

Uniformity and continuity of effective strain in AZ91D processed by multi-pass equal channel angular extrusion

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Abstract: AZ91D magnesium alloy was processed by equal channel angular extrusion(ECAE). The influence of extrusion temperature, extrusion pass and extrusion route on the ultimate strength of the extruded billet was analyzed. The process of multi-pass extrusion was simulated with the method of finite element analysis, and the continuity and uniformity of effective strain in multi-pass extrusion were investigated. The results show that extrusion pass plays the most important role in improving the ultimate strength of AZ91D magnesium alloy, the extrusion route is the second, and the extrusion temperature is the last. From the numerical simulation, there exists the continuity of the accumulated deformation in multi-pass extrusion and the effective strain increases linearly. The tendency of the strain uniformity is different in multi-pass extrusion with extrusion routes. The results of experiment agree with those of numerical simulation.

Key words: AZ91D alloy; equal channel angular extrusion; multi-pass; simulation

1 Introduction

Equal channel angular extrusion(ECAE) is a method to refine crystal grain, and has been studied widely for decades. It was developed by SEGAL in 1972, a scholar of former Soviet Russia, and then many people explored its deformation mechanism[1–4], distribution of strain[5–6], formation of texture[7], etc. SEGAL pointed out that its deformation mechanism is shearing deformation[8]. IWAHASHI et al[9] analyzed the calculation results of effective strain, and gave the formula to estimate the value of effective strain in multi-pass extrusion without friction. KIM et al[10–11] studied the texture flowage of AZ61 magnesium alloy in the ECAE process. Besides that, people studied the influence of die structure and extruded materials on the effect of refining crystal, and found that the effect of extrusion was different with the die structure, especially the included angle of channels, ϕ , the die outer corner angle, ψ , and the radius of outer angle, R [12]. And the effect was related with the extruded materials[13–14]. Totally, the knowledge about ECAE is still preliminary, especially the continuity and uniformity of strain in multi-pass extrusion, which need to be further studied.

As magnesium alloy has many advantages over other metals, it has become the focus in many industry fields, such as autocar, electron and communication. In this paper, ECAE technology was carried out to process AZ91D magnesium alloy and the process was numerically simulated by the software DEFORM-3D. The influences of technological parameters on ultimate strength, continuity of strain and uniformity of strain in multi-pass extrusion were studied.

2 Experimental

The detailed chemical compositions (mass fraction, %) of AZ91D magnesium alloy used in this experiments are: 9 Al, 1 Zn, 0.15 Mn, 0.005 Fe, 0.03 Cu, 0.002 Ni, and balance Mg. Fig.1 shows the schematic diagram of ECAE. It is obvious that the included angle of channels, ϕ , and the outer corner angle, ψ , are both 90° . The cross-section of the two channels is of the same size. The diameter of channels is 58 mm, the radius of inner corner is 5 mm, and that of outer corner is 34 mm.

By the orthogonal experimental design method, the influences of extrusion route, extrusion temperature and extrusion pass on the billet's ultimate strength were studied. Four kinds of extrusion routes were defined as

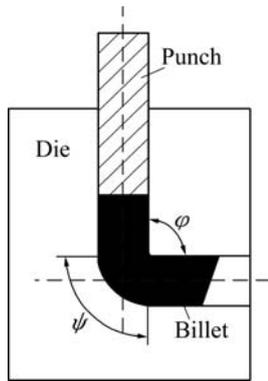


Fig.1 Schematic diagram of ECAE

route A, route B_C, route B_A and route C. For route A extrusion, the billet orientation was the same at each pass. For route B_C extrusion, there was a clockwise 90° rotation around the billet's axis after each pass. For route B_A, the billet had an alternately reversal 90° rotation after each pass, and for route C, there was a 180° rotation after each pass. Considering the characteristics of AZ91D magnesium alloy, the extrusion temperature was chosen as 275, 300, 325 and 350 °C respectively. The maximum extrusion pass was set to 4. The orthogonal table L₁₆(4³) was chosen to design this experiment. Table 1 lists the factor levels. The billets extruded by ECAE were cut along the axis and machined into the tensile test bar to detect their ultimate strength.

