Effect of Multidirectional Forging on Microstructure and Properties of AZ40 Alloy

Zhi Shengxing¹,²,³,a, Yuan Jiawei¹,²,³,b*, Li Xinggang¹,²,³, Li Yongjun¹,²,³, Ma Minglong¹,²,³, Shi Guoliang¹,²,³, Zhang Kui¹,²,³

¹State Key Laboratory of Nonferrous Metals and Process, GRINM Group Corporation Limited(GRINM), Beijing, China;
²GRIMAT Engineering Institute Co Ltd, Beijing, China;
³General Research Institute for Nonferrous Metals, Beijing, China

aemail: 877395772@qq.com, bemail: yuanjiawei@grinm.com

Abstract: AZ40 alloy was operated with the plastic deformation by multidirectional forging (MDF). The evolution rules of microstructure and texture during forging were analyzed by means of metallographic microscope and electron backscattering diffraction (EBSD), and the evolution mechanism of texture during forging is explored. The results show that, with the increase of passes of forging, the strength of the basal texture decreases. After four passes of forging, the original {0001} basal texture is changed to {1010} and {2110} cylindrical texture, and the Schmild factor of the alloy reaches the maximum. Through multidirectional forging, the anisotropy of the alloy is weakened, and the mechanical properties of each texture are improved compared with that of the extruded state. After four passes of forging, the plasticity of the alloy is the best and the elongation ratio reaches the maximum, which is 32.0%, 29.2% and 27.0%, respectively.

1. Introduction

As the lightest metal structural materials, magnesium and its alloys have a density of only 1.74 g/cm³, which is 1/4 of that of steel and 2/3 of that of Al, have the advantages of high specific strength, high specific stiffness and good damping performance, are known as "green functional materials in the 21st century" and have broad application prospects in aerospace, civil transportation and electronic products, but their poor corrosion resistance limits their further application[1-3]. With the continuous development and depletion of conventional oil and gas resources, unconventional oil and gas resources such as shale and petroleum gas will become important substitutes for future energy sources, and horizontal well staged fracturing technology is used as a main method for the exploitation of such oil and gas resources. Bridge plug is an indispensable plugging and fracturing tool in staged fracturing technology. As a new technology, the new soluble bridge plug has been widely used in many oil and gas companies[4,5]. Magnesium alloy has a broad application prospect in soluble bridge plugs due to its corrosion characteristics. New generation of soluble bridge plug, in which the expanding pipe is made of soluble rubber material and the rest is made of magnesium alloy[6]. Soluble rubber material not only dissolves slowly, which is easy to cause secondary blockage and other problems, but also tends to rebound when the bridge plug expands its pipe, resulting in plugging failure.

In order to realize the radial expansion of bridge plug during pipe expansion to achieve the purpose of plugging, it is required that the mechanical properties of magnesium alloy materials are less...
anisotropic. However, the magnesium alloy materials produced by conventional extrusion, forging, rolling and other deformation processes are easy to form strong basal texture, which cause strong anisotropy of mechanical properties of materials\cite{7-10}. After experiencing the primary deformation, the alloy often has strong anisotropy of mechanical properties and high yield strength, so it is often necessary to carry out the secondary deformation on the alloy after primary deformation to weaken the texture and reduce the anisotropy of properties. Multi-directional forging is widely used in industrial production because of its simple technological process, simple equipment and low processing cost. Compared with unidirectional forming process, multidirectional forging can weaken texture and start specific slip, which improves material properties. L.B. Tong et al.\cite{11} forged Mg–Gd–Y–Zn–Zr alloy in different multi-direction passes, and it was found that, with the increase of forging passes, the dynamic recrystallization degree of the alloy increases continuously, and the strength of basal texture decreases gradually, and the texture gradually transforms into another type of texture. After 6 passes of forging, the maximum strength of the texture is only 4, and the texture is obviously weakened. After forging, the tensile strength, yield strength and elongation of the alloy are improved compared with those of the original extruded alloy. M.A. Salevati et al.\cite{12} carried out multi-directional forging research on AM60 alloy, which is found that after 6 passes of forging, the average grain size of the alloy is 2.7μm, the yield strength of the alloy decreases, and the elongation increases compared with that of the initial alloy. The research of Beibei Dong et al.\cite{13} showed that, after forging Mg-13Gd-4Ye2Zn-0.5Zr for 3 passes in multiple directions, the grain size of the alloy is obviously refined, the average grain size is refined to 4.0μm, the texture distribution is uniform, and the texture distribution is changed from basal texture with higher strength to random distribution, and the delay rate of the alloy is significantly improved compared with the original one. Jamali et al.\cite{14} forged the extruded ZK60 alloy in multiple directions at 200℃, and it was found that the grain size is refined from 12.7μm to 1.9μm after 8 passes of forging. The research also shows that the basal texture after extrusion is replaced by the new texture.

