Effect of repetitive upsetting-extrusion on deformation uniformity and mechanical properties of Mg–Gd–Y–Zr alloy

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Abstract

Mg–8.3Gd–3.2Y–0.4Zr alloy underwent severe plastic deformation at 420 °C using 4-pass isothermal repetitive upsetting-extrusion (RUE) process. The deformation uniformity in different regions of the same sample after 4 passes of RUE was studied. The results showed that though there was slightly uneven deformation, the isothermal RUE process can improve uniformity. The strain in the central area is relatively small, and there are more deformed large grains. The dynamic recrystallization fraction at different positions is above 0.5, forming a more uniform microstructure, with the minimum average grain size being 10.66 μm. Discontinuous dynamic recrystallization and continuous dynamic recrystallization occur at the same time, which promotes grain refinement and improvement of microstructure uniformity. Dynamic recrystallization weakens the texture, resulting in the similar texture intensity of different positions of the sample. The bottom edge position with the most uniform microstructure obtained the best tensile properties, UTS reached 323 MPa.

1. Introduction

Magnesium is currently the lightest commonly used structural metal, and magnesium alloys have excellent mechanical properties, which have great application prospects for some industries that require lightweight [1]. The addition of rare earth (RE) elements, including Y and Zn, to magnesium alloys can significantly improve their overall properties, obtaining high strength and excellent corrosion resistance [2]. The dislocation configuration, shear band, random texture and recrystallization are related to the RE elements contained in the Mg–RE alloy [3]. Mg–Gd–Y–Zr alloy has received more and more attention due to its excellent mechanical properties at room temperature and high temperature [4].

Severe plastic deformation (SPD) technology has been widely used in recent years to achieve plastic deformation. The repetitive upsetting-extrusion (RUE) process is used is a kind of SPD technology. Typical SPD processing technology mainly includes high-pressure torsion (HPT) [5], equal channel angular pressing or equal channel angular extrusion (ECAP or ECAE) [6, 7], multi-axis forging (MAF) [8], cyclic extrusion (CEC) [9], etc. Repetitive upsetting-extrusion (RUE) applies three-dimensional compressive stress during the deformation process, which can accumulate a large amount of deformation without changing the size of the blank, promote grain refinement to obtain better mechanical properties, which is suitable for the deformation of Mg alloys [10].

Hu et al [11] applied RUE to the LY2 aluminum alloy, and found that increasing the number of deformation passes can achieve the required cumulative strain and obtain uniform fine grains. Xu et al [12] studied the structure evolution of the RUE AZ61 magnesium alloy, and found that the grains were refined to 4 μm after 3 passes at 285 °C. Chen et al [13] applied RUE on AZ80. The results showed that after 8 passes, a fine and uniform microstructure can be obtained. Zhang et al [14] studied the microstructure evolution of Mg–Gd–Y–Zn–Zr alloy under the different temperature RUE process, and found that the microstructure of the alloy in different deformation areas was different. However, the systematic influence of isothermal RUE on the deformation and microstructure uniformity of Mg–Gd–Y–Zr alloy is still hardly studied.
Under the isothermal RUE process, as the number of passes increases, the grains of Mg–Gd–Y–Zr alloy show a trend of becoming finer. The uniformity of the microstructure is not significantly improved after 4 passes. The four-pass isothermal RUE Mg-8.3Gd-3.2Y-0.4Zr alloy was selected in this paper to study the uniformity of the microstructure. The texture and the refine the mechanism changes in different regions were further analyzed. This will provide a theoretical basis for the further regulation of uniformity in the RUE process in the future.

2. Experimental procedure

The Mg-8.3Gd-3.2Y-0.4Zr (wt%) as-cast alloy blank was subjected to 520 °C for 16 h homogenization treatment and then was prepared by extrusion deformation at the strain of 4.57. The schematic diagram of the process is shown in figure 1. The cylindrical specimen \(d = 50 \text{ mm}, h = 230 \text{ mm}\) is first upset, then press the sample \(D = 70 \text{ mm}\), restore it to its original size. The upsetting and extrusion process is repeated to the required processing process, the principle is shown in figure 2(a). After 4 passes, the strain of each pass is calculated by the formula \(\varepsilon = 4 \times \ln d / D\) to be 1.36 [15].