Table 1 Factor level of orthogonal experimental design

Level	Extrusion temperature/°C	Extrusion pass	Extrusion route
1	275	1	A
2	300	2	B _C
3	325	3	B _A
4	350	4	C

3 Finite element analysis

The true stress—strain curves of AZ91D were obtained by compression test. The commercial finite element software DEFORM-3D was chosen to simulate the ECAE process. The material model was established in style of relationship $\bar{\sigma} = \bar{\sigma}(\bar{\epsilon}, \dot{\bar{\epsilon}}, T)$, which was recommended intensively by the software. This method defined the stress as the function of temperature, strain and strain rate, and the data from compression test were put into this software in listing table. This can promise the true mechanical property of material to the extent. Fig.2 shows the true stress—strain curves of AZ91D magnesium alloy in different strain rate at 310 °C.

The billet size was $d58 \text{ mm} \times 120 \text{ mm}$. Absolute style was used to mesh the billet, and define the

minimum size as 2 mm and the size ratio (ratio of the maximum size and the minimum size) as 2. As the main deformation zone was in the angular of channels, a refining window was placed there. The speed of punch was set to 5 mm/s, and the friction coefficient was set to 0.1. The re-mesh in the simulation process was done by software itself. When a pass was finished, the billet was replaced in the entrance of die according to extrusion route, then the next pass began, which could promise the multi-pass extrusion, as shown in Fig.3.

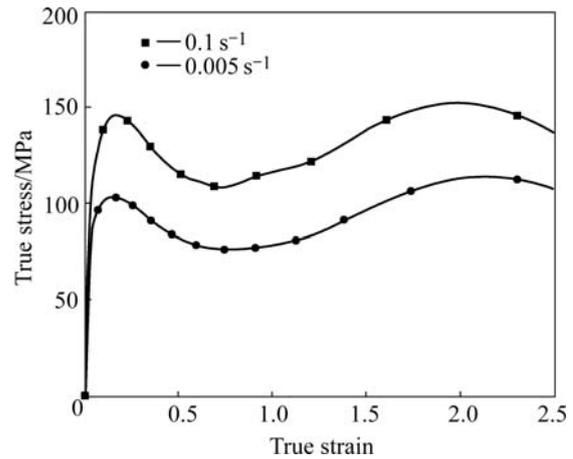


Fig.2 True stress—strain curves of AZ91D magnesium alloy at 310 °C

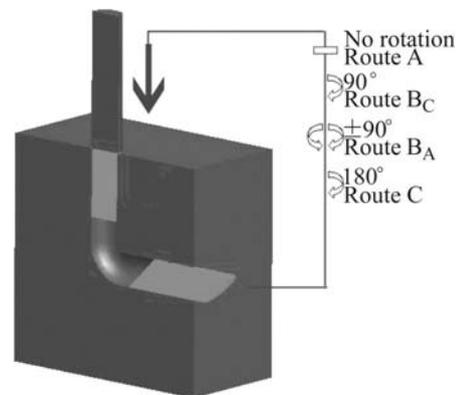


Fig.3 Schematic diagram of simulation of ECAE

4 Results and discussion

4.1 Experiments analysis

Table 2 lists the orthogonal experimental schemes and their results. From *K* value (*K* is defined in orthogonal experimental design method as the number got from adding value of corresponding experimental results), it can be known that the ultimate strength of AZ91D magnesium alloy increases continuously with the extrusion circle increasing. From *R* value (*R* is extreme difference) we know the most important parameter of improving material's ultimate strength is the extrusion pass, the second is the extrusion route, and the last is the

extrusion temperature. According to this experimental results, the preferred experimental scheme is scheme 13, namely 275 °C, route B_C and 4 passes.

Table 2 L₁₆(4⁵) orthogonal experimental scheme and results

No.	Level			Ultimate strength/MPa
	Temperature	Pass	Route	
1	1	2	3	233
2	3	4	1	245
3	2	4	3	264
4	4	2	1	232
5	1	3	1	238
6	3	1	3	202
7	2	1	1	211
8	4	3	3	242
9	1	1	4	195
10	3	3	2	257
11	2	3	4	244
12	4	1	2	186
13	1	4	2	286
14	3	2	4	236
15	2	2	2	241
16	4	4	4	268
<i>K</i> ₁	952	794	926	
<i>K</i> ₂	960	942	970	
<i>K</i> ₃	940	981	941	
<i>K</i> ₄	928	1 063	943	
<i>R</i>	32	269	44	

Fig.4 shows the curve of *K* value at different levels. It can be seen from Fig.4(a) that when the temperature is 300 °C, the ultimate strength of AZ91D magnesium alloy get to its peak. Route B_C is better than the other 3 routes in improving material's ultimate strength (Fig.4(b)). The more the number of passes, the higher property the alloy has (Fig.4(c)).