In this research, Mg-4Al-1Zn-0.5Mn mass% (AZ40) magnesium alloy was subjected to three different multi-directional forging passes at 300℃, and the effects of multi-directional forging on grain size, texture evolution and mechanical properties of the alloy were studied.

2. Materials and Methods

The experimental materials are extruded AZ40 magnesium alloy bars, and the original extrusion ratio of the materials is 17:1. The size of the bars is φ160x300mm, and the materials are forged by three different processes which are 2 passes forging, 4 passes forging and 6 passes forging. The forging process is shown in Figure 1. The forging temperature was 300℃, the forging speed was moderate, and the reduction was 50%. In order to reduce the friction between the materials and the anvil, so as to prevent the "Double Drum" phenomenon. Lubricating oil was coated on the materials and the anvil before forging to ensure the uniform deformation of the materials during forging.

![Diagram](a)
Tensile test and sampling of microstructure observation were carried out along three surfaces being perpendicular to A, B and C surfaces respectively. The sample size of microstructure observation is \( \phi 10 \text{mm} \times 10 \text{mm} \), and the sampling position is shown in Fig.2. The room temperature mechanical properties of the alloy are tested by SANS universal testing machine. The metallographic structure (OM) of the alloy was observed by Zeiss Axiovert 200MAT optical microscope. Before observation, it was polished with metallographic sandpaper until there was no obvious scratch, then polished to mirror surface with 1\( \mu \text{m} \) diamond polishing paste, and then corroded with picric ethanol acetic mixed solution.

Electron backscattering diffraction (EBSD) observation was carried out on the alloy by JSM-7900F scanning electron microscope. Before observation, the samples are polished with metallographic sandpaper until there is no obvious scratch, and electrolytic polishing was carried out on the polished samples. The electrolytic polishing equipment is DH1720-4 DC voltage and current stabilizing power supply, the cathode is stainless steel cathode, the electrolyte is 20% nitric acid alcohol, and the electrolytic polishing voltage is 20 V, the current is not more than 1A, the temperature is -30\( ^\circ \text{C} \), and the passes is from 30s to 50s. Considering that magnesium alloy is very easy to oxidize, in order to prevent the surface oxidation of the samples, the polished samples are soaked in absolute ethanol.
3. Materials and Methods

3.1. Microstructure of Initially Extruded Alloy

Fig. 3 presents metallographic photographs of the ED surface of the initially extruded AZ40 alloy, and the observation position is depicted in the figures. It is evident that the extruded material microstructure displays clear streamline characteristics (Fig. 3-a), and the alloy exhibits a certain degree of mixed crystal state (Fig. 3-b).

![Microstructure of the Extruded AZ40 Alloy (a) 50X; (b) 500X;](image)