Before the experiment, heat the mold and the material to 420 °C and keep it for 2 h to ensure that the temperature of the mold and the material is uniform during the experiment. The RUE experiment was carried out on an Instron 3382 drawing machine equipped with a resistance furnace at a punch speed of 0.5 mm s\(^{-1}\). Air cooling to room temperature after each pass. According to our previous research [16], as the number of deformation passes increases, the strain becomes more uniform, at the same time, the degree of grain refinement increases (figure 1). However, after 4 passes, the additional deformation passes increase the overall strain, the strain uniformity in the sample does not change significantly [16]. In order to better analyze the uniformity, we select 4 pass RUEed alloy for further analysis.

![Figure 1. Strain-Effective map of RUE at different deformation pass.](image1)

![Figure 2. (a) Schematic diagram of experimental process (b) observed position.](image2)
Sampling and observing the sample from different parts of the longitudinal section with a wire cutter, observation surface parallel to the extrusion direction (ED). The position of six areas observed are shown in figure 2, they are the top center position (TC), the top edge position (TE), the middle center position (MC), the middle edge position (ME), the bottom center position (BC), the bottom edge position (BE).

In order to further observe the microstructure of the sample, polish the observation surface, and then observe under the scanning electron microscope (SEM). Corrosion for 10 s in a corrosive solution made of 2.5 g picric acid + 2 ml glacial acetic acid + 5 ml water + 60 ml alcohol, the optical micrograph (OM) was observed using the Zeiss Axio Imager A2m optical microscope. Use XRD, EBSD and other technologies to test the sample, analyze the grain size, misorientation angle difference, texture and other characteristics.

3. Results and discussion

3.1. Microstructure characteristics

Figure 3 is the optical micrograph (OM) of the initial state alloy along longitudinal section. The grain distribution is relatively uniform, showing equiaxed crystals, with the average grain size of 42.99 \( \mu m \). A small amount of precipitated phases are distributed in the matrix (the red arrows in figure 3).

Figure 4 is OM of the sample at different areas after 4-pass isothermal RUE. After RUE, the grain size is significantly reduced compared to the initial alloy. The alloy grains in different regions have different degrees of dynamic recrystallization (DRX). The microstructure in the center area has many large grains with a grain size larger than 20 \( \mu m \). These grains are slightly elongated, and the aspect ratio is less than 1.5. They are surrounded by fine DRXed grains, showing a typical bimodal structure [17, 18]. The formation of grain boundaries can be observed in the inner of some large grains, indicating that the DRX process is in progress (blue frame in figure 4). Stress concentration is more likely to occur at the triple grain boundaries of large grains, forming a DRX area composed of fine grains (the yellow rectangle in figure 4). The microstructure of the central area in different locations is slightly different. The size of the large grains in the MC area decreases slightly, and the DRX area with fine grains is larger. The large grains of BC area have little obvious elongation phenomenon, and there are few fine grain regions and the grain size is relatively large.

The edge area of the alloy (figures 4(d)–(f)) shows a relatively uniform microstructure, the DRX area is enlarged. Some large grains are almost completely swallowed by the DRXed grains. The DRXed grains appear as equiaxed crystals and the grain size is relatively uniform. The size of a small amount of remaining large grains is obviously elongated in the ED direction relative to the central area, and the aspect ratio is greater than 2. The microstructure is obviously refined relative to the central area. This is due to the friction between the sample and the mold during the experiment, which makes the deformation degree of the edge of the sample significantly greater than the center of the sample. The residual large grains are elongated due to severe deformation, and at the same time, severe deformation promotes the occurrence of DRX and promotes the grain refinement on the edge of the sample [14]. The microstructures in different areas of the edge are not much different. The stress distribution in figure 1 also shows that the stress at the edge is relatively large but the difference in different areas is not obvious. The ME area has the residual coarse grains and the most uniform structure, due to the relatively
greater stress in the middle part during the deformation process, which is consistent with the simulation results in figure 1.

