Topical Review

Research progress of ultrafine grained magnesium alloy prepared by equal channel angular pressing

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Abstract

In this paper, the research status of equal channel angular pressing (ECAP) in the preparation of ultrafine grained magnesium alloy is introduced. The research results in recent ten years are summarized, including the principle and improvement method of ECAP process, plastic deformation mechanism of magnesium alloy, microstructure characteristics, texture evolution and mechanical properties of ultrafine grained magnesium alloy prepared by ECAP. It is pointed out that the influences of grain refinement and texture evolution on mechanical properties such as strength, superplasticity and anisotropy must be considered comprehensively. At the same time, the principle of grain refinement and texture modification in ECAP is also discussed; On the other hand, this paper summarizes the research progress of ECAP numerical simulation in analyzing the influence of ECAP process parameters on strain distribution uniformity, damage prediction, texture evolution and ductile fracture behavior. Finally, the development trend of ECAP process for preparing ultrafine grained magnesium alloy and its application prospect in the field of commercial manufacturing are introduced. Some urgent problems to be solved at this stage are discussed and solutions are put forward, which can provide references for in-depth research in the future.

1. Introduction

Since the 1990s, magnesium and its alloys have drew more and more attention, especially in sports equipment, electronic device, automobile, aerospace and biomedical fields. As the lightest metal material in structural materials, magnesium alloy has high specific strength and specific stiffness, good damping characteristics and recyclability. Although Mg has been used in some automotive parts, such as seat structure and mounting bracket, its application is mainly limited to die casting due to its poor plasticity at room temperature and difficult deformation. The poor mechanical properties of cast magnesium alloy also limit its application in structural parts with large stress. Compared with cast magnesium alloy, wrought magnesium alloy exhibits higher strength and ideal plasticity due to grain refinement during the deformation process, which can meet the plastic processing and application of some key structural parts, so its deformation research has become one of the hot spots in magnesium alloy research [1-6].

Severe plastic deformation (SPD) is a process in which large pieces of material are deformed by generating large plastic strains to produce ultrafine grained materials. SPD processing of magnesium alloys can successfully prepare ultrafine-grained microstructures, which has been proven to be one of the most promising strengthening methods [7-9]. At present, SPD technology mainly includes severe torsion straining process (STSP) [10], torsion extrusion processing [11], accumulative torsion back (ATB) [12], compression and backward extrusion [13], equal channel angular pressing (ECAP) [14], accumulative roll bonding (ARB) [15], cyclic extrusion and compression (CEC) [16], repetitive corrugation and straightening (RCS) [17], cyclic closed die forging (CCDF) [18], High pressure torsion (HPT) [19], constrained groove pressing (CGP) [20, 21], high pressure torsion extrusion (HPTE) [22], etc. ECAP is widely used in Al [2] and Cu [1] alloys, and the process is
mature. Kadiyan et al [1] reported that ECAP treatment of low alloy copper at 250 °C intermediate annealing temperature can obtain submicron grains and greatly improve mechanical properties. The tensile properties of Al-6063 T5 were improved by 94.25% after ECAP treatment. In recent ten years, more and more attention has been paid to the application of ECAP in magnesium alloys. ECAP, as a common severe plastic deformation (SPD) process, can effectively refine the grain size of magnesium alloys, and is the most effective method for preparing ultra-fine grained (UFG) magnesium alloys with excellent mechanical properties during the past decade [23]. Lin et al [24] reported that after 6 passes of ECAP at 453 k, the average grain size of ZA85 alloy reduced greatly from 150 μm to 1 μm, the ultimate tensile strength (UTS) and yield strength (YS) increased from 105 MPa and 74 MPa to 249 MPa and 162 MPa respectively at 473 K, and the elongation increased from 5.1% to 28.5%. Similarly, after 32 passes of ECAP [25], the yield strength and elongation of ZE41A alloy increased by 120% and 75%, respectively. In recent years, the research on the preparation of ultrafine grained magnesium alloy by ECAP mainly focuses on the grain refinement, texture evolution and mechanism, and the relationship between the microstructure and mechanical properties such as tensile strength, superplasticity and anisotropy has also been deeply analyzed, which lays a good foundation for the development of ultrafine grained magnesium alloy. Among them, the Superplasticity of magnesium alloy can make it possible for magnesium alloy to be used in the production of some structural precision components, which expands the application range of magnesium alloy. At the same time, with the rapid development of computer numerical simulation technology, finite element method and other process simulation techniques have been introduced into the research of ECAP ultrafine grained magnesium alloy, such as optimizing process parameters, analyzing the stress-strain distribution in the deformation process, etc. This paper not only introduces the previous research results in detail, but also summarizes the relevant literature in recent five years. The development history of ECAP process is summarized in all aspects and emphases. At the same time, the summary and analysis of the micro mechanism also provides a way for readers to deeply understand ECAP process and its application in magnesium alloy. This paper also systematically discusses the problems that need to be solved at present, and puts forward the corresponding solutions, so as to provide reference for further research in the future.

2. Equal channel angular pressing (ECAP) process

ECAP was proposed by Segal [26] in the 1980s to obtain ultrafine grained materials by means of large plastic deformation. The processing process is to press the well lubricated test sample through two intersecting channels with equal cross section, and impose simple shear to the test sample at the intersection of the channels, as shown in Figure 1 [8]. Two channels with equal cross section associate with the degree of angle Φ (internal mold/channel angle Φ), and the angle ψ is the curvature arc at the intersection point (external curvature arc/external rotation angle ψ).
In the ECAP process, the same sample can be repeatedly extruded for many times because there is no change in the cross section of the sample. Therefore, the material undergoes repeated shear deformation, which causes the material to produce a considerable amount of cumulative plastic strain, resulting in significant grain refinement, and finally ultrafine grained materials [27, 28]. Different deformation textures can be obtained by adjusting the shear direction and shear plane, so the process parameters can be designed according to the material properties to obtain ideal materials. In order to avoid the cracking of magnesium and its alloys during ECAP, the temperature during deformation is generally higher than 200 °C [29]. According to research reports, the equiaxed grain size of pure aluminum extruded along the Bc route [30] is similar to that of conventional cold deformation process (such as compression and extrusion) [31], which indicates that the deformation in ECAP is similar to that in conventional metal processing technology. But the difference is that the material processed by ECAP will accumulate extremely high strain, in which the sub grain boundary evolves into high angle grain boundary by absorbing dislocations, thus ultrafine grain arrays divided by high angle grain boundaries are produced. In contrast, limited by the total strain introduced in the deformation process, this evolution cannot be realized in the traditional metal processing technology. Some studies have reported that the magnitude of the shear strain (γ) imposed to the sample depends on the channel angle (Φ) and the angle related to the curvature arc (ψ). This relationship is shown in formula (1):[32]

\[ \gamma = 2 \cot \left( \frac{\Phi + \Psi}{2} \right) + \Psi \csc \left( \frac{\Phi + \Psi}{2} \right) \]  

(1)

