Novel Process Combined Extrusion And Severe Plastic Deformation For Plate Component With Rib-Web Structure of Magnesium Alloys

Nanyang Zhu

University of Science and Technology Beijing

Chaoyang Sun (✉ suncy@ustb.edu.cn)

University of science & Technology of Beijing

Lingyun Qian

University of Science and Technology Beijing

Mingjia Wang

Yantai University

Xintong Li

University of Science and Technology Beijing

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Abstract

Plates with rib-web structure of magnesium alloys can hardly be fabricated through conventional methods. In this work, the variable circular channel angular extrusion (VCCAEE) combined extrusion and severe plastic deformation is proposed, in which billet undergoes severe deformation at several variable circular angular channels. The FE model for VCCAEE of scaling plate with ribs is established and the experimental set up is designed. The feasibility of the novel process and the accuracy of the FE model are validated by the simulations and experiments. Stress state and the effective strain distribution in longitudinal section and cross section are analyzed. The results show that stress and strain distribution in longitudinal section is extremely inhomogeneous, and obvious stress concentration at the shear plane is founded. The microstructure in angular region is more uniform and finer, which validates that the severe shear deformation induced by the angular channel in the VCCAEE process could promote the deformation uniformity and grain refinement. The results of numerical simulation and experiments demonstrate that the VCCAEE process proposed in this paper is feasible and it has great potential to manufacture high-performance plate with ribs.

Introduction

Lightweight structures with lightweight materials were widely used in automobile and aerospace industries [1]. Magnesium alloys have received widespread attention in aerospace field due to their advantages of low density, high specific strength, high specific stiffness and good damping performance [2–4]. Owing to hexagonal close-packed (HCP) structure, only basal slip systems can be activated in ambient temperature, so magnesium alloys have poor ductility and formability at ambient temperature [5, 6]. As a typical load-bearing component, the standards for the comprehensive performance of the plate part with rib-web structure are gradually elevated, and microstructure refinement is an effective method to implement. The traditional processing methods for this kind of parts include welding and machining. However, machining has poor performance in work efficiency and material utilization, and often weakens the comprehensive mechanical properties because the metal streamlines were cut off [7–9]. And for welding, the comprehensive mechanical properties of welding joints cannot be guaranteed [10–13]. Thus, for this typical plate with ribs, the traditional processing methods could no longer meet the higher standards.

As a kind of local incremental forming technology, spinning has great advantages of high dimensional accuracy and low forming force in manufacturing rotational parts through accumulating multiple small strains [14–17]. Unfortunately, spinning tends to cause the fracture and underfilling of ribs, so it is hard to manufacture high performance parts with ribs [18, 19]. Isothermal forging and extrusion are also the important ways to form thin-walled components with ribs [20]. Tian et al. [21] proposed the axial closed extrusion (ACE) process to manufacture high-performance ring parts with mesh-like ribs, and validated the feasibility of ACE process in fabricating this kind of parts through discussing the distribution of the stress state, metal flow behaviors, temperature and effective strain. Han et al. [22] proposed an innovative radial envelope forming method to manufacture thin-walled cylindrical rings with inner web ribs

(TCRIWR), and clarified the motivation and principles in which formed the novel process by enveloping movement and geometry relationship between the constraining roll, feeding roll and TCRIWR. The simulation and experiments were executed to verify the feasibility of the proposal method. The design method of the novel process, determination method and modification method of interfering are also proposed to ensure the novel process working. In our previous works, we proposed the multi-stage variable speed (MSV) isothermal forging process to form the large size rib web component [23], and simulation and experiments were carried out to present the advantages of reducing forming load, grain refinement and enhance the mechanical properties. The results showed that the maximum load is 55.8% lower, and the formed component has an average grain size of 9 μm , ultimate tensile strength of 342 MPa and yield strength of 268 MPa, respectively. The above processes have made many innovative contributions to the forming of thin walled component with ribs, and provide an important reference for our works, but they have limited improvement in the comprehensive properties.

In the last decades, many improvement methods have been tried to enhance the comprehensive mechanical properties of materials, and the severe plastic deformation (SPD) technology is considered to be the most effective method to obtain high-performance materials with ultra-fine grains (UFG). Several SPD technologies are widely used, for instance, equal channel angular pressing (ECAP) [24], friction stir processing (FSP) [25], accumulative rolling bonding (ARB) [26], high pressure torsion (HPT) [27, 28], repetitive upsetting and extrusion (RUE) [29] and multi-directional forging (MDF) [30, 31], etc. However, most of the SPD methods mentioned above are generally used for the preparation of materials and are rarely used for the forming of specific parts. Thus, in order to make use of the technical advantages of the SPD methods in refining the structure and improving the comprehensive mechanical properties on the manufactured parts, some traditional plastic forming processes are referenced in new combined process. Korbel [32, 33] and Pięła [34] et al. developed KOB process which combined the rotating extrusion and conventional extrusion, and investigated the mechanical properties and microstructure of AZ31 magnesium alloy during the new process at room temperature. The results indicated that the KOB process can significantly improve the mechanical properties and refine the grains. Wang [35–37] et al. developed rotating backward extrusion (RBE) process which incorporate rotation with the conventional backward extrusion (CBE), and investigated the metal flow behavior and strain distribution in finite element simulation. The results showed that effective strain distribution and deformation uniformity could be improved because of the additional shear deformation.