3.2. Evolution rules of Texture of Alloy After Forging

Fig. 4-6 are IPF figures, inverse pole figures, and polar figures of AZ40 magnesium alloy with different passes of forging. As depicted in Fig. 4(a), fine grains produced by dynamic recrystallization are found in the extruded alloy, and most of the grains in the alloy align along the direction of <0001>||ND. The <0001>||ND, <1010>||ED, <2110>||ED directions of the alloy in the extruded state are also illustrated in Fig. 5(a), which is mutually confirmed with the results obtained by IPF figures. Combining the analysis of the polar figures in the extruded state in Fig. 6(a), it can be observed that the alloy produces a typical basal texture after extrusion, and the maximum polar density is 11.6, which is the same as that of extruded alloy in this article[15]. After 2 passes of forging, it can be seen from the Fig. 6(b) polar figures that the grains of the alloy are deflected, which is not a typical basal texture. The texture is deflected about 30° towards the ED direction, and the texture strength is greatly reduced from 11.6 to 9 in the extruded state, but the texture type does not change. Compared to Fig. 4(a) with Fig. 4(b), the red grains in the figures are reduced and replaced by randomly oriented pink, orange, blue, and green grains, but the entire grains in the figures are red grains, which is mutually confirmed with the conclusion that the texture shown in the polar figures is deviated, but the texture type does not change. It is not difficult to see from these figures that, after 2 passes of forging, the grain size is refined and the recrystallization ratio obviously increases, which is the same as the results of metallographic microstructure. During the forging process from 2 passes to 4 passes, the grains continue to rotate. It can be observed from Fig. 4(c) that the grains in the alloy are generally green and blue, that is, <1010>||ND and <2110>||ND directions. It can be seen from the inverse pole figures that some grains are in the direction of <0001>||ED and the other grains are in the direction of <0001>||TD. Combined with analysis of polar figures, the texture type of the alloy changes from the original basal texture to {1010} and {2110} cylindrical texture after 4 passes of forging, and the texture strength are about 4.1 and 3.4 respectively. (0001) polar figures show that the maximum pola density is 6.1, which is the strength superposition of the two textures at this point. After 6 passes of forging, it can be seen from the IPF figures that the grain color distribution in the figures is uniform. Compared with the microstructure after 4 passes of forging, the grain rotates and the texture distribute inconsistently. Compared with the extruded state, the texture type changes and the strength is weakened.
Fig. 4 IPF Figures of AZ40 Alloy After Different Passes of Forging
(a) Extruded  (b) 2 passes Forging  (c) 4 passes Forging  (d) 6 passes Forging

Fig. 5 Inverse Polar Figures of AZ40 Alloy After Different Passes of Forging
(a) Extruded  (b) 2 passes Forging  (c) 4 passes Forging  (d) 6 passes Forging
Fig. 6 Polar Figures of AZ40 Alloy After Different Passes of Forging
(a) Extruded  (b) 2 passes Forging  (c) 4 passes Forging  (d) 6 passes Forging

Fig. 7 is the distribution figures of crystalline boundary orientation difference of materials in extruded state and after different passes of forging. As shown in the figures, red lines represent crystalline boundaries of 2-5 degrees, that is, sub-crystalline boundaries. Green lines represent crystalline boundaries of 5-15 degrees, and crystalline boundaries below 15 degrees are collectively referred to as low-angle crystalline boundaries. Blue lines represent crystalline boundaries above 15 degrees, which are referred to as large-angle crystalline boundaries. It can be seen from the figure that the grains of the initially extruded AZ40 alloy undergo obvious dynamic recrystallization. It can be clearly seen from the observation of the microstructure that the fine grains formed by dynamic recrystallization are in streamlined distribution, which is the same as the microstructure observed by metallographic photographs, with a high proportion of large-angle crystalline boundaries and a small number of low-angle crystalline boundaries. After 2 passes of forging, the sub-crystalline boundaries in the alloy increase, and the proportion of low-angle crystalline boundaries increases greatly, which is adjacent to large-angle crystalline boundaries. After 4 passes of forging, most of the low-angle crystalline
boundaries are replaced by large-angle crystalline boundaries, and the proportion of low-angle crystalline boundaries is obviously reduced, and the recrystallization degree of the alloy is more sufficient than that after 2 passes of forging. After 6 passes of forging, the recrystallization of the alloy is basically completed, and the small grains formed by dynamic recrystallization in the previous forging process grow up in this process, the alloy grain size distribution is uniform, the low-angle crystalline boundaries are further reduced, and the sub-crystalline boundaries basically disappear, except for the large-angle crystalline boundaries, only a few low-angle crystalline boundaries of 5-15 degrees exist. It is because that, in the early stage of forging, the deformation is small and insufficient, and the dynamic recrystallization only occurs near the large-angle crystalline boundaries. After grain refinement, a large number of dislocation cells and dislocation tangles are generated inside, and the low-angle crystalline boundaries are mainly composed of dislocations, so there are many low-angle crystalline boundaries in the early stage of forging. However, the multidirectional forging process of magnesium alloy is different from moulding processes such as rolling, uniaxial extrusion, and so on. The direction of additional load in multidirectional forging process is changeable, so the accumulated deformation is very large. Because of the continuous deformation, dislocation density accumulates too much, and the distortion energy inside the material increases, the original clear grain interior is divided into many substructures, which are divided by a large number of entangled dislocations, thus increasing the proportion of large-angle crystalline boundaries and decreasing the proportion of low-angle crystalline boundaries.