Similarly, it is confirmed by calculation [33] and model test [34] that the cumulative equivalent strain (\( \varepsilon_{eq} \)) after continuous extrusion (extrusion pass N) can be expressed by formula (2):

\[ \varepsilon_{eq} = \frac{N}{\sqrt{3}} \left[ 2\cot \left( \frac{\Phi + \Psi}{2} \right) + \Psi \csc \left( \frac{\Phi + \Psi}{2} \right) \right] \]  

(2)

However, it should be noted that formula (2) shows the equivalent strain produced in the sample without friction, but in the actual ECAP process, friction between the sample surface and the die wall is inevitable. During ECAP processing, these strains are applied to the sample with a hydraulic press. The extrusion pressure requirements are shown in formula (3):[35]

\[ P = \tau_0 (1 + m) \left[ 2\cot \left( \frac{\Phi + \Psi}{2} \right) + \Psi \right] + 4m\tau_0 \left( \frac{l + l_0}{a} \right) \]  

(3)

Where \( \tau_0, m, l, l_0 \) and \( a \) are shear strength, friction coefficient, instantaneous length of specimen in inlet channel, instantaneous length of sample in exit channel and width of extrusion channel, respectively. There are four basic extrusion routes in ECAP, as shown in figure 2: For route A, the sample is extruded without rotation; for route Ba, the sample is rotated 90° alternately between successive passes; for route Bc, the sample is rotated 90° anticlockwise for each pass; for route C, the sample is rotated 180° pass [24, 30, 33]. The influence of extrusion route on material microstructure will be analyzed in detail in the following chapters.

In order to improve the ECAP process, back pressure (BP) was introduced into the die exit channel to get even strain distribution in the sample and prevent defects on surface. The back pressure equal channel angular pressing (BP-ECAP) has achieved good extrusion effect even for the hard to deform materials. The schematic diagram is shown in figure 3 [36–38]. The research of Oruganti et al [39] shows that ECAP samples can obtain better strain behavior by imposing high back pressure and low friction during ECAP. In addition, Bc route provides better uniformity of strain dispersion than other routes with 90° die channel angle [40]. A key limitation of traditional ECAP is that the sample must be removed from the mold and reinserted to obtain a high plastic strain. This process is particularly time-consuming and also requires a lot of labor intensity [41]. Therefore, in order to refrain from this limitation, some new methods, such as ECAP in rotary-die [42], lateral pressure [41] and cross-ECAP [43] are proposed and used accordingly.

For accurately estimating the influence of ECAP on the mechanical properties of magnesium alloys, both grain size and texture orientation must be considered. The processing temperature of ECAP is mainly concentrated in the high temperature area above 200 °C. At higher temperature, additional non-basal slip system is activated, dynamic recrystallization (DRX) is easy to carry out, and the effect of texture is gradually weakened [44]. Pre-aging treatment can effectively ameliorate the mechanical properties of ECAP magnesium alloy, because the pre-formed fine precipitates refine the alloy structure by hindering the growth of dynamic recrystallization (DRX) grains [45]. Jung et al [46] reported that the pre-aging treatment reduced the grain size of DRX in the Mg-7Sn-1Al-1Zn alloy treated by ECAP, and increased the number of precipitates, so the tensile strength and ductility of the alloy were better than those of the ECAP treatment without pre-aging. Horita et al [47] pointed out that the initial extrusion process improves the grain refinement efficiency of ECAP. Taguchi analysis is a low-cost and high-efficiency engineering method, which emphasizes that the improvement of product quality is not through inspection, but through design. Design of experiments (DOE) has been proved to
Figure 2. Four common extrusion routes of ECAP.

Figure 3. Schematic of equal channel angular pressing dies for applying the BP. Reprinted from [36], Copyright (2013), with permission from Elsevier.
be an effective method for ECAP process modeling [48]. Response surface methodology (RSM) establishes a mathematical model related to process parameters and process results, which can greatly simplify the tedious experimental research by combining it with statistical model. The RS model developed by kadiyan et al [48] can accurately predict the Vickers hardness and average grain size, and the error between the predicted data and the experimental data is less than 1%.

3. Microstructure of ECAP magnesium alloy

3.1. Microstructure characteristics

The material processed by ECAP will produce large plastic strain, and dynamic recrystallization and dynamic recovery will lead to grain refinement and obtain fine and even equiaxed grains, which will improve the microstructure and mechanical properties of the material [49]. Figure 4 shows the ECAP macro shear diagram at $\Phi = 90^\circ$ and $\psi = 0^\circ$ with three illustrations of X, Y and Z planes describing the deformation of grains and the slip system. It should be noted that this is only applicable to the macrostructure of materials processed by 1 pass and 2 passes ECAP [33]. The microstructure of as-cast pure magnesium after ECAP processing at 350 °C for 1 pass, 2 passes and 4 passes extrusion under A, Bc and C routes is shown in figure 5 [50]. About 900 μm coarse grains were surveyed in as-cast pure magnesium. After one pass ECAP processing, two kinds of grains with large size (200 μm) and small size (50 μm) appeared, and the large grains are encircled by tiny grains, which may be caused by DRX during ECAP processing. At the same time twins are also surveyed in large sized grains, which indicated that twins also occurred in the ECAP process. It should be noted that the refining degree of pure magnesium after 2 passes of ECAP is limited, and the grain size does not change significantly with the increase of extrusion pass. This is probably due to the overtop extrusion temperature, which leads to the grain growth easily. Therefore, it is necessary to reduce the extrusion temperature to obtain finer grains. Suwas et al [51] reduced the average grain size of pure magnesium to 6–8 μm after 4 passes of ECAP treatment at 250 °C, which can significantly improve the subsequent cold rolling performance. The improvement of cold formability is mainly attributed to the grain refinement caused by ECAP treatment and the introduction of initial non base texture. Yan et al [52] carried out ECAP on Mg-6Zn alloy at 160 °C–240 °C. It was found that at a lower temperature (160 °C, 200 °C), the alloy formed a bimodal structure coexisting with large and tiny grains, and the fine grains

Figure 4. Schematic illustration of ECAP shearing.
and precipitated particles were mainly distributed in the neighbouring region of the eutectic structure, while the
large grain was mainly formed in the areas with poor Zn elements that aloof from eutectic structure. In previous
studies \[53\], the bimodal or multimodal structure in single-phase alloys is caused by dynamic recrystallization
under nonuniform deformation, and gradually evolves into uniform and fine equiaxed grains with the increase
of strain. However, under the same extrusion passes, there is no bimodal grain structure in the ECAP structure of
Mg-6Zn alloy at 240 °C. Therefore, different from the single-phase alloy, the uneven distribution of solute is the
fundamental reason for the formation of bimodal structure with fine precipitates in Mg-6Zn alloy during ECAP
at low temperature.