From the above, this paper will focus on the combination of conventional plastic deformation process and SPD method to fabricate the high-performance component. Therefore, for the plate parts with rib-web structure, we developed the circular variable channel angular extrusion process which combined conventional extrusion and ECAP process. The complex cavity of integrated die was designed to implement the combination. The deformation mechanism was revealed and the feasibility of the developed process was validated by analyzing the metal flow behavior and forming force. In addition, the microstructure and stress state analysis show that the severe shear deformation could promote the deformation uniformity and grain refinement. The results demonstrate that the developed process is meaningful for providing a new feasible method for the manufacturing of large rib web.

VCCAE Process For Typical Component

A scheme of VCCAE process is described in Fig. 1, and the integrated die is composed of an upper die, a bottom die, a heating setup and a punch. The circular block tightly holds down the integrated die so as to firmly fix the circular-shaped die. The VCCAE process can be briefly depicted as follows: in the initial stage, a proper single punch intrudes along its axial direction in a vertical channel of circular cross section and forces the sample to extrude from the right angular region shown as region I into the horizontal channel. In the second stage, as the punch moves for more distance, the sample is squeezed into the second angular region as shown in region II from the horizontal channel. Subsequently, the material continues to flow into the next angular region shown as region III, and eventually fills the entire channel area. In the final stage, under the continuous action of the extruding force, the material begins to complete the filling of the rib structure, as shown in area IV.

There are three sub-processes of in VCCAE process, i.e. regions I, II, and III, as shown in Fig. 2(a). Considering the characteristic of the die, the deformation mechanism and metal flow behavior in region I is actually similar to T-ECAP process [38], which is considered as two back to back typical channel angular extrusion processes as shown in Fig. 2(b) like ECAP process [39]. Therefore, it is effective to discuss the one-half of the region I. And the regions II and III are the typical channel angular extrusion process as shown in Fig. 2(c). In other words, the entire process of the VCCAE process is the accumulation of multiple channel angular extrusion processes. Thus, the microstructure evolution of the material in each region affected by VCCAE process show a similar trend as by ECAE. However, the differences in dimension and shape of two processes are supposed to affect the accumulation of strain, and further cause some discrepancies in microstructure evolution.

The deformation mechanism in VCCAE process is simple shear deformation as like ECAP. There is an important feature of metal flow at the channels angular forced by the shear stress, which has great influence on the microstructural evolution. After each channel angular extrusion, the main influence factor of the equivalent effect variable is the inner and outer angles between the die channels, and the empirical formula shown as Eq. (1) [40], where β is the inner angle and θ is the outer angle. For ECAP process, in order to obtain a larger strain, multiple passes of extrusion are often performed, and the accumulated strain becomes larger as the extrusion passed increases.

$$\gamma = 2 \cot\left(\frac{\beta}{2} + \frac{\theta}{2}\right) + \theta \csc\left(\frac{\beta}{2} + \frac{\theta}{2}\right) \quad (1)$$

Severe plastic deformation techniques such as equal channel angular extrusion, as a deformation method that can effectively refine grains and improve the comprehensive mechanical properties of materials, have obvious advantages in the preparation of bulk ultra-fine-grained metal materials. As the development of ECAP technology, VCCAE process inherits the same shear deformation mode and has the potential to refine the microstructure of materials. Therefore, according to the Hall-Petch relationship [41], VCCAE process have the potential to improve the comprehensive mechanical properties of components

through the microstructure refinement. In other words, the VCCAE process could ensure the formation of components and improve their performance at the same time.

Experimental Procedures

The plate with ribs as a load-bearing component of the aircraft cabin, has a complex geometric shape like thin wall and ribs, and its service conditions are very harsh (high pressure). The plate with ribs is a typical thin-walled component with rib-web structure. The shape and key dimensions of the scaling part are shown in Fig. 3, which was focused in our research. The wall of the scaling part is thin of 15mm and its ribs are thin of 10mm and high of 27mm, that is, the ratio of height and thickness of rib is 2.7. The complicated shape and structure and harsh service requirements put forward high requirements on its forming process and performance, in this paper, we utilize the VCCAE process to study the high-performance precision forming of the scaling plate with ribs.