Based on the analysis of above experimental data, the next experiments were done to get the best extrusion scheme. Under the parameter of 300 °C, route B_C and 4 passes, the ultimate strength of AZ91D magnesium alloy can get to 293MPa. Increasing the extrusion pass beyond 5 provides little improvement in the strength property of billet.

Fig.4(a) shows the influence of extrusion temperature on material's ultimate strength. With the rising of temperature, the ultimate strength is increased. But when the temperature is above 300 °C, the ultimate strength descends. All of these are induced by the balance of refining crystal grain and grain coarsening. When the temperature is between 250 °C and 300 °C, the velocity of refining crystal grain is bigger than that of grain coarsening, so the material's ultimate strength is increased. When the temperature approaches 300 °C, the two velocities are equal approximately. At 300 °C,

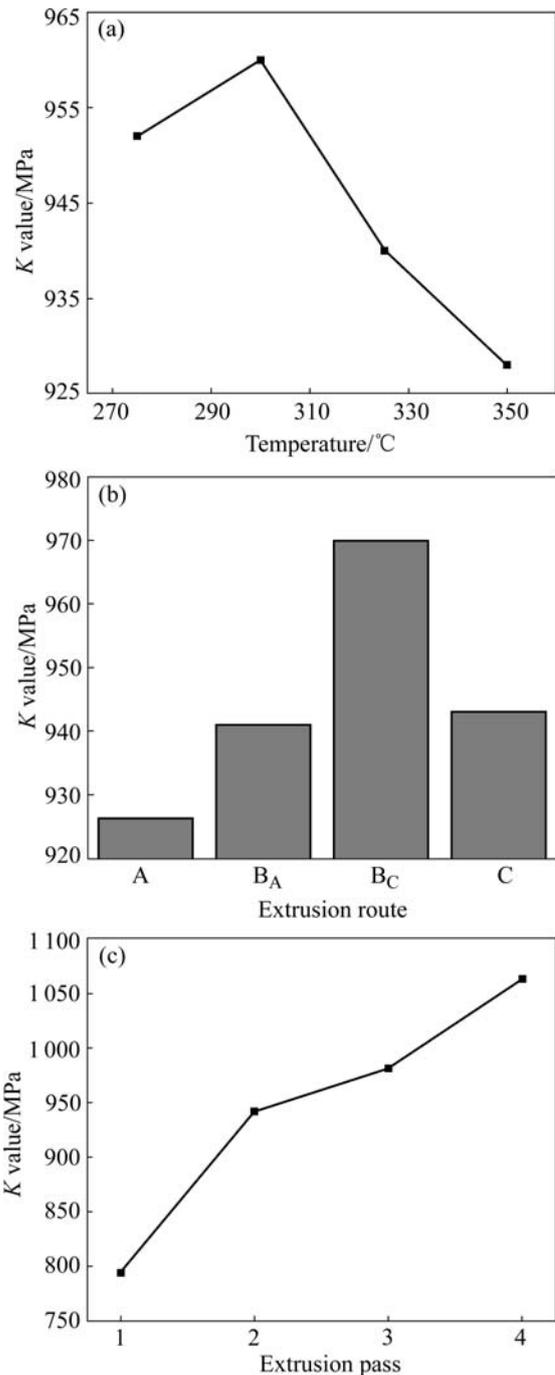


Fig.4 *K* value at different levels of parameters: (a) Temperature; (b) Route; (c) Pass

the best refined crystal grain is gotten, and the ultimate strength is the largest. When the temperature is above 300 °C, the velocity of refining crystal is smaller than that of grain coarsening, so the ultimate strength of billet begins descend.

Fig.4(b) shows the influence of extrusion route on material's ultimate strength. Route B_C can improve the billet's ultimate strength to the maximum extent. Route B_A and Route C have a little difference and Route A has the worst effect among them. This may be related to the number of shear planes which opened by route.

Fig.4(c) shows the influence of extrusion pass on material's ultimate strength. It is obvious that the ultimate strength of AZ91D magnesium alloy increases continuously with the passes increasing from 1 to 4. And the later experiments proved that the 5th pass has little effect on the billet's ultimate strength.