It is reported in \[54, 55\] that ECAP treatment also affects the precipitation process and morphology of the
second phase at different melting points in the alloy, that is, ECAP can not only cause fine grain strengthening by
reducing the grain size, but also have a significant effect on the precipitation strengthening of the alloy. Cheng
et al\[54\] discovered that Mg2Sn phase was precipitated in Mg-8Sn-6Zn-2Al alloy during ECAP, which has a low
melting point. Mg2Sn phase can decrease the average grain size of DRX and raise the volume fraction of tiny

Figure 5. Microstructure of pure magnesium processed by ECAP (a) 0 pass, (b) 1 pass, (c) 2 passes along route A, (d) 4 passes along
route A, (e) 2 passes along route Bc, (f) 4 passes along route Bc, (g) 2 passes along route C, (h) 4 passes along route C. Reprinted from
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grains after ECAP. Yan et al [56] found that the tensile strength of Mg-6Zn alloy after two passes of ECAP treatment at 160 °C can significantly improve the tensile strength from 260 MPa to 340 MPa, and the yield strength from 200 MPa to 265 MPa. However, with the increase of deformation, the strength of ECAP treated alloy after 4 passes and 6 passes is not different from that of 2 passes ECAP. The results of TEM and XRD show that ECAP induces the precipitation of laves-MgZn2 and Mg4Zn7 phases. ECAP introduces a large number of dislocations as diffusion channels to produce non-equilibrium grain boundaries with a large number of vacancies. The segregation of alloy elements in the grain boundaries reduces the effective diffusion activation enthalpy. After 4 passes of ECAP, a large amount of Mg4Zn7 phase appears, but after 6 passes of ECAP, the amount of Mg4Zn7 phase decreases obviously. This is due to the fact that MgZn2 phase is an equilibrium phase, which is stable between room temperature and 315 °C, while Mg4Zn7 is a metastable phase and is replaced by the final product as a transition phase during severe deformation.

3.2. Influencing factors

Various experimental parameters (extrusion route, applied strain, extrusion temperature and speed, etc.) of ECAP processing have marked impacts on the microstructure and mechanical properties of magnesium alloys [57–59].

The shear direction of adjacent passes of extrusion route A is perpendicular to each other, and the shear direction of ECAP continuous extrusion pass is only in the Y plane, and the shear degree is evenly distributed between two groups of orthogonal planes. For route Bc, the shear direction of continuous extrusion passes is on the plane intersecting 120° and the shear strain is in Y plane and Z plane (parallel to transverse direction and ED) due to the rotation between continuous extrusion passes, so the grain refinement effect is the best. In the adjacent passes, the shear directions of route C are reversed on the same shear plane and parallel to each other, and the initial coarse grains deform repeatedly during ECAP, which may lead to the accumulation of more dislocations in the shear band and promote the dynamic recrystallization of the alloy. Therefore, ECAP processing along route C has a better effect on grain refinement than route A [30]. It is found in [60] that the ECAP alloys along different extrusion routes show the same structural characteristics, that is, the coarse grains of 10 μm are embedded in a large number of 1–2 μm fine grain bands, but more fine equiaxed grains are obtained in the alloys extruded along the C route. Moreover, studies have shown that compared with other extrusion routes, ECAP treatment along route C often results in more uniform microstructure [2]. Tong et al [61] studied the change of orientation difference angle of Mg-Zn-Ca alloy after ECAP. The results showed that the proportion of low angle grain boundaries (LAGBs) was about 16% after ECAP one pass extrusion, making clear that DRX has not been fully developed. The proportion of LAGBs decreases with the increase of ECAP passes. After 4 passes of extrusion, the proportion of LAGBs in the alloy with route Bc is lower than that of route A and C. The high-speed development of LAGBs to high angle grain boundaries (HAGBs) indicates that DRX is more fully carried out in the extrusion process along the Bc route and the corresponding grain size is smaller than that of the alloys extruded along A and C routes.

For different series of magnesium alloys, one pass ECAP treatment can significantly refine the microstructure of the alloy, and the grains are mostly banded. With the increase of extrusion passes, the grains gradually evolve into uniform and fine equiaxed grains. Wang et al [62] found that a bimodal structure appeared in AZ80 Alloy after one pass ECAP treatment at 523 K. The average size of coarse grain is 10 μm, which represents the residual part of the original structure, while the fine grain is the result of DRX at 523 K extrusion temperature and strong strain stimulation. With the increase of extrusion passes, the volume fraction of coarse grains increases obviously. The average size of coarse grains in 2 passes is 7 μm, although the average size of coarse grains in 4 passes increases to 11 μm, the volume fraction of coarse grains decreases and the microstructure tends to be equiaxed.

Fine DRX grains can be obtained at lower temperature and higher strain rate, while the microstructure is more uniform when processed at high temperature and low strain rate. The average grain size decreases with the decrease of ECAP temperature, but it also increases the tendency of surface cracks when the temperature is low. Kadiyan et al [1] also reported that ECAP treatment at high annealing temperature can reduce the tendency of microcrack formation. In addition, with the increase of strain, the volume fraction of DRX grains increases significantly [63–65]. Krajnak et al [66] found that compared with 220 °C, AX41 alloy can obtain uniform microstructure with less passes during ECAP processing at 250 °C. However, the final grain size obtained by 8 passes extrusion at 250 °C is 4 μm, which is larger than the grain size of 2.7 μm at 220 °C, and the mechanical properties also decrease due to the large grain size.

Similarly, Hong et al [67] found that in the test temperature range (400 °C, 440 °C, 480 °C), the samples of Mg-9Gd-4Y-0.5Zr alloy extruded at 400 °C and aged at 200 °C/60 h have the best mechanical properties, the tensile strength reaches 508 MPa and the elongation is 8%. The microstructure observation shows that the sample has a bimodal structure with both coarse-grained and recrystallized fine-grained regions, and its ultra-
high strength is due to the strong texture in the coarse-grained and nano-sized precipitates. Zhou et al [65] studied the effect of ECAP on the microstructure of Mg-9Al-1Si alloy at different temperatures (310 °C, 330 °C, 350 °C). It can be seen that DRX occurs in the alloy during ECAP, and coarse-grained region appears with the increase of extrusion temperature. When the extrusion temperature is 330 °C, the alloy shows a typical bimodal structure with both coarse and fine grain regions. With the increase of temperature, the grain growth rate, atomic diffusion rate and precipitation growth rate increase, which leads to the obvious grain growth in the coarse-grained region. At the same time, the grain boundary in the DRX region is pinned by a large number of fine precipitates. Therefore, compared with 310 °C, the grain size of fine grain area at 330 °C is much smaller. However, when the temperature continues to rise to 350 °C, the pinning effect of precipitates weakens, the coarse grained area increases sharply, and the grains in the fine grained area also grow significantly, which leads to the enlargement of the average grain size. A large number of fine Mg17Al12 phases are precipitated in the ECAP process, and the morphology and distribution of the precipitated phases change with the rise of temperature, which depends on the diffusion rate of Al in the matrix and the nucleation ability of Mg17Al12 phase. The highest tensile strength and elongation of the alloy can be obtained when the extrusion temperature is 330 °C. Some studies [67, 68] also show that bimodal structure can significantly improve the plasticity of the alloy (Typical bimodal structure and the effect of fine grains on deformation are shown in figure 6). The large grains (> 1 μm) preferentially adapt to the strain during deformation and can effectively store dislocations. Moreover, the small grains can play a role in adjusting the deformation, so that the alloy can obtain good elongation.