According to the article, the common dynamic recrystallization mechanisms are generally divided into four categories, namely twin recrystallization mechanism [16-19], crystalline boundary bow-out recrystallization mechanism [17,18], grain induced recrystallization nucleation mechanism [16,18,19] and sub-crystalline rotation mechanism [18,19]. The twin recrystallization mechanism of greatly occurs when there are few slip systems and poor plasticity. The crystalline boundary bow-out recrystallization mechanism is that, when crystalline boundary migrates from low dislocation density to high dislocation density in high strain stage, it will lead to crystalline boundary bow-out recrystallization, and the new dynamic recrystallized grains generally have the same orientation as the parent phase. Grain induced recrystallization requires that, when the second phase precipitates, grains can increase local stress and recrystallize around themself. The mechanism of sub-crystalline rotation is that grains rotate under the action of external force or driven by crystalline boundary orientation gradient, and sub-crystal usually develops near the parent crystalline boundary. In the forging process of this experiment, no twin crystal is found through microstructure observation, and there are few second phases in AZ40 alloy, so twin recrystallization mechanism and grain induced recrystallization nucleation mechanism are not the recrystallization mechanism in this forging process. It can be seen from the IPF figures in Fig.4 that the orientation of recrystallized grains is arbitrary, which is different from that of coarse parent grains. Combined with the previous analysis of crystalline boundary orientation in the forging process, with the continuous forging, the grains rotate, low-angle crystalline boundaries decrease and large-angle crystalline boundaries increase, and the recrystallization mechanism changes to sub-crystalline rotation mechanism.
Fig. 7 Crystalline Boundary and Grain Orientation Figures of AZ40 Magnesium Alloy Forged by Different Passes

(a) Extruded (b) 2 passes Forging (c) 4 passes Forging (d) 6 passes Forging

Table 1 shows the critical shear stress under various deformation mechanisms at different deformation temperatures. It can be seen from the table that, at 300°C, the critical shear stress of tensile twin crystal is lower than that of tapered slip, so under the same stress condition, tensile twin crystal is easier to start than tapered slip, and no twin crystal microstructure is observed in the metallographic microstructure and EBSD microstructure photographs after different forging passes, so under this multidirectional forging deformation condition, tapered slip does not start. Therefore, {0001}<1120>, {1010}<1120> and {2110}<1120> are slip systems that may slip under this forging deformation condition. Fig. 8 shows the Schmmd factor distribution figures of alloys {0001}<1120>, {1010}<1120> and {2110}<1120> in extruded state and forged after different passes. Among that, red grains represent that the Schmmd factor value of the grains is close to 0.5, which indicates that these grains are in soft orientation, with small critical shear stress value and are easy to slip. Blue grains represent that the Schmmd factor value of the grains is close to 0, which indicates that these grains are in hard orientation, with large critical shear stress value and are not easy to slip. It can be seen from the figure that the red grains in the extruded alloy account for less, and the grains in the alloy are mainly blue and green grains, which shows that the Schmmd factor of the extruded alloy is small and it is difficult to slip. With the continuous increase of deformation, after 2 passes of forging, the alloy grains rotate, and some grains change from hard orientation to soft orientation. It is obvious from the figure that the red grains increase and the Schmmd factor of the alloy increases compared with the extruded state. After 4 passes of forging, it can be seen from the figure that, compared with 2 passes of forging,
the green grains with lower Schmind factor of the alloy are obviously reduced, and the whole grains represent in red. The Schmind factor value of more than half of the grains is close to 0.5, and the Schmind factor value of the alloy reaches the maximum. After 6 passes of forging, it can be seen from the figure that most of the grains are orange-red and green and in soft orientation, and the Schmind factor of the alloy increases compared with that of the 2 passes of forging, but there are still a few grains with smaller Schmind factor, which is smaller than that of the alloy forged after 4 passes.