Fig.5 shows the microstructures of AZ91D extruded for different extrusion passes with extrusion route B_C. It can be seen that the crystal grains become finer and more homogeneous with the increment of extrusion passes. Firstly the crystal grains are elongated by the 1st pass, and then begin to break. The former 4 passes have an advantage of refining the crystal grains than the 5th pass, which is consistent with the fact that the ultimate strength gotten from the former 4 passes is almost equal to that from the former 5 extrusion passes. It is obvious that the crystal grains are mostly under 30 μm after 4 extrusion passes.

4.2 Uniformity of strain

The uniformity of strain has a direct influence on

the billet's ultimate strength. For ECAE, there is a complex stress in the front and the end of extruded billet, which leads to the complexity of strain distribution. This is called "end effect"[15]. The "end effect" makes it difficult to analyze the ECAE process. But it is impossible to erase it. Fig.6 shows the scatter diagrams of effective strain on cross-section by different routes. The cross section is a plane having an angle of 45° with the vertical direction at the corner of channels, and so called "cross direction" is a horizontal diameter parallel to the channel on this cross section, and "longitudinal direction" is a line normal to the longitudinal direction on the cross section.

It can be seen that in route A, the distribution of effective strain is homogeneous on the cross direction, and almost all show a horizontal line. But in the longitudinal direction, the uniformity of effective strain is bad. For the first pass, the degree of irregularity is the biggest. The maximum of effective strain appears at the inner corner, and the minimum appears at the place leaving the outer corner about 1/4. With the increase of