### 3.3. Refinement mechanism

It is generally believed that ECAP grain refinement mechanism involves mechanical shear, strain accumulation and DRX in ECAP process. Most studies have reported the effect of ECAP on grain refinement, but the description of grain refinement mechanism is still vague. Segal [69] suggested that the shear band and subgrain rotation caused grain refinement. In each pass of ECAP processing, thin shear bands oriented along the intersection of channels are formed, and most of them are HAGBs. In the subsequent passes, the evolution of shear plane induced in the material and the rotation mode of strain regulation determine the grain refinement of different processing routes. For the plane plastic flow of route A and route C, subgrain rotation controls the evolution of HAGBs. However, for route B and route D, the cross of shear bands forms a stable large angle grain boundary spatial network on the micro scale, which effectively refines the grains. Zhu et al [70] considered that the grain refinement during ECAP is affected by the interaction of cumulative strain, shear plane, crystal structure and deformation texture. For FCC metals with dislocation slip as the main deformation mechanism, the latter is the main control mechanism in the channel angle Φ = 90° mold, while the former is the main control mechanism in the channel angle Φ = 120° mold. It is considered that the texture evolution and its relationship with the shear plane are the key factors affecting the grain refinement. The viewpoint of grain refinement mechanism makes further effort to mend the basis of Segal.

In many initial coarse grained materials, multi-pass ECAP can obtain good grain refinement. However, most of the models proposed are based on ductile materials such as Al and Cu at room temperature. These models have obvious limitations for Mg processed by ECAP above room temperature. The ECAP refinement mechanism of Al and Cu is mechanical shear and strain accumulation at room temperature. The ECAP shear deformation of FCC Al is mainly caused by dislocation slip, which produces complex dislocation entanglement network and leads to microcrystalline during deformation. The thermal activation process that helps grain refinement is less important because mechanical shear alone is sufficient to produce new grain boundaries. At room temperature, the deformation of Mg and its alloys is mainly based on {0002} {11 20} basal slip and {10 12} {10 11} twin deformation; with the further rise of deformation
temperature, the activity of prismatic and pyramid slip systems increases. Therefore, the ECAP processing of Mg and its alloys is usually above 200 °C. Therefore, the model of grain refinement caused by mechanical shear is not suitable for hexagonal close packed crystal structure (HCP) materials (such as Mg), in which twinning plays an important role in deformation regulation. The grain refinement mechanism of this material can not only be considered from the mechanical or geometric point of view, but also ignore the recovery process under high temperature ECAP processing [71]. Therefore, Su et al [71] put forward a mechanism of Mg grain refinement under ECAP processing to explain the effects of shear band and dislocation entanglement in grains, as shown in figure 7. The nucleation of new grains occurs mainly in the shear band and along the grain boundary. Dislocations rearrange in the grains to form a sub grain structure, which results in the formation of new grain boundaries. The newly formed grains grow at the expense of the original grains. When the dislocations are trapped in the LAGBs, the LAGBs change into the HAGBs. He et al [72] also believes that dislocations rearrange into a subcrystalline boundary during ECAP. With the increase of deformation degree, the subgrain absorbs movable dislocations and evolves into large angle grain boundaries, thus forming stable and fine recrystallized grains.

During high temperature deformation, large grain size magnesium alloy mainly deforms by activating non-basal slip, while microcrystalline magnesium alloy mainly deforms through grain boundary slip (GBS) mechanism. In addition, when the deformation is small, twins also play an important role [73–78]. Yan et al [79] found that the ECAP grain refinement mechanism of magnesium alloy is a process of heterogeneous dynamic recrystallization nucleation and growth. During ECAP, a large number of twins are produced in the grains, which intersect with each other, leaving a tortuous grain boundary. Dynamic recrystallization nucleates and grows on the grain boundary and

Figure 7. Grain refinement mechanism of ECAP pure magnesium. Reprinted from [71], Copyright (2006), with permission from Elsevier.
twin boundary, and divides the original coarse grain into smaller fine grains, forming a bimodal structure with both coarse and fine grains. Su et al. [71] observed that the average grain size of AZ31 alloy reduced gradually after continuous ECAP processing, and proposed a grain refinement mechanism, that is, multiple recrystallized grains nucleate uniformly and grow continuously in the whole volume of the processed material until the grain boundaries contact each other, which eventually leads to the formation of equiaxed grains. However, Galiev et al. [73] found that in the magnesium alloy deformed at high temperature, the grains nucleate along the grain boundary and recrystallize, resulting in the appearance of necklace structure and multi-mode distribution of grain size. Biswas et al. [74] also reported that the grain size distribution of pure magnesium was uneven when processing at a lower temperature. Taking these experimental phenomena into account, a new grain refinement model was proposed by Figueiredo [53]. The fine grains nucleate near the original grain boundary and inside the twin, but the unrefined area can still be observed far away from the grain boundary, thus forming a bimodal grain structure. The results of Poggiiali et al. [75] verified this model. The fine grains nucleate at the grain boundary and twin boundary, resulting in uneven grain size distribution. After ECAP processing, the grain size of the material exhibits a bimodal distribution. The evolution trend of the degree is consistent with the prediction in the literature [53]. However, some previous studies, such as Yamashita et al., [8] observed that the grain distribution of coarse-grained pure magnesium after ECAP treatment at 673 K is almost uniform, which is obviously inconsistent with this model. It is considered that when the exit channel is kept at high temperature, the grain growth may occur after full ECAP processing.

4. Texture of ECAP magnesium alloy

In general, ECAP treated magnesium alloys exhibit strong texture, which reduces yield stress and improves plasticity, despite significant grain refinement. The plastic strain caused by simple shear is the basic process of ECAP processing technology, which leads to the transformation of main crystal direction of materials. Especially, the change of texture will have a significant impact on many structure sensitive properties. Therefore, the study of texture evolution in ECAP process is helpful to analyze the mechanism of plastic strain and phase transformation process [61, 80, 81].

4.1. Texture formation mechanism

Near room temperature, the critical shear stress (CRSS) of non-basal slip is much higher than that of basal slip [82]. Because of the limited slip system, HCP metal has poor plasticity, so ECAP should be carried out at high temperature. During high temperature ECAP treatment, the activation of prismatic slip system leads to the transformation of basal texture to prismatic texture, and the volume fraction of non-texture components decreases [83].

In order to quantitatively describe the deformation mechanism, N S Martynenko et al. [83] calculated the orientation factors of basal, prismatic and pyramid slip system and twin system \( \{1012\} \{10\overline{1}\} \) (The system is usually activated in hexagonal crystal structure [84]). It is found that the basal slip system, the pyramid slip system and the twins are most active in the initial state, and the prismatic slip system is activated after ECAP treatment. The reason for the transformation from dispersed basal texture to prismatic texture is believed to be related to the homogeneous and fine distribution of intermetallic compound particles, which preferentially appear on the base plane and promote the dislocation slip on the prismatic surface. Therefore, the transition from basal slip to prismatic slip in ECAP treatment results in the increase of plasticity.