Table 1 The Critical Shear Stress under Various Deformation Mechanisms at Different Deformation Temperatures

| Slip Mechanism | 200°C | 250°C | 300°C |
|----------------|-------|-------|-------|
| Basal Slip     | 0.49  | 0.47  | 0.46  |
| Cylindrical Slip| 11.42 | 2.52  | 1.86  |
| Tapered Slip   | 19.27 | 10    | 64    |
| Tensile Twin Crystal | 2.92 | 2.92 | 2.92 |

![Fig.8 The Schmind Factor Distribution Figures of AZ40 Magnesium Alloy Forged by Different Passes](image)

(a) Extruded  (b) 2 passes Forging  (c) 4 passes Forging  (d) 6 passes Forging

3.3. Texture Evolution Mechanism in Multidirectional Forging Process

According to the previous analysis of texture evolution rules of extruded AZ40 alloy in different forging passes, the texture evolution mechanism in this process, that is, grain rotation mechanism, is explored. Fig.9 shows the grain rotation model during the texture evolution of extruded AZ40 alloy during forging. In this model, the A, B and C surfaces of the alloy are consistent with the extruded A, B and C surfaces shown in
the experimental scheme in Fig.3. The ED, TD and ND directions of the initially extruded alloy are taken as coordinate axes. In the extruded alloy, the ED direction is perpendicular to the C surface, and the TD and ND directions are equivalent directions. For convenience of description, the A surface is taken as the surface governed by ED and TD, the B surface is taken as the surface governed by ED and ND, and the C surface is taken as the surface governed by TD and ND. After forging, the shape of the forged alloy is simplified to a cylinder. According to the previous analysis and pole figure analysis in Fig.6, the extruded AZ40 magnesium alloy is a typical basal texture with high texture strength, that is, the \{0001\} basal surface of most grains is parallel to ED direction, as shown in Fig.9(a). After forging for 2 passes, the C and A surfaces of the alloy are compressed once, and the basal texture deflects about 30 degrees in the direction of ED. A few grains keep the original basal texture, and the texture strength is greatly reduced, as shown in Fig.9(b). After 4 passes of forging, \{10\overline{1}0\} and \{2\overline{1}0\overline{1}\} cylindrical textures are formed. Some grains of the alloy are rotated until the \{10\overline{1}0\} crystal surface is parallel to the A surface, and the \{2\overline{1}0\overline{1}\} crystal surface inside other grains is parallel to the A surface, as shown in Fig.9(c). It is obviously can be seen from the figure that the <0001> grain direction of most grains is parallel to the ED direction. After 6 passes of forging, the grain orientation is random and the texture is scattered. The \{10\overline{1}0\} texture produced after 4 passes of forging deflects 20-30 degrees in TD direction, and the texture strength decreases accordingly. However, the \{2\overline{1}0\overline{1}\} texture produced after 4 passes of forging is decomposed into two parts after being deflected by 60 degrees in TD direction, and the grains of the two parts are deflected by 30 degrees in ED direction, and the grain orientations of the two parts are symmetrical about TD axis, the texture strength is lower than that of the \{2\overline{1}0\overline{1}\} texture, and the texture is weakened. The geometric relationship of grains is shown in Fig.9(d).