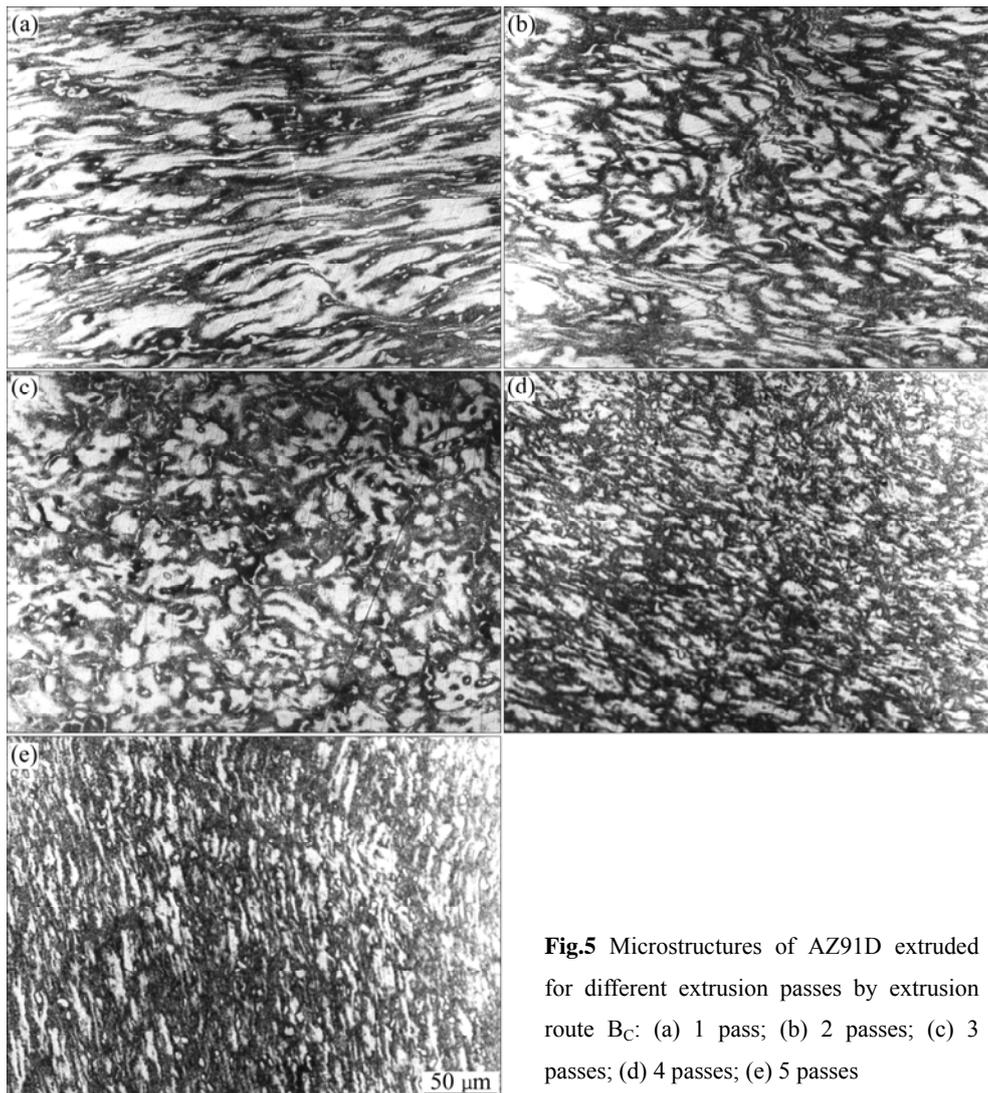


Fig.5 Microstructures of AZ91D extruded for different extrusion passes by extrusion route B_C: (a) 1 pass; (b) 2 passes; (c) 3 passes; (d) 4 passes; (e) 5 passes