Krajnak et al. [66] found that after one pass ECAP, the original extrusion texture of the material changed significantly, forming two texture components. In the first texture component (expressed as A), the base plane is perpendicular to the extrusion direction. In the second texture component (expressed as B), the basal plane is parallel to the theoretical shear plane activated during ECAP, and the basal plane is inclined about 45° with respect to the extrusion direction. Figure 8 shows the main orientation of hexagonal crystal cells in the samples treated along different extrusion routes for 8 passes. Among them, the texture component B formed by one pass ECAP can be interpreted as the activation of basal slip system, resulting in \((0001)\) basal plane rotation and parallel to the theoretical shear plane activated during extrusion (see figure 9(a)). Texture component A is derived from a combination of compression twins that appear in the feed channel, thus activating the pyramid slip system, resulting in \(\{11\overline{2}2\} \) pyramid plane remaining parallel to the ECAP shear plane (see figure 9(b)).

Similarly, the existence of compression twins in extruded pure magnesium has been reported in many other [85, 86]. Since the strength of texture component A is higher than that of component B in one pass, it can be concluded that for \(N = 1\) (N is extrusion pass), the influence of pyramid slip on texture evolution is greater than that of basal slip, which may be due to the fact that compression twins are easier to activate than base slip.

Minarik et al. [87] explained the formation of texture component A. After repeated ECAP processing, a new texture component B was formed in AE21 and AE42, and LAE442 alloys. The basal plane deviated about 55° from the extrusion direction. Texture component B is the dominant component in AE21 and AE42 alloys, while in LAE442, this texture component only takes a secondary position, more of which is a new texture component.
parallel to the extrusion direction, which means the change of deformation mechanism. Based on the analysis of the experimental data, it is concluded that the addition of Li to magnesium and magnesium alloy can shorten the distance between atoms and greatly reduce the c/a value, thus reducing the activation energy required to activate...
prismatic and pyramid slip. At high temperature, the activity of the slip system is also related to the grain size, and it is difficult to activate the basal slip system in large-grained materials. However, basal slip is the main control system in the deformation process of small-grained materials. Therefore, due to the decrease of grain size, the activity of non-basal slip system decreases during ECAP repeated processing. The typical texture component B is formed in AE type alloy because the activation degree of basal slip system is higher than that of non-basal slip system. Texture component B was also observed in AZ31, AZ61 and Mg-Li alloys. However, most of the grains in Mg-Li alloys have basal planes perpendicular to the extrusion direction\cite{7,88–90}. Similar texture component A was also observed in \cite{90}, but the analysis of these texture components was omitted in the discussion due to the dominance of the more common texture component B mentioned above.

The formation mechanism of texture component B was first proposed by Mukai\cite{82}. The texture of commercial AZ31 magnesium alloy was obtained by simple shear of ECAP, which was different from that of conventional extrusion alloy. It can be clearly seen from figure 10 that the proportion of basal planes in conventional extruded alloys depends largely on the extrusion direction. However, the magnitude of peaks in ECAP treated materials is equal in parallel and perpendicular to the extrusion direction, indicating that the distribution of basal planes in both directions is similar. In conventional extrusion, the basal planes of most grains are arranged along the extrusion direction, and ECAP process can impose simple shear on the material at 90° angle channel, which results in the rearrangement of basal planes along the shear direction.

The basic mechanism of texture formation during ECAP is the rotation of the slip plane which dominates the slip system and is parallel to the direction of the theoretical shear plane activated during ECAP. Because the shear

Figure 10. X-ray diffraction spectra of (a) directly extruded and (b) ECAP/annealed AZ31 alloys. Reprinted from \cite{82} Copyright (2001), with permission from Elsevier.
The plane activated in ECAP (extrusion pass N ≥ 2) varies with the extrusion route, the activation of dislocation slip system in different routes is also different [66]. For routes A and Bc, the shear planes after the Nth and (N + 1) passes are not parallel, and the active basal plane rotates after (N + 1) passes. On the contrary, in route C, the shear planes are parallel and the basal plane keeps the direction favorable to the slip. For {1122} pyramid slip, the case in route A is similar to that in route C. Due to the formation of compression twins in the feed channel, the microcrystals composed of the active pyramid slip system in N passes still maintain the direction favorable to the pyramid slip in the (N + 1) pass. In the extrusion process along route Bc, the mechanism of texture formation is similar to that of route C. However, the rotation of texture component B in 2 passes of Bc route extrusion is the result of 90° sample rotation between successive ECAP passes.

### 4.2. Texture evolution

The conventional extruded magnesium alloy has strong texture, and the basal plane is mostly parallel to the extrusion direction, resulting in poor plasticity perpendicular to the extrusion direction. Therefore, a possible way to increase the ductility of wrought magnesium alloy is to change its structure by changing the distribution of the basal plane.

It was reported in [88] that the mechanical properties of the material were strongly affected by texture formation after ECAP with Bc route. Although the grain size was reduced to 800 nm, the tensile yield strength measured in the extrusion direction decreased significantly after more than 2 passes ECAP treatments. Krajnak et al. [66] found that the texture of AX41 alloy treated by ECAP is closely related to the extrusion route. Two main texture components were observed in all samples, but their strength was different under different extrusion routes. Therefore, the Schmid factor of a single slip system is different. The results show that the same texture component can be obtained by pre-extruded [91] and hot rolled [92] AZ31 magnesium alloy processed by three extrusion routes (A, Bc and C) at 250 °C and 220 °C, respectively. In addition, in the pure magnesium processed at 250 °C, with the increase of ECAP passes, the texture also shows the same dependence on the extrusion route [51]. Suh et al. [93] studied the texture evolution of hot-rolled AZ31 sheet during ECAP treatment along three extrusion routes A, C and D (see figure 11). It can be seen that a texture component inclined to rolling direction of ~75° is formed in the sheet after ECAP treatment for one pass, which is derived from the activation of {1010}〈1120〉 prismatic and {1122}〈1123〉 pyramid slip systems. According to the literature reports, the addition of Ce can significantly reduce the value of $c/a$.
c/a [97], increase the dislocation width [98], reduce the stacking fault energy [99]. Sabat et al [6] concluded through data analysis that adding Ce only to Mg without random texture treatment would not obtain Mg-Ce alloy with high ductility. Compared with pure Mg, the CRSS values of prismatic and pyramid \((C + a)\) slip and tensile twins are reduced by adding Ce. Excessive Ce in Mg-Ce alloy helps to pin the grain boundary and allows the random texture of nucleation during hot deformation to be retained during subsequent processing annealing. The final texture is determined by the extrusion route rather than the absolute deformation strain, and the complex strain route deformation seems to be conducive to texture randomization. According to the tensile test data in [87], it is concluded that the texture evolution of ECAP treated magnesium alloy can be effectively restrained by adjusting the c/a ratio, and the negative effect of texture on strength can be avoided.

5. Mechanical properties of ECAP magnesium alloy

The poor formability of magnesium and its alloys at room temperature greatly limits their application in the industrial field. The reason is related to the hexagonal close packed crystal structure (HCP), resulting in a small number of available slip systems. Improving the mechanical properties of magnesium alloy can greatly improve its industrial application. The current research mainly focuses on strength and formability. The large plastic deformation during ECAP can lead to significant changes in microstructure and texture. Conversely, the evolution of texture may change the mechanical properties and anisotropy of ECAP processed materials, and texture may also be a key factor in grain refinement [70].