Studies have shown that the second phase in the Mg–Gd–Y–Zr alloy plays an important role in the deformation process [19]. The distribution of the second phase is similar in different positions in the central area, and a small amount of the second phase is distributed inside the grains and at the grain boundaries. In the DRX area, the amount of the second phase increases slightly. In the edge area, the number of second phases increased significantly, and a large number of them were distributed at the grain boundaries, while very few distributions inside the grains. The precipitation range is significantly enlarged and the distribution is more uniform. The second phase at the grain boundary hinders the migration of dislocations during the deformation process, causing the accumulation of dislocations to form sub-grain boundaries, and gradually transform into high-angle grain boundaries (HAGBs), which activate particle-stimulated nucleation (PSN) mechanism to complete DRX process [20]. In the ME region with the largest deformation, a large number of second phases are uniformly distributed in the microstructure, and the grains are refined obviously.

XRD phase analysis was performed on the six regions of the material sample, as shown in figure 5. The result shows that the precipitated phase is Mg5(Gd,Y), the microstructure in different areas changed but the phases did not change significantly, indicating that the uneven deformation did not lead to the formation of new phases [21]. Due to the increase in the internal dislocation density of the RUE alloy, some small peak displacements can be seen in the XRD pattern [22].

In order to further characterize the distribution characteristics of the second phase, backscattered electron (BSE) pictures of the alloys in different regions were taken (figure 6). The second phase shows a brighter contrast. It can be observed that the alloy precipitated phases are not uniformly distributed in the central area (figures 6(a)–(c)), and the distribution is relatively concentrated in some areas. Combining with the OM diagram (figure 4), it can be inferred that this is a DRX concentrated area. Around the large deformed grains, fine precipitates can be observed distributed along the grain boundaries. The size of the second phase in the MC area is the largest and the distribution is relatively uniform, and its fraction is account for 6.49%. The precipitated phase in the BC accounts for only 2.45% due to deformation. The precipitated phases in the edge area present a more uniform distribution, the number and the size are obviously increased, accounting for more than 6%. The distribution in different areas of the edge is similar, the size of the second phases in the ME and BE areas has increased, showing a more uniform dispersion distribution. The friction between the blank and the mold results in greater metal flow in the bottom region than in the top region, resulting in increased deformation, which promotes the precipitation of the second phase, further promotes DRX, and the edge grain distribution is fine and uniform.

3.2. Dynamic recrystallization characteristics
The formation of DRXed grains during the deformation process plays an important role in improving the uniformity of the structure. In order to further characterize the changes of DRX in different parts of the material,
we conducted EBSD analysis on different areas. The OIM diagrams of different areas are shown in figures 7(a)–(d). The same or similar colors represent the same or similar crystal orientations.

After RUE, the microstructure is mainly composed of deformed large grains (rectangular frame in figures 7(a)–(c)) and DRXed areas with fine grains (elliptical frame in figures 7(a)–(c)). The color inside the large grains changed significantly, indicating a large strain gradient [14]. There are many fine grains generated by DRX around the large grains with random colors, indicating that they have a relatively random orientation. There are many large grains in the central area, and the internal color changes drastically. Due to the uneven strain, DRXed grains appear concentrated in some areas. Because of the larger strain in the MC region, the distribution of fine grains is more, while the color change in the large grains in the BC region is relatively small, with small DRXed grains unevenly distributed.

The uniformity of the structure in the edge area is obviously improved, and significant grain refinement occurs. The residual large grains are obviously elongated along the ED direction (rectangular frame in

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**Figure 5.** X-ray diffraction patterns of RUEed alloy after 4 passes in different areas.

**Figure 6.** BSE images of RUEed alloy after 4 passes in different areas. (a) TC; (b) MC; (c) BC; (d) TE; (e) ME; (f) BE.

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The deformation area is composed of fine DRXed grains. As the region moves from the top to the bottom, the deformation area distributes longer along the ED direction (elliptical frame in figures 7(d)–(f)). This is due to the friction between the blank and the mold during the deformation process, resulting in increased metal flow in the outer area and increased deformation.

