Effect of ECAP Deformation on Microstructure and Properties of Pure Magnesium

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Abstract. In this paper, the effect of the deformation of equal-channel angular pressing (ECAP) on the microstructure and the mechanical properties at room temperature was studied under the extrusion temperature of 350°C and extrusion path of BC. The results show that the grain size of pure magnesium is obviously refined with the increase of the number of extrusion passes. The yield strength, tensile strength and elongation of the as-cast sample are 20MPa, 55MPa and 14.7% respectively. The yield strength and tensile strength of the 3-pass extrusion sample can be increased by 350% and 170%, respectively. The tensile strength and yield strength of the 4-pass extrusion sample are reduced compared with the 3-pass extrusion sample, but the elongation is further increased. The grain refinement of alloy ECAP process is mainly a combination of mechanical shear and dynamic recrystallization.

1. Introduction
Magnesium, with a density of 1.74g/cm³ and physical properties such as strong electromagnetic shielding property, strong vibration damping property, high electrical conductivity, high thermal conductivity, and extremely high specific strength, is widely used in aerospace, electronic communication, automobile and other fields, and is honored as "the green engineering material of the 21st century" [1-4]. Equal-channel angular pressing (ECAP), through the sample in two equal improving the strength of the material [5-8]. This technology has become one of the most rapid large plastic deformation channels at a certain Angle, the sample grain is refined, thus ialation technology development [9-11].

In this paper, ECAP technology is mainly used to carry out multi-pass extrusion of as-cast pure magnesium, and the microstructure and mechanical properties of as-cast pure magnesium before and after hot extrusion are studied to obtain excellent comprehensive properties.

2. Experiment
The raw material used in this experiment is the purchased industrial magnesium ingot with purity of 99.99%. Firstly, a number of Φ 15mm × 65mm round rods are cut out from the Φ 300m high-purity magnesium ingot by WEDM. Before ECAP deformation, the surface of the sample needs to be polished to be smooth without obvious cutting marks, and then evenly coated with vaseline and graphite powder mixed lubricant. After the inner channel of ECAP die (Φ = 120 ° and fillet ψ = 25 °) is evenly coated with lubricant, the sample is put into the mold, the mold is heated to 350 °C for about 15 min, and ECAP deformation is conducted for 1, 2, 3 and 4 passes according to BC path (the sample is rotated 90 ° clockwise in the next pass), and the extrusion speed is 0.15 mm / s.
3. Experimental results and analysis

3.1. Optical microstructure
The metallographic diagram of the original as-cast microstructure of pure magnesium is shown in Figure 1. As-cast pure magnesium has large grain size and irregular shape.

![Figure 1. OM microstructure of as cast pure magnesium: 200×(a), 500×(b).](image)

![Figure 2. OM micrographs of Mg after different ECAP passes:(a)Pass1;(b)Pass2;(c)Pass3;(d)Pass4.](image)

Figure 2 (a) shows the metallographic structure of pure magnesium after one extrusion. After one ECAP deformation, the original coarse grain was obviously broken up, but the original grain boundary was still observed, and the grain boundary was clear. The grain sizes of the fragmentation pairs are different, indicating uneven deformation, and parallel strip structures can be observed in the figure.

It can be seen from Figure 3 (b) that after two times of extrusion, the grains are further refined. In the figure, the elongated grains can be observed, and obvious recrystallization small grains appear around the crushed grains, and the original intact grain boundary cannot be observed.

As shown in Figure 2 (c) and (d), with the increase in the number of deformations, grains become smaller, grain boundaries become fuzzy, and deformation bands disappear. Only recrystallization grains with grain growth can be observed. Most of the positions are not distinguishable by optical microscopy.

3.2. Hardness testing and analysis
As shown in Figure 3, the relationship between the vickers hardness of the longitudinal section and each channel after the DEFORMATION of high-purity magnesium via Bc path ECAP is shown. As can be seen from the figure, the original as-cast microstructure of pure magnesium is relatively soft with a hardness of only 32HV. After the first ECAP deformation, the hardness of the longitudinal section increases sharply, which can reach 42HV, and the hardness increases by about 33%. This is mainly due to the strong shear deformation, the strong shape deformation made original gross grain of
fragmentation, line into high density dislocation lath organization, grain of fragmentation, greatly increasing the grain boundary which affects the dislocation movement, produce the effect of strain hardening, the hardness is improved significantly [13]. After 2 or 3 courses, the hardness increased, but the change rate was slow. This may be related to the dynamic recovery of the tissue. Recrystallization improves the refinement effect to a certain extent, and grain refinement increases the strength. After 4 passes, the hardness decreases to a certain extent compared with the last pass, but the hardness of the 4 passes is higher than the first pass, which may be related to the growth of recrystallized grains.