Early studies reported that the tensile yield strength of magnesium alloy increased significantly after ECAP processing [100, 101]. In [101], the grain size of ECAP treated alloy is reduced to 1 \(\mu\)m, and the fatigue limit is greatly increased. The improvement of properties is closely related to grain refinement. However, some studies have found the opposite behavior [89, 102–104], that is, the tensile yield strength decreases after ECAP treatment. In some ECAP treated magnesium alloys, the failure of the Hall-Petch relationship between yield strength and grain size can be explained by the gradual texture transformation in the repeated ECAP process, resulting in lower yield strength at higher extrusion passes. Masoudpanah et al [102] compared the microstructure and mechanical properties of AZ31 magnesium alloy processed by extrusion and ECAP, it was found that the extruded alloy has higher yield strength. Although the grain size of the material decreases significantly after ECAP treatment, the yield strength decreases after 4 passes of ECAP treatment. The \((1010)\) fiber texture will be formed in the metal with HCP crystal structure after axisymmetric deformation under low temperature extrusion, which makes it difficult for the extruded material to slip on the basal plane. For magnesium alloy with limited non-basal slip activity, the strength will naturally increase. However, in the ECAP process, the Schmid factor on the \((0001)\) basal plane increases with the rotation of the basal plane, so lower stress is required for the yield of ECAP materials. Jahadi et al [103] found that although the grain size decreased from 20.4 \(\mu\)m to 3.9 \(\mu\)m after multiple ECAP treatments, the yield strength results were not consistent with the Hall-Petch relationship. The ECAP yield strength of each pass will decrease. Compared with the extruded alloy (162 MPa), after 4 passes of ECAP, the yield strength has dropped by 23%. The plasticity is significantly improved. Compared with the extruded plasticity (15%), the plasticity of the ECAP alloy in the 2, 3, and 4 passes is increased by 37%, 53% and 43%, respectively. The decrease in yield strength of AZ61 treated with ECAP is also attributed to the change in texture [89]. In the 8 passes extruded sample, most of the basal plane deviates from the extrusion direction and lies in the direction between extrusion and transverse direction. In ECAP, the rotation of the basal plane is considered to be caused by the shear parallel to the basal plane, and the rotation of the initial texture occurs. The increase of Schmid factor on the \((0001)\) basal plane leads to the yield of the material under lower stress. The same behavior was observed in [102, 104], due to higher texture softening rate rather than strengthening effect of grain refinement.

The grain boundary slip and diffusion process are the main mechanisms leading to high plasticity. The research of Figureiredo [105] shows that when the grain size is 5 \(\mu\)m or less, the low strain rate deformation of pure magnesium mainly depends on the grain boundary slip. For the alloy with ultra-fine grain size, grain boundary slip becomes the main mechanism during deformation, rather than dislocation proliferation [80]. Koike et al [106] carried out tensile tests on AZ31 magnesium alloy rolled sheet from room temperature to 523 K, and proved the occurrence of grain boundary slip at room temperature through the displacement of grain boundary lines of deformed samples. At the same time, the contribution of grain boundary slip to the total tensile deformation of AZ31 magnesium alloy at room temperature was studied. When the strain rate and grain size were \(10^{-3}\) s\(^{-1}\) and 8 \(\mu\)m, the contribution was about 8%. However, the dependence of elongation on grain size is not enough to explain the large increase of tensile plasticity. In [82], the ECAP treated AZ31 alloy maintains a high elongation at room temperature, but this significant increase in plasticity cannot be achieved only by activating basal slip. This is because according to Von-Mises criterion, basal slip only provides two independent slip systems, far less than five independent systems required for uniform deformation. Therefore, it is considered that some prismatic and pyramid slip systems can be easily activated during ECAP. In order to facilitate comparison, the mechanical properties of several typical ECAP magnesium alloys are summarized in
Table 1. Mechanical properties of typical ECAP magnesium alloys.

| Material                  | Processing                  | Average grain size/μm | σUTS/MPa | σ0.2/MPa | Elongation/% | References |
|---------------------------|-----------------------------|------------------------|----------|----------|--------------|------------|
| pure Mg                   | As cast                     | 900                    | 70       | 22       | 3.7          | [50]       |
|                           | ECAP 4A 350 °C              | 68                     | 148      | 67       | 5.7          |            |
|                           | ECAP 4Bc 350 °C             | 70                     | 165      | 49       | 3.8          |            |
|                           | ECAP 4C 350 °C              | 38                     | 173      | 68       | 5.6          |            |
| AZ31                      | EX-ECAP 8Bc 200 °C          | 0.7                    | 282      | 217      | 30           | [7]        |
| AZ31                      | As rolled-ECAP 2A 225 °C    | 10.1                   | 283      | 189      | 19.4         | [92]       |
|                           | As rolled+ECAP 2C 225 °C    | 9.1                    | 279      | 183      | 20.5         |            |
|                           | As rolled+ECAP 2D 225 °C    | 10.5                   | 276      | 158      | 18.5         |            |
| Mg-10Al-0.5Si             | ECAP 2Bc 380 °C             | 30                     | 282      | —        | 9            | [114]      |
|                           | ECAP 3Bc 380 °C             | 30                     | 286      | —        | 11.2         |            |
| AM90                      | HT-ECAP 4Bc 275 °C          | 3                      | 202      | 100      | 4.4          | [115]      |
| ZA62                      | HT-ECAP 6Bc 160 °C          | 2                      | 330      | 280      | 9            | [100]      |
| Mg-6Zn                    | ECAP 2Bc 160                | —                      | 341      | 264      | 23           | [52]       |
|                           | ECAP 4Bc 160                | —                      | 334      | 277      | 21           |            |
| Mg-9Al-1Si                | HT-ECAP 2Bc 330 °C          | 350                    | 14.7     | —        |              | [65]       |
| Mg-5.25Zn-0.6Ca           | bimodal grain               | 290                    | 10.8     | —        |              |            |
|                           | EX-ECAP 4A 250 °C           | 1                      | 332      | 246      | 15.5         | [61]       |
|                           | EX-ECAP 4Bc 250 °C          | 0.7                    | 287      | 180      | 21.9         |            |
|                           | EX-ECAP 4C 250 °C           | 0.8                    | 228      | 131      | 12.6         |            |

* Extrusion
* Homogenization treatment

Table 2. Superplasticity of ultrafine grained magnesium alloy prepared by ECAP.