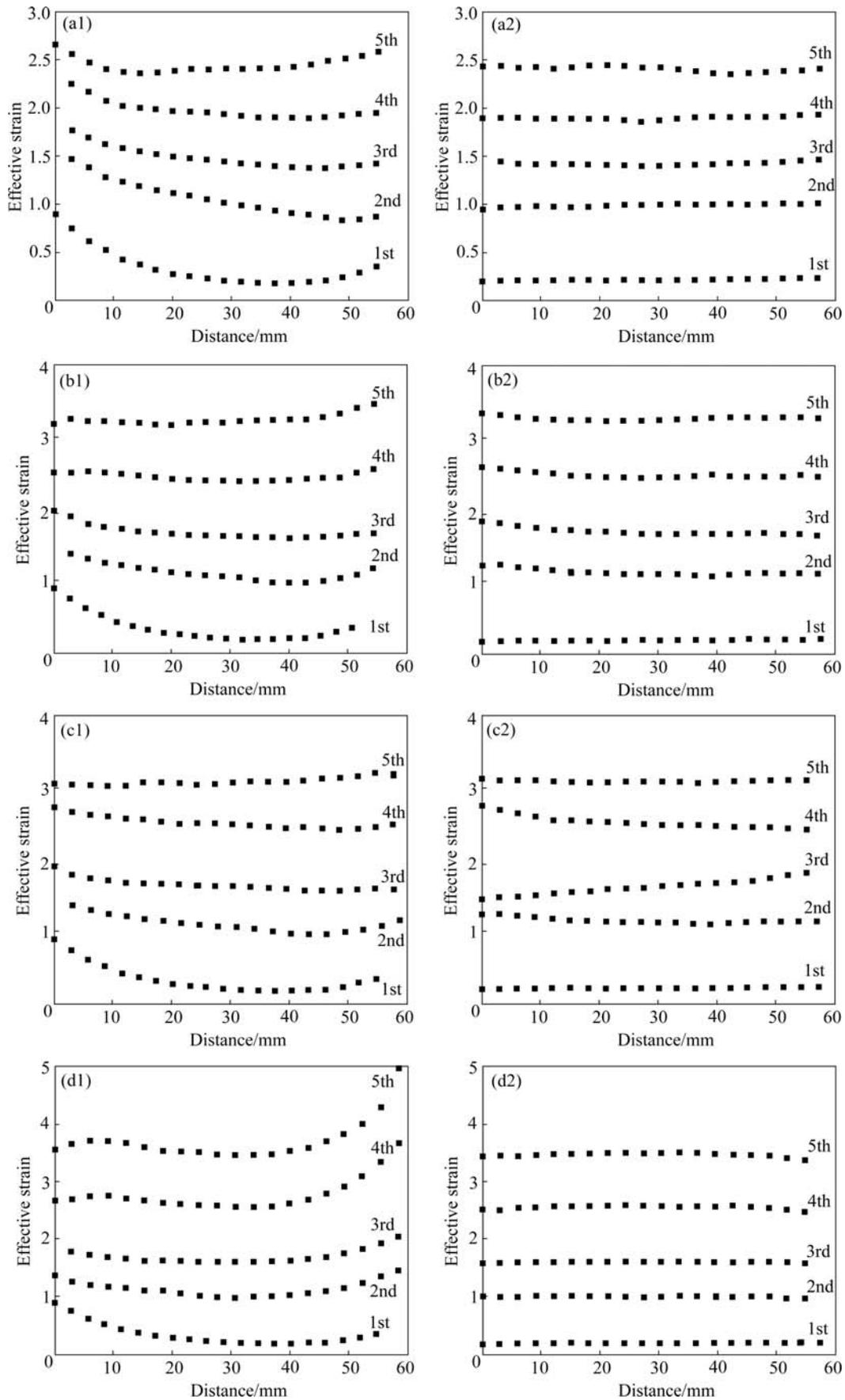


Fig.6 Scatter diagram of effective strain on cross-section by different routes: (a1) In longitudinal direction of Route A; (a2) In cross direction of Route A; (b1) In longitudinal direction of Route B_C; (b2) In cross direction of Route B_C; (c1) In longitudinal direction of Route B_A; (c2) In cross direction of Route B_A; (d1) In longitudinal direction of Route C; (d2) In cross direction of Route C

pass, the uniformity becomes better, but the places of the maximum and the minimum keep unchanged. After the first pass, the identical section of effective strain is about 50%. With the increase of passes, it becomes greater, and after the fourth passes, it can get to the value of 80%.

In Route B_C, it can be seen that the distribution of effective strain is homogeneous in the cross direction or longitudinal direction, showing a horizontal line. Compared with route A, the speed towards uniformity in longitudinal direction is much greater. After 3 passes, the effective strain is equal approximately.

It can be seen that in route B_A, the effective strain in longitudinal direction becomes more homogeneous with the increase of passes. After the fourth passes, the

effective strain is almost the same approximately. But in the cross direction, the uniformity of effective strain is worse, especially after the third and fourth passes, and the uniformity even become worse than that after the first and second circle. But after the fifth passes, the billet has a better uniformity again.

In Route C, the effective strain in cross direction is homogeneous, and there is no great change for each pass. But the uniformity of effective strain in longitudinal direction becomes much worse with the increase of pass. The change of effective strain becomes larger, and the identical sections of effective strain become less.