Figure 3. Effect of ECAP passes on Vickers-hardness.

3.3. XRD analysis of ECAP deformed pure magnesium
The XRD pattern of vertical cross-section of pure magnesium after 0, 1, 2, 3 and 4 passes of ECAP deformation is shown in Figure 4. It can be found from the figure that, with the change of the number of extrusion passes, the diffraction intensity of each crystal surface of the sample also changes with the change of the selection orientation. Among them, the relative diffraction intensity of the base surface (0002) does not change significantly with the relative number of extrusion passes. The relative strength of cylinder (1010) rose sharply after one deformation, and remained stable after the strength decreased in the subsequent passage. The relative strength of cone (11(10)) also increased significantly, but the change of relative strength was not obvious in the subsequent course. Cone (1(12)) a peak appears after one pass and remains unchanged in the following passage. The relative strength of cylinder (1120) decreases after the first round, and the change is not obvious after that.
In summary, it can be seen from the above analysis that the diffraction peak strength of the crystal surface of the original sample $(0211)$ is much greater than that of the other crystal surfaces, indicating that in the cylinder $(1120)$ the upper grains have a significant preferential orientation. After one pass, the cylinder $(1120)$ relative strength decreases greatly, while the cylinder $(0110)$ and the cone $(1110)$ strength increases greatly, so that the second cylinder $(1120)$ no preferred orientation, the orientation changes to the cylinder $(1010)$ and the cone $(1010)$. After 2, 3 and 4 courses of ECAP deformation, the preferred orientation is mainly on the cone surface $(1010)$.

3.4. Mechanical property analysis of ECAP deformed pure magnesium

After the tensile test at room temperature, all experimental data were summarized to obtain the mechanical properties of multi-pass ECAP deformation of pure magnesium samples, as shown in Table 1. The relationship between yield strength (YS), tensile strength (UTS) and elongation rate (EL) and number of extrusion channels (Pass) is shown in Figure 6.

The yield strength, tensile strength and elongation of pure magnesium as cast are 20MPa, 55MPa and 14.7%, respectively. After ECAP deformation, various performance indexes of pure magnesium have been greatly improved, among which the comprehensive performance of pure magnesium after three passes deformation is the best, its yield strength, tensile strength and elongation are 91MPa, 149MPa and 9.5%, respectively, which are increased by 350% and 170% compared with the first two terms in the as-cast state.

| ECAP pass/N | YS/MPa | UTS/MPa | EL/% |
|-------------|--------|---------|------|
| 0           | 20     | 55      | 14.7 |
| 1           | 52     | 85      | 13   |
Table 1: Ultimate Tensile Strength, Yield Strength, and Elongation

| Passes | YS (MPa) | UTS (MPa) | EL (%) |
|--------|----------|-----------|--------|
| 2      | 74       | 122       | 12     |
| 3      | 91       | 149       | 9.5    |
| 4      | 61       | 137       | 15     |

Figure 5. Effect of ECAP passes on ultimate tensile strength, yield strength and elongation.

In conclusion, the structure of the material plays a decisive role in the improvement of its properties. After the strong plastic deformation of pure magnesium, the original coarse grains are significantly refined, forming a high-density lath structure, and the dislocation density is also significantly improved. At the same time, the appearance of twins [10] also hinders the movement of dislocations, which greatly improves the strength of the material. After two passes, the recovery recrystallization is significant, the grains are more refined, and the combined action of dynamic recovery and work hardening makes the strength of the material reach the maximum at three passes, and then the performance of pure magnesium declines due to the growth of recrystallization grains and the reasons of texture [7,10].

4. Conclusion
1) The original grain size of pure magnesium is large. After the deformation of ECAP, the grain size is obviously refined. After multi-pass deformation, the original grain boundary cannot be observed, and the grains are mainly recrystallized.

2) Mechanical performance analysis shows that the strength and hardness of pure magnesium increase with the increase of the number of passes, and the strength and hardness are the highest after three passes, which are 91MPa, 149MPa and 42HV respectively. The subsequent decline may be related to the growth of recrystallized grains and the change of grain orientation.

3) Grain refinement in pure magnesium ECAP deformation can be attributed to the joint action of mechanical shear and dynamic recrystallization. The shear action was significant in the early stage, while the dynamic recrystallization dominated the late stage of deformation.

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