| Material                  | Processing                  | Average grain size/μm | Temperature/°C | Strain rate/s^-1 | Elongation/% | References |
|---------------------------|-----------------------------|------------------------|----------------|------------------|--------------|------------|
| WE43                      | HT-ECAP 8Bc 350 °C          | 0.34                   | 350-400        | 1 × 10^-2        | 1230         | [108]      |
|                           |                             |                        | 400            | 1 × 10^-3        | 1000         |            |
| WE43                      | HT-ECAP 8Bc 375 °C          | 1.5                    | 500            | 1 × 10^-3        | 860          | [112]      |
|                           |                             |                        | 475            | 2 × 10^-2        | 960          |            |
|                           |                             |                        | 475            | 3 × 10^-3        | 1120         |            |
| AZ61                      | EX-ECAP 4Bc 200 °C          | 0.6                    | 200            | 3 × 10^-4        | 1320         | [116]      |
| ZK60                      | ECAP 2Bc 200 °C             | 0.8                    | 200            | 1 × 10^-4        | 3050         | [117]      |
| ZK60                      | EX-ECAP 4 200 °C            | 1.2                    | 250            | 1.67 × 10^-3     | 628          | [118]      |
| ZWK510                    | EX-ECAP 8Bc 200 °C          | 0.6                    | 200            | 1.67 × 10^-3     | 865          | [119]      |
| Mg-5.5Zn-1.0Y-0.48Zr      | HT-ECAP 8Bc 350 °C-450 °C   | 5                      | 350            | 1.7 × 10^-3      | 800          | [120]      |
| Mg-4.3Zn-0.7Y             | ECAP 8Bc 350 °C             | 3.5                    | 350            | 1.5 × 10^-4      | 600          | [121]      |
| Mg-9Al                    | EX-ECAP 2Bc 200 °C          | 0.7                    | 150            | 1 × 10^-4        | 800          | [122]      |
|                           |                             |                        | 225            | 1 × 10^-2        | 360          |            |
| Mg-0.6Zr                  | EX-ECAP 1 300 °C            | 1                      | 300            | 3.3 × 10^-4      | 400          | [47]       |

* Extrusion
* Homogenization treatment

table 1. Superplasticity is defined as at least 500% material elongation. The research results on superplasticity of ultra-fine grained magnesium alloy prepared by ECAP process are summarized in table 2. Superplasticity is a deformation process which depends on thermal activation and grain boundary slip. Therefore, increasing temperature or decreasing grain size are effective ways to improve superplasticity. It should be noted that the increase of temperature also leads to grain growth. As far as industrial production is concerned, higher requirements are put forward for superplastic magnesium alloy. The alloy must still have good superplasticity at strain rate of 10^-2 s^-1 and above, that is, high strain rate superplasticity (HSRS) [107–110]. Compared with friction stir processing (FSP) [111], ECAP is generally considered to be more difficult to achieve HSRS in magnesium alloys. However, FSP can not produce bulk materials with uniform microstructure, which is very limited in industrial applications. Kang et al [112] realized HSRS in Mg-Y-Nd-Zr alloy for the first time by combining homogenization treatment with ECAP. The grain size of the alloy was 1.5 μm, and a thermally stable second phase particle β was observed. At 500 °C 1 × 10^-3 s^-1 and 475 °C 2 × 10^-3 s^-1, the elongation reaches
Experimental research is usually necessary, but it needs a lot of time and cost, and the because of its simple and effective characteristics. Through the technology, the distribution of internal workpiece by analyzing the internal variables are not available. Numerical simulation has become an effective tool to grasp the distribution and flow law of material field during processing. As a kind of process simulation technology, finite element method is widely used in the analysis and research of metal material plastic forming because of its simple and effective characteristics. Through the finite element analysis, the influence of processing parameters and route on the variation of workpiece internal variables can be revealed, and the optimal ECAP process parameters and processing route can be determined.

At present, most of the simulation research on ECAP is based on the finite element method, such as Xu et al [128] through a large number of numerical simulation, the distribution law of cumulative effective strain in the main deformation area of workpiece in ECAP process under different channel angle and external angle is given. Djavanroodi et al [129] proved that increasing the coefficient of friction or applying back pressure can improve the uniformity of deformation using the finite element method. However, the previous research on ECAP process by FEM method shows that most of them are carried out under two dimensional (2D) plane strain conditions. In order to study the effects of longitudinal and transverse strain behavior, damage prediction and required stamping load after ECAP, Mahallawy [40] and Ghazani et al [130] introduced three dimensional (3D) finite element simulation. The simulation results of Ghazani et al [130] show that the equivalent plastic strain of cross ECAP is mainly concentrated in the central region, and the strain distribution state is much more complex than that of conventional ECAP.

In a word, effective strain, strain distribution uniformity and damage prediction are all affected by ECAP process parameters, such as die channel angle, external angle, back pressure, friction coefficient, extrusion route, extrusion temperature, extrusion passes and solution treatment [128–131]. Ebrahimi et al [131] studied the strain and damage behavior of 7025 aluminum alloy after one pass ECAP by using the finite element method. The analysis shows that the influence of die channel angle on strain behavior and damage prediction is more important than external rotation angle and friction coefficient. When the channel angle $= 90^\circ$, the surface crack is the main cause of damage in ECAP process; for ECAP sample with channel angle of $90^\circ$, the near center crack is the possible cause of damage. Djavanroodi et al [129] analyzed the deformation behavior of commercial pure magnesium alloy after ECAP, the isotropic deformation of the material is significantly improved compared with other materials with strong texture. It is reported in [113] that the elongation of as-extruded WE43 alloy at strain rate $10^{-3} \text{s}^{-1}$ is 1216%, which is similar to that reported by Vavra et al [108], but the latter is measured at high strain rate of $10^{-2} \text{s}^{-1}$.

It is well known that texture weakening of magnesium alloy can improve its formability, so texture weakening during superplastic deformation at high strain rate is helpful to obtain excellent superplasticity [123, 124]. But strong texture can significantly improve the deformability in a specific direction. Magnesium alloys processed by severe plastic deformation usually have strong texture. The promotion of texture on dislocation creep will improve the deformation ability of magnesium alloys in the direction of research. However, the influence of anisotropy should be avoided in industrial application [125]. After ECAP treatment, the strength and plasticity of AZ91 alloy increased significantly [126], but its mechanical behavior showed obvious anisotropy. After 12 passes of ECAP treatment, $\alpha$—Mg grains were obviously refined in all directions, forming uniform equiaxed grains, while the distribution and morphology of $\gamma$—phase particles and eutectic were not uniform.

The effect of texture on superplasticity was studied in [125, 127]. Wu et al [125] found that the sample stretched along the rolling direction has the best superplasticity, and the preferred grain orientation will increase the dislocation mobility, resulting in obvious anisotropy of superplasticity. Valle et al [127] studied the effect of texture and grain size on the creep deformation mechanism of AM60 alloy in the temperature range of 423–723 K. The results showed that the texture effect disappeared in the low stress index region, and the grain boundary slip was the main deformation mechanism. In the high stress index region, with the increase of temperature, the texture effect decreases and the contribution of grain boundary slip increases.

6. ECAP numerical simulation

It is extremely important to determine the optimal ECAP process and realize the uniform deformation of workpiece by analyzing the influence of process parameters and extrusion route on strain distribution and value. Experimental research is usually necessary, but it needs a lot of time and cost, and the flow characteristics and the distribution of internal field variables are not available. Numerical simulation has become an effective tool to grasp the distribution and flow law of material field during processing. As a kind of process simulation technology, finite element method is widely used in the analysis and research of metal material plastic forming because of its simple and effective characteristics. Through the finite element analysis, the influence of processing parameters and route on the variation of workpiece internal variables can be revealed, and the optimal ECAP process parameters and processing route can be determined.

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aluminum in ECAP process by using 3D finite element simulation method, and compared the finite element analysis results with theoretical and experimental values, and there was a good consistency between them.