The VCCAE experiment was performed on the 20 MN hydraulic press. And the billet of pre-extruded AZ80 magnesium alloy was processed into a cylindrical shape with height of 202 mm and diameter of 59 mm. The experimental setup for VCCAE process of scaling cover plated is shown in Fig. 6. The experimental setup is equipped with isothermal heating system and data acquisition system, which can ensure that the temperature of the die remains basically constant during the experiment. Before loading the billet, the cavity of the combined die is lubricated with molybdenum disulfide and heated to 380°C for heat preservation. The billet was heated up to 400°C and held isothermally in heating furnace for 2 hours to eliminate thermal gradient. The hydraulic press can drive punch to axially extrude cylindrical billet with speed of 1 mm/s.

After extruding, the sample was cooled to room temperature in the air. As shown in Fig. 5(a), the sample of cover plate was cut into two same part from the central axis position, and a 3 mm thin slice is cut out on the central axis surface as shown in Fig. 5(b). The thin slice was divided into five specimens for analysis of microstructure evolution, and the way of dividing is shown in Fig. 5(c). After normal grinding and polishing processes, the central axis surface of specimens was subsequently etched with a solution of 1.5 ml picric acid saturated solution, 1 ml distilled water, 12 ml ethyl alcohol and 1 ml acetic acid. The microstructure characterization in the center region of each specimen was carried out using DM4000M optical microscope.

Fe Modelling

The material of plate with ribs is selected as AZ80 magnesium alloy, which shows strain rate sensitivity behavior, temperature sensitivity behavior and work hardening behavior. The process parameters in simulation are determined from the hot processing map [42]. As shown in Fig. 6, the FE model of forming the scaling plate with ribs is established. The constitutive equations with a correlation coefficient of 0.985 of AZ80 magnesium alloy [23] is given as follow:

$$\sigma = \frac{1}{\alpha} \ln \left\{ \left(\frac{A \exp\left(\frac{Q}{RT}\right)}{A} \right)^{1/n} + \left[\left(\frac{A \exp\left(\frac{Q}{RT}\right)}{A} \right)^{2/n} + 1 \right]^{1/2} \right\} \quad (2)$$

$$\begin{cases} \alpha = 0.0156 - 0.0711\varepsilon + 0.764\varepsilon^2 - 3.176\varepsilon^3 + 6.835\varepsilon^4 - 7.395\varepsilon^5 + 3.166\varepsilon^6 \\ \ln A = 38.1 - 395.1\varepsilon + 3568.1\varepsilon^2 - 15522.9\varepsilon^3 + 34391.09\varepsilon^4 - 37578.9\varepsilon^5 + 16073.8\varepsilon^6 \\ n = 8.2 - 59.8\varepsilon + 325.5\varepsilon^2 - 909.2\varepsilon^3 + 1409.5\varepsilon^4 - 1151.6\varepsilon^5 + 387.9\varepsilon^6 \\ Q/100 = 219.7 - 2127.6\varepsilon + 19333.6\varepsilon^2 - 84390.2\varepsilon^3 + 187615\varepsilon^4 - 205720\varepsilon^5 + 88294\varepsilon^6 \end{cases} \quad (3)$$

where A , Q , n and α are material parameters, σ represents the flow stress and its unit is MPa, ε denotes the strain and T is the absolute temperature. R is the universal gas constant ($8.314 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$).

Considering the VCCAE hot forming process of magnesium alloy is a rigid-visco-plastic thermal deformation process, and in order to promote the convergence of the numerical simulation, the FE model was established by used of the DEFORM-3D software, which adopts explicit iterative algorithm. The FE model of the VCCAE consists of upper die, bottom die, punch and billet, respectively. Considering the width of ribs in simulation is 10 mm, so the size of meshes is limited in the range of 1 ~ 2 mm to avoid the severe distortion of meshes around ribs. On the other hand, the absolute meshes was adopted and adaptive mesh criterion is applicable to automatically conduct the mesh reproduction when meshes are seriously distorted, and the type of mesh is tetrahedral. The cylindrical specimen with the height of 202 mm and diameter of 59 mm is set as to be plastic body, and all other tools are regarded as rigid bodies. The initial temperatures of AZ80 magnesium alloy billet and rigid bodies are set as to be 400°C and 380°C, respectively. The material of die is H-13 steel. The boundary conditions for the heat transfer by convection and radiation are took into account. Heat transfer coefficient between die and workpiece is 11 N/s/mm/C, and the heat dissipation coefficient between die/billet and air is 0.02 N/s/mm/C. The shear friction coefficient of 0.2 between the workpiece and rigid bodies in the process of VCCAE was consistently adopted.