4.3 Continuity of strain

Fig.7(e) shows the change of effective strain in

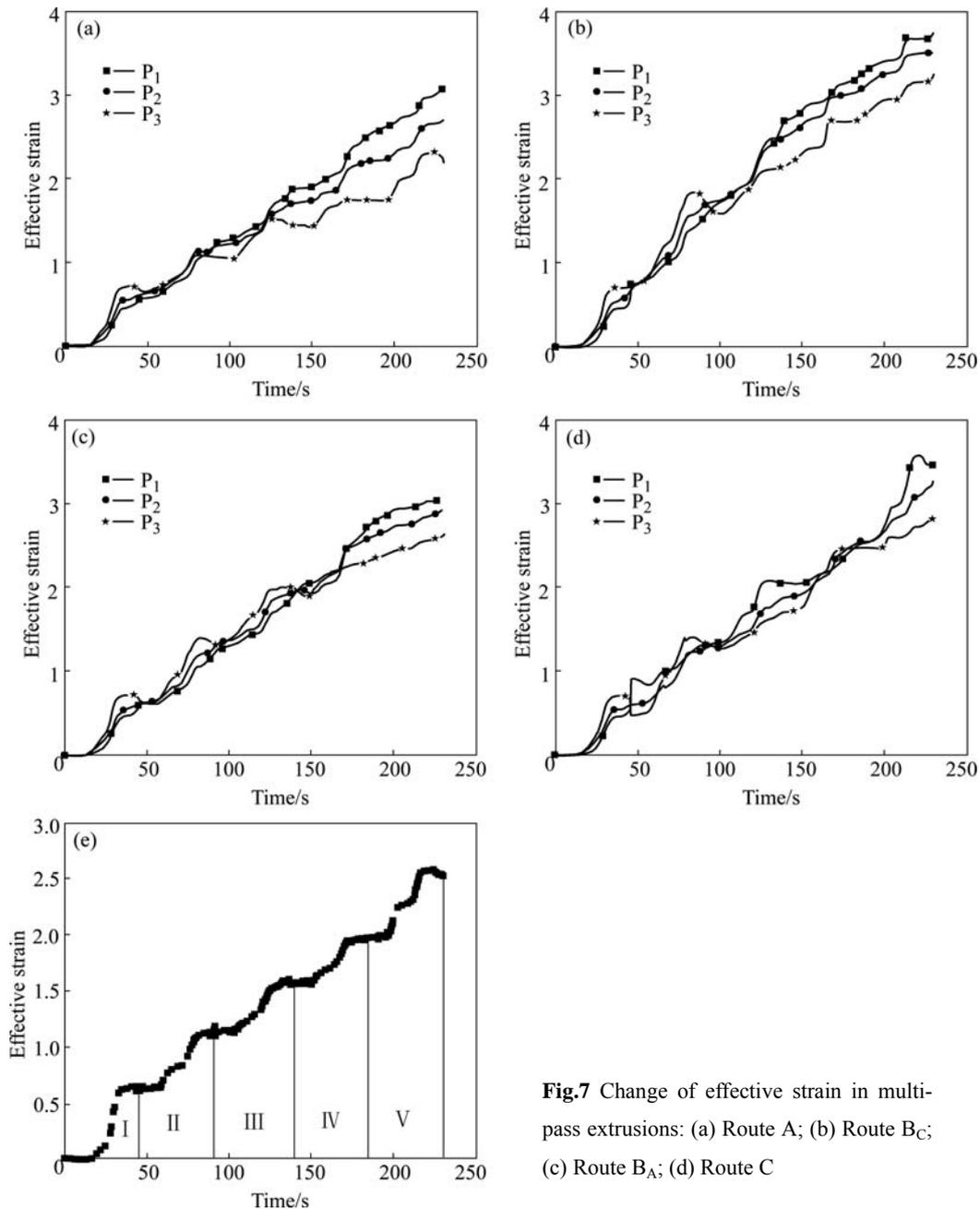


Fig.7 Change of effective strain in multi-pass extrusions: (a) Route A; (b) Route B_C; (c) Route B_A; (d) Route C

multi-pass extrusion. It can be seen that there are 5 similar stages, which are corresponded to the 5 extrusion passes. Every stage has the same tendency, which means that every extrusion pass has the same deformation mechanism. Every stage can be divided into 3 parts. Firstly, the effective strain doesn't vary and keeps constant. Then the billet reaches the angular of channel, and begins to deform. In this part, the effective strain rapidly increases. This part is the most important, in which the main deformation in ECAE process occurs. It can refine the crystal grain and improve the ultimate strength of billet. Finally, the strain becomes flat, even descends. This is because the billet comes into the straight channel again, and the effective strain keeps constant or diminishes a little because of the elastic recovery.

Figs.7(a), (b), (c) and (d) show the change of effective strain in multi-pass extrusions of route A, route B_C, route B_A and route C respectively, in which P₁, P₂ and P₃ are three equispaced points on the line connecting the inner corner with the outer corner in the billet vertical section. It can be seen that the total of effective strain in each route increases continuously with the time prolonging linearly basically. There is no reduction of effective strain, whatever in any extrusion route, and in all these stages, which is different from that described in some documents. Among the 4 routes, route B_C has the biggest value of slope. It means route B_C has advantage to improve material's ultimate strength. And after 5 passes, the effective strain by route B_C can get to the value of 4.0, which is bigger than that by other routes. This is coincident to that the mechanical properties of billet processed by route B_C are the best. For the other 3 routes, there is no obvious difference. The total of effective strain through 5 passes is about 3.5.

5 Conclusions

1) There exists the continuity of the accumulated deformation in multi-pass extrusion. For all the 4 routes, the strain rises straightly. Route B_C has the greatest increasing rate of strain, and its effective strain can reach the value of 3.8 by 5 passes. There exists different tendency of strain uniformity in multi-pass extrusion, the effective strains of route A, route B_C and route B_A become more homogeneous with the increase of extrusion pass, but that of the Route C becomes worse.

2) The extrusion pass plays the most important role in improving ultimate strength of AZ91D magnesium. The more the numbers of extrusion pass, the higher the property of alloy. The effect of the former 4 passes is greater than that of the fifth pass. The second is the

extrusion route. The best way to improve ultimate strength is Route B_C, the second Route C, the third Route B_A, and the last route A. Compared with other experiment parameters, the extrusion temperature plays least role in improving ultimate strength. For AZ91D magnesium alloy, when the temperature of material and die are both 300 °C, the billet extruded gets its best property.

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