Through the EBSD results, the overall grain size of the material is analyzed. Figure 8 shows the grain size distribution of samples in different regions. The grain size distribution in the central area of the sample is relatively dispersed, the highest number of grains smaller than 10 μm are all below 0.06, and the large-size grains still account for a higher proportion (figures 8(a)–(c)). The average grain size of different regions is significantly different. The MC region has the finest grain size of 15.99 μm due to the maximum strain. The grain size of the BC region is larger than that of the MC region by 7.63 μm, and the TC region is larger than that of the MC region by 3.42 μm. Compared with the center area, the average grain size at the edge of the sample is smaller, the number of small grains is above 0.1, and the large grains are significantly reduced, the bimodal structure gradually disappears. The average grain size decreased slightly and the grain distribution range narrowed.
(figures 8(d)–(f)), and the structure was more uniform, confirming the results in figure 7. In contrast, the edge grains are more uniform than the center grains. The minimum average grain size of the ME region is 10.66 μm. The TE and BE regions have slightly increased grain sizes relative to the ME region, but the difference is within 2 μm, indicating that the uniformity of the edge area is improved, which is attributed to the greater deformation caused by friction, which promotes continuous grain refinement [14].

The region where the grain orientation spread is less than 2° is defined as the DRX region, which is separately shown in figure 9. It can be observed that the DRXed area in the edge area increases significantly, DRX fraction in the central area is below 0.45, and the DRX fraction in the edge area is above 0.55.

The distribution of DRXed grains in the central area is not uniform. The size of DRXed grains in the same area is similar, but the grain size of different areas is different (figures 9(a)–(c) different color ellipses). During the deformation process, the DRX in the edge region is more complete, and the grains are more uniform. The DRXed grain size in different regions is similar, and better uniformity is obtained.

The grain size distribution of DRXed grains and unDRXed grains in different regions are respectively shown in figure 10. The DRXed distribution trend of different positions in the central area is similar, and the average grain size is 4.75–5.53 μm. The DRX in the BC region is activated later due to the smaller strain, and the DRX grain is slightly smaller. The trend of DRX distribution in the edge area is basically the same, and a higher peak appears at about 3 μm. The average grain size at different positions on the edge is 4.75–4.88 μm, and the difference is significantly smaller than that in the center area. The unDRXed grain size fluctuation range in the central region is 28.0 ± 3.5 μm, which is larger than the fluctuation of 25.3 ± 1.3 μm in the edge region, and the distribution trend of the edge region is more similar, that is, the edge area has a more uniform microstructure.

In order to reveal the dynamic recrystallization formation and grain refinement evolution, we further analyzed the KAM distribution of different area, and the results are shown in figure 11. It can be found that the areas with higher KAM values are mainly concentrated around the grain boundaries. The KAM values inside the coarse grains are higher, and the fine grain areas have lower KAM values. Combined with the OIM diagram, it can be concluded that many low-angle grain boundaries (LAGBs) are generated in areas with high KAM values. During the deformation process, dislocations are generated and slip inside the grain, and accumulate at the grain boundary, which provides a strain gradient for dynamic recrystallization [20]. Due to the larger strain in the edge region, the critical condition of dynamic recrystallization is reached in more regions. The accumulated dislocations are transformed into grain boundaries to form dynamic recrystallization, which reduces the KAM value of the DRX region.

The distribution of misorientation in the different region is shown in figure 12. The misorientation in different regions all have extreme values in the range of less than 5°. The number of LAGBs in center area is significantly smaller than that of the edge, the number fraction of the HAGBs is larger than the edge. This shows that during the RUE process, the amount of deformation at the edge of the sample is greater than the center, and the material generates a large number of dislocations due to severe deformation [13]. When the strain reaches a certain level, the dislocations are rearranged to form LAGBs. The LAGBs continue to accumulate new
dislocations, and gradually change the HAGBs to form new grains, that is, continuous dynamic recrystallization occurs, promoting grain refinement and making the structure more uniform.

Studies have shown that both continuous dynamic recrystallization and discontinuous dynamic recrystallization play an important role in promoting grain refinement in the hot deformation process of magnesium alloy[22]. We select grain R1 from the TC area for further analysis. Mark the parent grains as P1 and

Figure 10. The grain size distribution of DRX grains and unDRXed grains of the RUEed alloy after 4 passes in different areas. (a) DRX grains in the central area; (b) DRX grains in the edge area; (c) unDRXed grains in the central area; (d) unDRXed grains in the edge area.