Results And Discussion

5.1 Feasibility analysis of VCCAE process

In order to reveal the feasibility of VCCAE process, the variation laws of forming force in VCCAE process are investigated, as shown in Fig. 7, and the process of VCCAE could be divided into three stages according to the variation trend of forming force. In the upsetting stage when the displacement of punch Δ /is 4.5 mm, the forming force sharply ascends to about 250 kN, which is caused by that the working hardening plays a dominant role in upsetting process. In the stable forming stage, the increasing rate of forming force obviously descends, which can be attributed to temperature rise and the occurrence of dynamic recrystallization (DRX). The severe plastic deformation caused severe deformation heat effect, which maintains or even increases the material temperature by thermal diffusion. On the other hand, for

magnesium alloys with low stacking fault energy metal materials during hot deformation process, massive dislocation multiply and accumulate caused by working hardening, although the dynamic recovery is accompanied by strain hardening, the dynamic recovery process is often slow and hard to simultaneously offset the dislocation proliferate and accumulation [43]. When dislocations accumulated to a certain extent, i.e. the dislocation density reaches the critical recrystallization dislocation density, the mainly softening mechanism is DRX [44]. The grain boundaries of a large number of recrystallized grains could coordinate the deformation, besides the DRX would eliminate a large number of dislocations. Thus, softening is greatly enhanced and basically offset the working hardening. In particular, cavity corner changes will lead to increasing deformation resistance, so the forming force slightly increases when $\Delta l = 25.1$ mm and $\Delta l = 98.7$ mm, respectively. In the last filling stage, the forming force significantly increases from 503 kN to 2023 kN when the displacement improves from 159 mm to 184.4 mm, because in this stage the deformation only occurs at the corner position of cavities where the metal flowability is pretty poor.

The cavity of the integrated die is intricate, so the metal flow behavior is complicated in VCCAE process of plate with ribs, which inevitably causes inhomogeneous deformation. In view of this, the metal flow diagrams showed in Fig. 8 were used to investigate the mechanism of VCCAE process. As described in Figs. 8(a) and 8(b), the metal mainly flows along the radial direction (RD) to fill the crown part in the cavity of the integrated die. Due to the inhomogeneous deformation, the metal flow velocity around the top of the ribs is inhomogeneous, as shown in Fig. 8(c). With the motion of punch, the metal flows to fill the waist part and there are bulges in the position of the ribs as shown in Fig. 8(d), which is consistence with the law of least resistance. As depicted in Figs. 8(e)-(f), the metal continue flows to gradually fill the web part and finally fill the ribs. According to the enlarged view of the Figs. 8 (d)-(f), the metal gradually flows to ribs rather than the RD direction, and it demonstrates that the growth of ribs is slower than the other part of the plate with ribs, which confirmed the principle of the VCCAE process.

The formed part of VCCAE process of plate with ribs is shown in Fig. 9. The deviation in shape between experimental and simulation results could be attributed to two aspects. On the one hand, the friction coefficient between the billet and die is regarded as a constant in the simulation, but the actual friction coefficient is variable and affected by temperature and stress. On the other hand, the shape of die could slightly change during the extruding process and extracting the extruded parts because of the slight elastic deformation, but die is always be rigid in simulation. In summary, the experimental results demonstrate that the shape of the experimental results is in good accordance with that of the simulation. The growth laws of crown, waist, web and ribs is in agreement with the principle of the VCCAE process. Thus, the feasibility of VCCAE process forming plate with ribs is validated.

5.2 Distribution laws of stress and strain

In order to figure out the deformation mechanism of billet in the VCCAE process, the effective stress distribution with different stroke is investigated. The distribution laws of effective stress in the scaling plate with ribs under VCCAE process are displayed in Fig. 10. As shown in Fig. 10(a), after the upsetting stage of VCCAE process i.e. when the stroke is 4.5 mm, although there is slightly bulge at the outer

surface of billet, the effective stress has reached to 50 MPa in the center of crown part. When the punch stroke reaches 25.1mm, metal has filled the whole crown part, and the maximum value 47 MPa of effective stress distributed in region I which shown in Fig. 2(b), that is to say, deformation mainly appears at this position. Similar distribution phenomenon could be found that the deformation mainly distributed in region I and region II, resulting in the severe plastic deformation, and metal could fill the crown part and waist part in this stage. Furthermore, the web, crown and waist all almost satisfy the requirement of shape when the stroke reaches 159 mm, so the effective stress in these positions sharply descends. On the other hand, with the increment of punch stroke, there are obvious bulge at the rib part of cavities, and the effective stress distribution in longitudinal section is extremely inhomogeneous. In addition, the part of ribs connected with the waist deformed before the part connected with the web.

