.

(3) The volume fraction of recrystallized grains increased first and then decreased with the increases of the extrusion ratio, when the extrusion ratio was 13:1, the volume fraction of recrystallized grains was the highest, which was 34.1%. The volume fraction of sub-grain increased and the deformation grain decreased with the
increased of the extrusion ratio, and the grain boundary was dominated by low-angle grain boundaries of alloy with different extrusion ratios.

(4) Twin grain boundary formed after thermoplastic deformation, and its volume fraction increased first and then decreased with the increased of the extrusion ratio, which was positively correlated with the strength of alloy. The volume fraction of twin grain boundary reached the highest about 0.45% when the extrusion ratio was 13:1, however, the overall volume fraction of twin grain boundary was low in this alloy, therefore, the effect of twin grain boundary on mechanical properties is limited.

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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). Source data are available from the corresponding author upon reasonable request.

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Conflicts of interest

The authors declare no conflict of interest.

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