![Fig.9The Schmimd Factor Distribution Figures of AZ40 Magnesium Alloy Forged by Different Passes](image)

(a) Extruded  (b) 2 passes Forging  (c) 4 passes Forging  (d) 6 passes Forging

### 3.4. Mechanical Properties of Forged Alloy

Tensile tests are carried out on the samples of A, B and C surfaces of AZ40 alloy in extruded state and after forging deformation for 2 passes, 4 passes and 6 passes. The mechanical properties of AZ40 alloy in extruded state and after forging for each passes are shown in Fig.10. Due to the obvious basal texture of extruded alloy, the anisotropy of mechanical properties of the materials is obvious. The yield strength of extruded alloy in ED direction is obviously higher than that in TD direction, while the elongation in ED direction is 15.5%, which is lower than that in TD direction. After two passes of forging, the yield strength of the A, B and C surfaces of the alloy is lower than that of the extruded state, and the elongation of the B surface is increased to 29.0%, which is due to the deflection of the basal texture of the alloy caused by forging, and the Schmimd factor figures of the alloy can also confirm this. After 4 passes of forging, the yield strength of the alloy decreases, and the cylindrical texture of \{10\overline{1}0\} and \{2\overline{1}0\overline{1}\} makes it easier to start the cylindrical slip system around all directions, and the plasticity of the alloy is greatly improved. The elongation of A, B and C surfaces of the alloy reaches the maximum, which are 32.0%, 29.2% and 27.0% respectively, and the Schmimd factors
of the alloy also reaches the maximum, which are consistent with the elongation of the alloy. After 6 passes of forging, the elongation of the alloy is reduced compared with that of 4 passes of forging, but the elongation of each surface is obviously improved compared with that of the extruded alloy. It can be seen from the results that, after 4 passes and 6 passes of forging processes, the anisotropy of mechanical properties, especially elongation, of the alloy is weakened, and the mechanical properties of all surfaces of the materials are more uniform. According to the yield strength, elongation and previous microstructure analysis, the alloy performance is the best after 4 passes of forging, so 4 passes forging process should be selected as the forging process of extruded AZ40 alloy.

![Fig.10](image)

**Fig.10 The Mechanical Properties of AZ40 Magnesium Alloy Forged by Different Passes**

(a) Extruded State  (b) A Surface  (c) B Surface  (d) C Surface

4. Conclusion

In this article, the multidirectional forging experiments of extruded AZ40 alloy in different passes are carried out, and the microstructure changes and texture evolution rules of the alloy during forging are studied, and the texture evolution mechanism during the forging process is explored. The main conclusions are as follows:

1. The obvious streamline microstructure is observed in the ED direction of extruded state. After two passes of forging, the alloy grains are refined and the alloy occurs the dynamic recrystallization. After four passes of forging, the dynamic recrystallization degree of the alloy increases. After 6 passes of forging, the recrystallization of the alloy is basically completed, and the small grains formed by dynamic recrystallization grow to a certain extent. After 6 passes of forging, the grains are still refined compared with the extruded state.

2. The initially extruded alloy has a typical \{0001\} basal texture with high texture strength. After 2 passes of forging, the basal texture deflects about 30 degrees in ED direction, and the texture strength is greatly weakened. After 4 passes of forging, the original basal texture changes to \{1010\} and \{2110\}
cylindrical texture, and the texture strength is about 4.1 and 3.4 respectively. After 6 passes of forging, the \{10\overline{1}0\} texture deflects 20-30 degrees in TD direction, and the texture strength decreases. However, after 6 passes of forging, the \{2\overline{1}10\} texture is decomposed into two parts after being deflected by 60 degrees in TD direction, and the grains of the two parts are deflected by 30 degrees in ED direction, and the grain orientations of the two parts are symmetrical about TD axis, the texture strength is lower than that of the \{1\overline{1}0\} texture, and the texture is weakened.

(3) The initially extruded alloy shows obvious anisotropy. By multidirectional forging, the anisotropy of mechanical properties of the alloy is weakened, and the elongation is obviously improved compared with that of the extruded alloy. After 4 passes of forging, the elongation of each surface of the alloy reaches the maximum, which are 32.0%, 29.2% and 27.0% respectively, and are consistent with the Schmied factors and texture evolution rules of the alloy.

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