The stress states in the process of VCCAE process of plate with ribs is complicated, so inevitably caused the inhomogeneous deformation. The effective strain distribution in symmetry longitudinal section was selected to systematically reflect the deformation degree of web, waist, crown and ribs. In addition, three typical cross sections were also selected to display the effective strain distribution around ribs. Figure 11 shows the effective strain distribution in longitudinal section and cross sections, respectively. The effective strain distribution along the path from A to F in longitudinal section are shown in Fig. 11(a). The abscissa represents the actual distance on the path from A to F. The effective strain at web from A to B ranges from 3.2 to 3.5. On the path B to F, the maximum effective strain at junction (as shown in Fig. 2(a)) is 5.5, and the effective strain shows a trend of gradual decrement from the junctional part between waist and crown to web, which indicates that deformation of the junctional part is the largest. The effective strain gradually increases from the center of the lower surface of the crown to the radial direction of the upper surface. Particularly, the strain in the shear direction (as shown in Fig. 2 (b)) is larger than that at the point D. The reason caused the effective strain distributions at junction and shear direction may attributed to the caused by the severe shear deformation at the angular of channel (as discussed in Sect. 2).

In order to further investigate the distribution laws of effective strain, the effective strain distribution in three cross sections of upper section, medium section, and lower section were depicted in Figs. 11(b), 11(c) and 11(d). The effective strain gradually increases from the lower section to the upper section, because the shear deformation of material in the upper section is larger than that in lower. Moreover, the effective strain distributions in the three cross sections show a similar trend that strain gradually descends from the outer edge to the center in the radial direction. On the other hand, the effective strain distribution perpendicular to the radial direction is uniform. In particular, the effective strain in upper cross section affected by the severe deformation at the junctional part, so the effective strain is high and the fluctuations is very small in rib part.

5.3 Stress state analysis

For the VCCAE process, the shearing deformation induced by the variable channel angular plays a critical role in refining the microstructure. In order to better reveal the forming mechanism of scaling plate with ribs in VCCAE process, points B, C and D are selected as typical points to illustrate the severe shear

deformation on plastic forming. The contribution of shear deformation could be measured by the Lode parameter which can be expressed as [45]:

$$\mu_b = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} \quad (4)$$

where μ_b is the Lode parameter, σ_1 , σ_2 and σ_3 denote the three principal stress respectively. $\mu_b = 0$ means pure shear stress state, while $\mu_b = -1$ or $\mu_b = +1$ represent the uniaxial compressive or the uniaxial tensile stress state. In other words, the smaller absolute value of Lode parameter implies the more shear deformation [46]. In addition, the hydrostatic pressure μ_m also plays important role in plastic deformation, and it can be described as:

$$\mu_m = \frac{\mu_1 + \mu_2 + \mu_3}{3} \quad (5)$$

The Lode parameter and hydrostatic pressure at points B, C and D were calculated from the simulated stress states according to Eq. (4) and Eq. (5). Figures 12(a) and (b) displays the stress state parameters variation at typical points during the VCCAE process. The results show that the hydrostatic pressure at point D is the highest, and the Lode parameter here is always approximately 0. It means that the stress state at point D is uniaxial tensile stress state. Compared with point D, the hydrostatic pressure of point B and point C decreases sequentially, and the absolute value of Lode parameter is between 0 and 1, which means that the stress state of point B and C is the simple shear stress state. As shown in Fig. 11 and Fig. 12, high hydrostatic is helpful for the realization of metal plasticity, while the stress state also plays important role in the metal deformation. The reason could be attributed that the strong shear deformation and optimized stress state could not only promote the formation of high density of high angle grain boundaries (HAGBs) but also provide enough energy for DRX nucleation and DRX grain growth [47].

5.4 Microstructure analysis

According to Sect. 5.3, the effective strain of the outer edge of crown part is obviously higher than the other part, and it gradually descends from the upper cross section to the lower cross section in waist part and rib. Therefore, in order to further investigate the effect of the VCCAE process on the grain size of AZ80 alloy plate with ribs, several regions are selected in longitudinal section (see in Fig. 5). The microstructure evolution in all regions can be obtained from the OM observation in Fig. 13. Previous researches have indicated that DRX is the main deformation mechanism of Mg-Al alloys at the temperature ranging from 200°C ~ 400°C, which usually caused the new generated grains and growth of new DRX grains around the deformed grains [48].

It can be observed from Fig. 13(e) that the microstructure in the center of crown part (region IV) is mainly composed of incomplete DRX grains and few fine grains. Meanwhile, it can be also seen in region I (shown in Fig. 13(b)) and region VII (shown in Fig. 13(h)) that the microstructures in these regions are consisted of coarse deformed grains and fine DRX grains around them. Furthermore, compared with the

region II (shown in Fig. 12(c)) and region VI (shown in Fig. 13(g)), the average grain size is finer ($\sim 10 \mu\text{m}$) and microstructure is more uniform in region III (shown in Fig. 13(d)) and region V (shown in Fig. 13(f)). Combined with the variation of the effective strain in longitudinal section (shown in Fig. 12(a)), microstructure in regions III and V with equiaxed fine grains could result from that the severe strain caused by the angular channel can significantly improve the dislocation density in these regions, which promote the nucleation and growth of the DRX grains. Therefore, it can be inferred that the deformation uniformity and the grain refinement ability can be increased by the angular channel in the VCCAE process. It is worth noting that this work only involved variable circular channel angular extrusion process of scaling plate with rib-web structure of magnesium alloy. In fact, many other plate shape parts with ribs could be also formed by this novel process. In the future, more intensive studies focusing on the optimization of cavity shape and process parameter will be executed for the other typical components.