Figure 11. KAM distribution maps of the RUEed alloy after 4 passes in different areas. (a) TC; (b) MC; (c) BC; (d) TE; (e) ME; (f) BE.
P2. The color changes drastically inside P1 and P2, and a large number of LAGBs (black arrows in figure 13) are distributed inside. The misorientation is counted along AB. The misorientation are different from point to point, and the misorientation from point to origin gradually accumulates, indicating that the crystal lattice inside the P1 has continuous rotation. LAGBs continuously absorb and accumulate dislocations, forming HAGBs, and continuous dynamic recrystallization (CDRX in figure 13) occurs in areas where LAGBs are enriched. At the same time, it was observed that the grain boundary at the edge of the parent grain was zigzag, and the existing grain boundary protruded to the adjacent grains, forming LAGBs in the protruding part, which was further packed by dislocations and passed along the zigzag GBs. This forms new DRX grains, which is a typical discontinuous dynamic recrystallization process [23] (DDRX in figure 13). The above shows that the continuous dynamic recrystallization and discontinuous dynamic recrystallization start at the same time during the RUE process, and the grain refinement makes the structure more uniform. All the grains are displayed in the (0001) pole figure (figure 13(b)). The DRXed grains are obviously deflected from the parent grain orientation, which helps to weaken the texture of the material and obtain smaller anisotropy [24].

3.3. Texture characteristics
Magnesium alloys are prone to produce fiber textures with basal orientation characteristics during the extrusion process [25, 26]. Strong fiber texture will produce anisotropy of material properties and affect the uniformity of material mechanical properties. Further analysis of the texture of the RUE alloy, figure 14 shows the (0001) pole figure of all grains DRX grains and unDRXed grains in different regions. It can be seen from the figure 14 that after RUE all areas show a typical extrusion structure, that is, almost all the (0001) basal plane is parallel to the
ED. The distribution of (0001) pole figures in different regions is relatively uniform with the intensity from 4.363 to 5.411.

From the perspective of all grain pole figures, the maximum basal texture intensity in the edge region is slightly smaller than the texture in the center region, but the difference is not obvious. The pole figure distribution of unDRXed grains is basically similar to that of all grains, indicating that unDRXed grain has a greater contribution to the overall texture. The pole figure distribution of DRX grains is more dispersed, and the maximum pole intensity is smaller as $2.5 \pm 0.5$, which effectively weakens the texture [17].
It is worth noting that the DRXed fraction of the edge region is significantly higher than that of the center region, but the overall pole figure intensity does not decrease significantly. Observing the distribution of unDRXed pole figure, it is found that the intensity of unDRXed pole figure in the edge area reaches more than 10, which is much greater than the pole figure intensity of unDRXed area in the central area (6.5 ± 1.5). This is due to the large strain in the edge area due to friction, and lattice rotation occurs inside the grains. The unDRXed grains are elongated along the ED, showing a strong extrusion texture. Although the number of DRX increases and the distribution is random, unDRXed contributes a lot to the overall pole figure distribution. The random texture of the enhanced DRX grains weakens the strong extrusion texture caused by the edge unDRXed grains, and the overall texture strength is not significantly reduced. This also explains that in the BC region, due to the small amount of deformation, the unDRXed grains did not undergo a large lattice rotation, and the strong extrusion texture was not formed, resulting in a more dispersed unDRXed pole figure distribution, and the overall pole figure also showed a more diffuse distributed.

3.4. Mechanical properties

Figure 15 shows the mechanical properties of the initial alloy and RUE alloy at six different areas measured by tensile tests at room temperature. The YS and UTS of the initial alloy are 208 MPa and 263 MPa, respectively, and the FE is only 6.5%. After 4 passes of RUE, the mechanical properties of different areas are significantly improved. The values of UTS, YS and FE at different positions in the center area are similar as 312 ± 3 MPa, 238 ± 3 MPa, and 9.4 ± 0.3%, respectively, which are about 50 MPa higher than the initial tensile strength. The microstructure of the edge area is more uniform, and the mechanical properties improvement is greater than the center area. The mechanical properties of different areas at the edge are also similar. UTS, YS and FE are 320 ± 3 MPa, 239 ± 2 MPa, 10.4 ± 0.2 MPa, respectively. Compared with the central area, the tensile strength is increased by about 8 MPa, and the yield performance and elongation are also slightly increased.