Before using the damage prediction model based on the finite element method to simulate the ECAP process [131], it is necessary to analyze the distribution of damage factors, refine the mesh in the areas where cracks may occur, and then distribute the crack sources in these areas filled with fine grids. Due to the distribution of crack origin, the accuracy of calculation will inevitably be reduced, and the location of crack initiation or dynamic propagation cannot be accurately predicted.

In addition, large plastic deformation of the material caused by ECAP processing will lead to grievous deformation of the mesh, resulting in the decline of simulation accuracy. These problems can be overcome by other alternative methods. Smoothed particle hydrodynamics (SPH) is a meshless numerical simulation method [132, 133], which has received extensive attention in recent years. This method does not need to divide the mesh, so it eliminates the problems of precision reduction and numerical divergence caused by mesh deformation. It is suitable for the calculation that cannot be solved by traditional finite element method. The most attractive feature of SPH is that it only uses particles, and does not need to maintain the connectivity of the mesh in the calculation process, which makes it possible to simulate very complex fluid flow, and particles can always be tracked. This is a significant advantage over mesh based technology. However, due to the lack of connectivity between particles, SPH method can not provide the surface position explicitly. It is very inconvenient to solve the problem of surface effect (such as surface tension) on flow behavior. To solve this problem, Lin et al. [132] proposed a particle based free surface detection algorithm, and applied it to the simulation of SPH surface tension effect. The algorithm reconstructs the local geometry around each particle by constructing Delaunay triangulation, checks the Delaunay triangulation of surface particles to identify surface particles, and obtains the surface normal and curvature from the geometric information around the surface particles. The algorithm can detect any broken and merged surfaces, and the stability and accuracy of the interface force simulated by the algorithm are verified by comparing with the theoretical values. The research of Niu et al. [134] shows that the simulation numerical values based on SPH and finite element method have high similarity, and the accuracy of simulation results based on SPH method is further verified through control experiments.

In recent years, active work has been carried out on the simulation of texture evolution and ductile fracture behavior during ECAP processing [135–140]. Li et al. [135] studied the texture evolution of annealed pure copper billet during ECAP by using the finite element and polycrystalline joint simulation method. It was found that Taylor and VPSC models can well reproduce the ECAP texture of one pass, among which VPSC model has higher prediction accuracy, and when extended to 16 passes of ECAP along A and C routes respectively, the prediction of texture by the model is still valid. In the simulation of texture evolution process, it is usually assumed that the ideal simple shear can be used. Although the main characteristics of experimental texture can be predicted successfully, the accuracy of texture prediction can be further improved by using more realistic deformation history, which can be analyzed by finite element calculation [136]. The finite element simulation and experimental evidence show that the actual deformation of the material deviates from the ideal simple shear condition, and the most important is that the deformation distribution in the material is nonuniform [137]. In the material processed by ECAP, uneven texture may occur. For example, Tidu et al. [138] observed that after 16 passes of extrusion along route C, the ECAP material presented obvious texture gradient. In the process of plastic deformation, low plasticity will increase the tendency to induce cracks, which will lead to the material fracture without necking. Horita et al. [141] found that ECAP can significantly improve the strength of the material, but also reduce the elongation at break. They believe that this change in mechanical properties is related to dislocation movement. Mohammad Ali Kazemi et al. [142] found that the crack growth rate increased significantly after 1 pass ECAP treatment, while the crack growth rate after 5 passes ECAP treatment was lower than that of the original material, which was related to the change of elongation and grain refinement. Therefore, the research and simulation of ductile fracture behavior is of great significance for predicting the occurrence and propagation of ductile failure of metal materials. The evolution and expansion of micro defects lead to macro fracture. In order to effectively predict the fracture of materials, many ductile fracture criteria based on internal damage accumulation have been proposed. Khan et al. [139] established a ductile fracture criterion considering stress vector and hydrostatic pressure, and the prediction results show high accuracy. Li [143] and Khan et al. [144] evaluated the applicability of the ductile fracture model based on the experimental and simulation results, and the results showed that the stress and strain state, texture evolution and so on would affect the prediction accuracy of the model. Kaye [145] and Maire [146] quantify the damage growth of the material during plastic deformation, and take the void density, size and aspect ratio as functions of local deformation and stress triaxiality. Summarizing the previous studies [139, 143, 144, 147–149], it can be found that the research on ductile fracture behavior was mainly based on porous plastic model [150] and continuous damage mechanics model [149]. The original Gurson damage model can not accurately describe the ductile fracture behavior of materials [151]. Tvergaard et al. [152, 153] modified the Gurson model and proposed a ductile fracture model based on pore nucleation, growth and aggregation, that is, the Gurson Tvergaard Needleman (GTN) model.
GTN model is the most ideal model for analyzing ductile fracture behavior of materials [139, 140, 154]. Ali et al [155] found that the GTN model curve is well matched with the experimental results. According to the data analysis, the results showed that the damage and cavity during ECAP plastic deformation will eventually lead to the complete failure of the material.

7. Challenges and future development

1) ECAP process is widely used in Al and Cu alloys. However, in recent years, ECAP has achieved good grain refinement effect in Mg and its alloys, and has gradually developed into a more mature processing method. Many recent studies have fully proved the great commercial potential of ECAP in the preparation of ultrafine grained magnesium alloy. Therefore, more stringent requirements are put forward for the application of ECAP in ultrafine grained magnesium alloy in the future, that is, further quantification of ECAP process parameters that determine the grain refinement degree is needed. At the same time, considering the cost of labor and time, it is necessary to further improve the continuity of ECAP process in industrial manufacturing.

2) However, for Mg and its alloys, the ECAP extrusion temperature is generally no less than 200 °C, and the temperature has a certain effect on the grain refinement mechanism. For different ECAP magnesium alloys, the grain refinement mechanisms are also slightly different, including grain boundary slip, dislocation slip and twin deformation, but there is no convincing theory on the micro mechanism. Grain boundary slip is considered to be the main mechanism of ECAP deformation, but there is no conclusive evidence that this mechanism is universal. Further research is needed to fully represent the evolution of microstructure during ECAP process and improve the ability to predict the grain size and mechanical properties of materials under different process parameters. In addition, the contribution of bimodal microstructure characteristics in ECAP magnesium alloy to the improvement of strength and plasticity is worthy of careful study, leading to the specific material and process parameters selection of this microstructure feature is still not clear. At the same time, the in-depth study of ECAP deformation mechanism and its unusual material properties can also provide a reference for the development of other ultrafine grained materials.

3) Although computer simulation has made great progress in the research of ECAP magnesium alloy, the results of numerical simulation will be different due to the different materials and models selected by researchers. It is necessary to further summarize the optimal process parameters which are generally applicable to industrial production. In addition, the finite element numerical simulation can approach the real deformation history of ECAP to a great extent, but the problem that the accuracy of the finite element method decreases due to the large plastic deformation in the ECAP process has not been solved well. Moreover, the newly emerging SPH numerical simulation method with good prospects still needs a lot of work to explore its applicability to ECAP magnesium alloy.

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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).

Declaration of competing interest

The authors declare no conflict interest.

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