Conclusions

In this paper, a novel variable circular channel angular extrusion process is proposed, and the novel process in forming typical component is investigated by FE simulation and experiment. The following conclusions are drawn:

- (1) The novel variable circular channel angular extrusion process is put forward to manufacture plate component with rib-web structure of magnesium alloys. The proposed process innovatively combines conventional extrusion and equal channel angular extrusion process, and material will undergo severe shear deformation for three times induced by the integrated die consist of variable angular channels.
- (2) Metal flow behaviors and the shape of simulated part are good agreement with that in experiment, which indicated the feasibility of the proposed process and the reliability of the FE model. In addition, the effective stress distribution in longitudinal section is extremely inhomogeneous, and obvious stress concentration at the shear plane of the variable channel angular is founded. Furthermore, the high hydrostatic pressure is helpful for deformation while the simple shear stress state can also promote the severe plastic deformation.
- (3) From the microstructure analysis, the microstructure is more uniform and finer ($\sim 10 \mu\text{m}$) in angular region, which indicate that the severe shear deformation induced by the angular channel in the novel process could promote the deformation uniformity and the grain refinement ability.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

All the people and organizations involved agreed to participate.

Consent to Publish

All the people and organizations involved agreed to publish this article.

Authors Contributions

Nanyang Zhu: Methodology, Software, Investigation, Writing-reviewing and editing

Chaoyang Sun: Conceptualization, Methodology, Software

Lingyun Qian: Software, Validation, Data curation

Mingjia Wang: Formal analysis, Validation

Xintong Li: Formal analysis, Validation

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

The data sets supporting the results of this article are included within the article and its additional files.

References

- [1] Hagnell MK, Langbeck B, Åkermo M (2016) Cost efficiency, integration and assembly of a generic composite aeronautical wing box. *Compos Struct* 152:1014-1023
- [2] Zhang J, Huang H, Yang CB (2017) Effects of hot ring forging on microstructure, texture and mechanical properties of AZ31 magnesium alloy. *Mater Sci Eng A* 679:20-27

- [3] Chen Q, Zhang XH, Lin J, Zhan H, Zhao ZD, Xie ZW, Yuan BG (2019) Isothermal closed-die forming process of magnesium alloy upper receiver: numerical simulation and experiments. *Int J Adv Manuf Technol* 102(1):685-694
- [4] Chu GN, Sun L, Wang GD, Fan ZG, Li H (2019) Axial hydro-forging sequence for variable-diameter tube of 6063 aluminum alloy. *J Mater Process Technol* 272:87-99
- [5] Hadadzadeh A, Wells MA (2017) Analysis of the hot deformation of ZK60 magnesium alloy. *J Magn Alloys* 5(4):369-387
- [6] Wong TW, Hadadzadeh A, Wells MA (2018) High temperature deformation behavior of extruded AZ31B magnesium alloy. *J Mater Process Technol* 251:360-368
- [7] Li BZ, Jiang XH, Yang JG, Liang SY (2015) Effects of depth of cut on the redistribution of residual stress and distortion during the milling of thin-walled part. *J Mater Process Technol* 216:223-233
- [8] Gao HJ, Zhang YD, Wu Q, Li BH (2018) Investigation on influences of initial residual stress on thin-walled part machining deformation based on a semi-analytical model. *J Mater Process Technol* 262:437-448
- [9] Sun YW, Jiang SL (2018) Predictive modeling of chatter stability considering force-induced deformation effect in milling thin-walled parts. *Int J Mach Tools Manuf* 135:38-52
- [10] Bocchi S, Cabrini M, D'Urso G, Giardini C, Lorenzi S, Pastore T (2018) The influence of process parameters on mechanical properties and corrosion behavior of friction stir welded aluminum joints. *J Manuf Process* 35:1-15
- [11] Chen SJ, Li XX, Jiang XQ, Yuan T, Hu YZ (2018) The effect of microstructure on the mechanical properties of friction stir welded 5A06 Al alloy. *Mater Sci Eng A* 735:382-393
- [12] Sun T, Reynolds AP, Roy MJ, Withers PJ, Prangnell PB (2018) The effect of shoulder coupling on the residual stress and hardness distribution in AA7050 friction stir butt welds. *Mater Sci Eng A* 735:218-227
- [13] Yang ZB, Zhao X, Tao W, Jin C (2019) Effects of keyhole status on melt flow and flow-induced porosity formation during double-sided laser welding of AA6056/AA6156 aluminium alloy T-joint. *Opt Laser Technol* 109:39-48
- [14] Zhan M, Yang H, Guo J, Wang XX (2015) Review on hot spinning for difficult-to-deform lightweight metals. *Trans Nonferrous Metals Soc China* 25(6):1732-1743
- [15] Lin YC, Chen JY, He DG, Li XH, Yang J (2020) Marginal-restraint mandrel-free spinning process for thin-walled ellipsoidal heads. *Adv Manuf* 8(2):189-203