Studies have shown that both texture and grain refinement can have a significant impact on mechanical properties [27]. According to the analysis of 3.3, the texture change in different regions is very small, so the improvement of the mechanical properties of different regions is mainly related to the grain refinement. The increase of fine DRXed grains and high dislocation density will lead to a significant work hardening effect and increase the yield strength of the sample. In the ME region with the largest strain, we obtained the relatively highest mechanical properties, whose UTS, YS and FE were 323 MPa, 240 MPa, and 10.3% respectively. Compared with the initial state, UTS increased by 22.8%, YS increased by 15.4%, and FE increased by 58.5%. This is due to the finest grains in the ME region, and the refined grains lead to an increase in grain boundaries, resulting in grain boundary strengthening and improved alloy performance [28]. At the same time, it conforms to the Hall-Petch equation: \( \sigma_y = \sigma_0 + Kd^{-1/2} \), where \( \sigma_y \) is the tensile yield strength (YS), \( \sigma_0 \) and K are material constants, and d is the average grain size. The smaller the average grain size, the greater the yield strength of the alloy.

![Figure 15. Mechanical properties of the RUEed alloy after 4 passes in different areas. (a) TC; (b) MC; (c) BC; (d) TE; (e) ME; (f) BE.](image-url)
4. Conclusions

By conducting an isothermal RUE experiment on Mg–Gd–Y–Zr alloy, the evolution of its microstructure texture and deformation mechanism in different regions was studied, and the following conclusions were obtained:

1. There was slightly uneven deformation after 4-pass isothermal RUE process. The strain in the central area is relatively small, existing more coarse grains. The strain is larger due to friction at the edge, the grains are refined and the second phase is uniformly distributed. The maximum strain in the ME region obtains the most uniform microstructure with the minimum average grain size of 10.66 μm.

2. During the deformation process, discontinuous dynamic recrystallization and continuous dynamic recrystallization occurred simultaneously, which played important role in obtaining a uniform microstructure and texture due to the DRXed grains with small size and random orientation. The dynamic recrystallization fraction at different positions in the edge area is all above 0.5, which is larger than the central area, having a significant effect on grain refinement and texture intensity reduction.

unDRXed3) RUE significantly improves the mechanical properties. The mechanical properties of different positions are slightly different, and the mechanical properties of the edge area with better uniformity are slightly higher than the center area. The ME area with the most uniform microstructure has the highest tensile properties, UTS is 323 MPa, TYS is 240 MPa, and FE is 10.3%.