- [16] Wen X, Tan JP, Li XH (2020) Optimization of spinning process parameters for the large-diameter thin-walled cylinder based on the drum shape. *Int J Adv Manuf Technol* 108(7):2315-2335
- [17] Yuan S, Xia QX, Long JC, Xiao GF, Cheng XQ (2020) Study of the microstructures and mechanical properties of ZK61 magnesium alloy cylindrical parts with inner ribs formed by hot power spinning. *Int J Adv Manuf Technol* 111(3):851-860
- [18] Luo W, Chen F, Xu BB, Yang ZJ, Guo YM, Lu B, Huang T (2018) Study on compound spinning technology of large thin-walled parts with ring inner ribs and curvilinear generatrix. *Int J Adv Manuf Technol* 98(5):1199-1216
- [19] Zeng X, Fan XG, Li HW, Li SH (2018) Flow forming process of thin-walled tubular parts with cross inner ribs. *Procedia Manuf* 15:1239-1246
- [20] Qian DS, Li GC, Deng JD, Wang F (2020) Effect of die structure on extrusion forming of thin-walled component with I-type longitudinal ribs. *Int J Adv Manuf Technol* 108(5):1959-1971
- [21] Tian DY, Han XH, Hua L, Huang B, Yang SW (2020) A novel process for axial closed extrusion of ring part with mesh-like ribs. *Int J Mech Sci* 165:105186
- [22] Han XH, Hua L, Peng L, Feng W (2020) An innovative radial envelope forming method for manufacturing thin-walled cylindrical ring with inner web ribs. *J Mater Process Technol* 286:116836
- [23] Cai Y, Sun CY, Wang WR, Li YL, Wan L, Qian LY (2018) An isothermal forming process with multi-stage variable speed for magnesium component assisted by sensitivity analysis. *Mater Sci Eng A* 729:9-20
- [24] Gautam PC, Biswas S (2021) On the possibility to reduce ECAP deformation temperature in magnesium: Deformation behaviour, dynamic recrystallization and mechanical properties. *Mater Sci Eng A* 812:141103
- [25] Peng JH, Zhang Z, Huang JA, Guo P, Li YZ, Zhou W, Wu YC (2019) The effect of the inhomogeneous microstructure and texture on the mechanical properties of AZ31 Mg alloys processed by friction stir processing. *J Alloys Compd* 792:16-24
- [26] Rao XX, Wu YP, Pei XB, Jing YH, Luo L, Liu Y, Lu J (2019) Influence of rolling temperature on microstructural evolution and mechanical behavior of AZ31 alloy with accumulative roll bonding. *Mater Sci Eng A* 754:112-120
- [27] Alizadeh R, Mahmudi R, Ngan AHW, Huang Y, Langdon TG (2016) Superplasticity of a nano-grained Mg-Gd-Y-Zr alloy processed by high-pressure torsion. *Mater Sci Eng A* 651:786-794
- [28] Tang LL, Zhao YH, Liang NN, Islamgaliev RK, Valiev RZ, Zhu YT (2016) Localized deformation via multiple twinning in a Mg-Gd-Y-Zr alloy processed by high-pressure torsion. *Mater Sci Eng A* 677:68-75