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References

[1] Yan Z et al 2019 Research on AZ80 + 0.4%Ce (wt%) ultra-thin-walled tubes of magnesium alloys: the forming process, microstructure evolution and mechanical properties Metals 9 563
[2] Kui Z et al 2011 Hot deformation behavior of Mg–7.22Gd–4.84Y–1.26Nd–0.58Zr magnesium alloy Rare Met. 30 87–93
[3] Bayani H and Saenoori E 2009 Effect of rare earth elements addition on thermal fatigue behaviors of AZ91 magnesium alloy Journal of Rare Earth (English Edition) 027 255–8
[4] Wen-Xiang W U et al 2011 Research progress of high strength and heat resistant Mg–Gd–Y–Zr alloys The Chinese Journal of Nonferrous Metals 21 2709–18
[5] Li Y et al 2020 Accelerated and enhanced aging hardening response of the pre-aged and HPT-processed Mg–Zn–Y alloy by HAADF-STEM Mater. Lett. 261 127096
[6] Ma X et al 2019 Dynamic precipitation and recrystallization in Mg–9wt%Al during equal-channel angular extrusion: a comparative study to conventional aging Acta Mater. 172 185–99
[7] Ebrahim H S et al 2018 Investigation on microstructure and mechanical properties of AA1/Mg–Zn–Mg–Cu laminated composite fabricated by accumulative roll bonding (ARB) process Materials Science and Engineering A 718 311–20
[8] Nugmanov D R et al 2018 Origin of plastic anisotropy in (ultra)-fine-grained Mg–Zn–Zr alloy processed by isothermal multi-step forging and rolling: experiments and modeling Materials Science and Engineering A 713 81–93
[9] Pardis N et al 2011 Cyclic expansion–extrusion (CEE): a modified counterpart of cyclic extrusion–compression (CEC) Materials Science and Engineering A 528 7537–40
[10] Zhang G et al 2019 Effects of repetitive upsetting-extrusion parameters on microstructure and texture evolution of Mg–Gd–Y–Zn–Zr alloy J. Alloys Compd. 790 68–57
[11] Lianxi H et al 2006 Ultrafine grained structure and mechanical properties of a LY12 Al alloy prepared by repetitive upsetting–extrusion Materials Science and Engineering A 422 327–32
[12] Xu Y et al 2014 Repetitive upsetting extrusion process and microstructure evolution of AZ61 magnesium alloy Mater. Res. Innovations 18 173–7
[13] Chen Q et al 2011 Microstructure development and thixoextrusion of magnesium alloy prepared by repetitive upsetting-extrusion J. Alloys Compd. 509 7303–15
[14] Zhang G et al 2018 Effect of isothermal repetitive upsetting extrusion on the microstructure of Mg–12.0Gd–4.5Y–2.0Zn–0.4Zr Alloy Mater. Sci. and Eng. A 527 2265–75
[15] Wang Q et al 2010 Microstructure evolution of AZ series magnesium alloys during cyclic extrusion compression Materials Science and Engineering A 527 2265–75
[16] Liu D 2019 Mechanical properties, corrosion resistance and biocompatibilities of degradable Mg–RE alloys: A review Journal of Materials Research and Technology 8 1538–49
[17] Meng Y et al 2020 The evolution of long-period stacking ordered phase and its effect on dynamic recrystallization in Mg–Gd–Y–Zn–Zr alloy processed by repetitive upsetting-extrusion J. Alloys Compd. 828 15454
[18] Lu S et al 2019 The effect of twinning on dynamic recrystallization behavior of Mg–Gd–Y alloy during hot compression J. Alloys Compd. 803 277–90
[19] Liu K et al 2010 Effect of ageing treatment on the microstructures and mechanical properties of the extruded Mg–7Y–4Gd–1.5Zn–0.4Zr alloy Materials Science and Engineering A 527 828–34
[20] Robson J D, Henry D T and Davis B 2009 Particle effects on recrystallization in magnesium–manganese alloys: particle-stimulated nucleation Acta Mater. 57 2739–47
[21] Fang C et al 2016 The application of Al-Ti-B preform in Al-free Mg–Zn alloy via the yttrium addition Materials Science and Engineering A 658 (Mar.21) 376–80
[22] Ramezani S M et al 2019 Achievement of fine-grained bimodal microstructures and superior mechanical properties in a multi-axially forged GWZ magnesium alloy containing LPSO structures Journal of Alloys & Compounds 793 134–45
[23] Zhang Y, Zeng X Q, Lu C and Ding W J 2006 Deformation behavior and dynamic recrystallization of a Mg–Zn–Y–Zr alloy Materials Science and Engineering A 428 91–7
[24] Yao Y et al 2020 Microstructure, texture and mechanical anisotropy of Mg–Gd–Y–Zr sheets processed via different rolling routes and reductions Mater. Charact. 161 110120
[25] Jiang M G et al 2018 Unveiling the formation of basal texture variations based on twinning and dynamic recrystallization in AZ31 magnesium alloy during extrusion Acta Mater. 157 53–71
[26] Mukai T et al 2003 Guide for enhancement of room temperature ductility in Mg alloys at high strain rates Mater. Sci. Forum 419-422 171–6
[27] Zhang Z et al 2018 Microstructure and mechanical properties of Mg–Gd–Y–Zn–Zr alloy prepared by repetitive upsetting and extrusion Mater. Trans. 59 669–73
[28] Dong B et al 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