- [29] Zhang G, Wang ZX, Chen WB, Cao Y, Wu JY, Qiang GH, Ji AL, Wu JH, Jiang CP (2019) Dual effects of gossypol on human hepatocellular carcinoma via endoplasmic reticulum stress and autophagy. *J Cell Biochem* 113:48-57
- [30] Jiang MG, Yan H, Chen RS (2015) Twinning, recrystallization and texture development during multi-directional impact forging in an AZ61 Mg alloy. *J Alloys Compd* 650:399-409
- [31] Dong BB, Zhang ZM, Yu JM, Che X, Meng M, Zhang JL (2020) Microstructure, texture evolution and mechanical properties of multi-directional forged Mg-13Gd-4Y-2Zn-0.5Zr alloy under decreasing temperature. *J Alloys Compd* 823:153776
- [32] Bochniak W, Marszowski K, Korbel A (2005) Theoretical and practical aspects of the production of thin-walled tubes by the KOB method. *J Mater Process Technol* 169(1):44-53
- [33] Korbel A, Bochniak W (2004) Refinement and control of the metal structure elements by plastic deformation. *Scripta Mater* 51(8):755-759
- [34] Pięła K, Wróbel M, Sztwiertnia K, Jaskowski M, Kawałko J, Bieda M, Kiper M, Jarzębska A (2017) Zinc subjected to plastic deformation by complex loading and conventional extrusion: Comparison of the microstructure and mechanical properties. *Mater Des* 117:111-120
- [35] Che X, Wang Q, Dong BB, Meng M, Zhang ZM (2020) Numerical and experimental analysis of rotating backward extrusion as a new SPD process. *Met Mater Int* 26(12):1786-1796
- [36] Dong BB, Che X, Wang Q, Meng M, Gao Z, Ma J, Yang FL, Zhang ZM (2020) Refining the microstructure and modifying the texture of the AZ80 alloy cylindrical tube by the rotating backward extrusion with different rotating revolutions. *J Alloys Compd* 836:155442
- [37] Che X, Dong BB, Wang Q, Liu K, Meng M, Gao Z, Ma J, Yang FL, Zhang ZM (2021) The effect of processing parameters on the microstructure and texture evolution of a cup-shaped AZ80 Mg alloy sample manufactured by the rotating backward extrusion. *J Alloys Compd* 854:156264
- [38] Hasani A, Seps M, Feyzi S, Toth LS (2021) Deformation field and texture analysis in T-ECAP using a flow function. *Mater Charact* 173:110912
- [39] Segal VM (1999) Equal channel angular extrusion: from macromechanics to structure formation. *Mater Sci Eng A* 271(1):322-333
- [40] Iwahashi Y, Wang JT, Horita Z, Nemoto M, Langdon TG (1996) Principle of equal-channel angular pressing for the processing of ultra-fine grained materials. *Scripta Mater* 35(2):143-146
- [41] Yuan W, Panigrahi SK, Su JQ, Mishra RS (2011) Influence of grain size and texture on Hall–Petch relationship for a magnesium alloy. *Scripta Mater* 65(11):994-997

- [42] Cai Y, Wan L, Guo ZH, Sun CY, Yang DJ, Zhang QD, Li YL (2017) Hot deformation characteristics of AZ80 magnesium alloy: Work hardening effect and processing parameter sensitivities. *Mater Sci Eng A* 687:113-122
- [43] Che X, Wang Q, Dong BB, Meng M, Gao Z, Liu K, Ma J, Yang FL, Zhang ZM (2021) The evolution of microstructure and texture of AZ80 Mg alloy cup-shaped pieces processed by rotating backward extrusion. *J Magn Alloys*
- [44] Quan GZ, Shi Y, Wang YX, Kang BS, Ku TW, Song WJ (2011) Constitutive modeling for the dynamic recrystallization evolution of AZ80 magnesium alloy based on stress–strain data. *Mater Sci Eng A* 528(28):8051-8059
- [45] Qian LY, Fang G, Zeng P, Wang Q (2015) Experimental and numerical investigations into the ductile fracture during the forming of flat-rolled 5083-O aluminum alloy sheet. *J Mater Process Technol* 220:264-275
- [46] Zhao SL, Zhang HM, Cui ZS, Chen D, Chen Z (2021) Strength and ductility improvement of an in-situ TiB₂/Al–Zn–Mg–Cu composite by elliptical cross-section torsion extrusion. *Compos B Eng* 216:108843
- [47] Segal VM (2002) Severe plastic deformation: simple shear versus pure shear. *Mater Sci Eng A* 338(1):331-344
- [48] Tang LQ, Jiang FL, Teng J, Fu DF, Zhang H (2019) Strain path dependent evolutions of microstructure and texture in AZ80 magnesium alloy during hot deformation. *J Alloys Compd* 806:292-301

Figures

- ①. Punch
- ②. Block
- ③. Upper die
- ④. Billet
- ⑤. Bottom die
- ⑥. Heating setup

Figure 1

Schematic illustration of variable circular channel angular extrusion process

Figure 2

Scheme of the shear plane in VCCAE process: (a) schematics of VCCAE process, (b) two back to back ECAP process, (c) typical ECAP process

Figure 3

Schematic diagram of scaling plate with ribs

Figure 4

Experimental setup for VCCAIE process of scaling plate with ribs: (a) hydraulic press, (b) punch, (c) the integrated die

Figure 5

The specimens for OM observation (c) was cut from (a) scaling part at (b) the symmetry plane

Figure 6

FE model of variable circular channel angular extrusion process

Figure 7

Figure 8

Metal flow behavior in VCCAE process of scaling plate with ribs

Figure 9

The experimental results: (a) experimental scaling plate with ribs, (b) compared with simulation

Figure 10

The effective stress distribution of scaling plate with ribs in VCCAE process

Figure 11

The effective strain distribution in (a) longitudinal section and cross section at (b) Upper section, (c) Medium section and (d) Lower section

Figure 12

Stress state parameters variation at points B, C, and D: (a) Lode parameter, (b) Hydrostatic stress

Figure 13

Microstructure of AZ80 magnesium alloy in initial billet and in scaling plate with ribs with VCCAE process