We report microstructure evolution and mechanical properties of Mg alloy AZ31 processed by a new severe plastic deformation technique which combines forward extrusion, equal channel angular extrusion (ECAE) and change channel angular extrusion (CCAE). Under all of the processing temperatures ranging from 623 K to 723 K, the grain size of the as-extruded sample was remarkably refined, which is attributed to the grain subdivision and dynamic recrystallization during the drastic deformation. We have also found the strength and tension-compression asymmetry were improved. Simultaneously, micro-fracture of tensile exhibited the characteristics of ductility, indicating plasticity of Mg alloy AZ31 was improved by compound channel extrusion. [doi:10.2320/matertrans.MC201004]

(Received November 4, 2010; Accepted February 15, 2011; Published April 13, 2011)

Keywords: magnesium alloy AZ31, compound channel extrusion, microstructure and mechanical property, fracture behavior

1. Introduction

To fight against the energy consumption and environment degradation, improving efficiency and reducing cost have become an inevitable trend. As an extremely light metal, magnesium alloys are of excellent specific strength, excellent sound damping capabilities, good castability, hot formability, and excellent machinability which are very attractive in a variety of technical applications, especially in electronics, aerospace, transportation industries, sports industries, etc.\(^1\)\(^-\)\(^3\) Therefore, most products are processed by casting, which greatly limits the wide use of Mg alloys. To expand the application field of Mg alloys and improve its mechanical properties, hot plastic deformation method is a trend of development. Furthermore, mechanical properties of wrought magnesium products was enhanced compared to the cast products.\(^4\)\(^-\)\(^5\)

Recently, severe plastic deformation has become a promising processing to get ultrafine grains for improving ductility and strength of alloys.\(^6\)\(^-\)\(^12\) In addition, it provides a reliable method for improving the room-temperature mechanical properties of hexagonal close-packed materials. A. Galiev et al.\(^13\) reported that Mg alloy exhibits distinct plastic deformation mechanism at different temperature range. When the temperature over 498 K, the ductility of Mg alloy increases greatly with the temperature due to the behaviors of recovery and recrystallization.\(^14\) Thus above this temperature, Mg alloys can be plastically deformed smoothly, such as rolling\(^15\) and extruding.\(^16\) In the case of extruded Mg alloys, many researches focus on equal channel angular extrusion (ECAE).\(^17\)\(^-\)\(^19\) The process involves pushing the work-piece though two channels of equal cross section that meet at an predetermined angle.\(^20\) However, ECAE technology cannot be applied to the actual production owing to most ECAE billets needing initial extrusion. Another reason is that that process cannot be extruded continuously either. Considering some aspects like economic benefit and efficiency, many passes of ECAE is not good for the practical application.

In this work, we apply a new severe plastic deformation technology-compound channel extrusion, in order to reduce the passes of extrusion and improve the work efficiency. The microstructures, mechanical properties, the deformation behavior and fracture behavior of Mg alloy AZ31 were investigated.

2. Experimental Procedures

The material used for the current study was a commercial Mg alloy AZ31 with the following chemical composition (in mass%): 3% Al, 1% Zn, 0.3% Mn and Mg (balance), supplied in form of cast ingots. In order to improve the uniformity of alloy composition, ingots were homogenized at 673 K for 15 h. And then, these ingots were machined into cylindrical samples with a cross-section dimension of φ80 mm × 150 mm as starting materials for the compound channel extrusion process. The compound channel extrusion die is schematically shown in Fig. 1. We carried out this experiment using XJ-500 horizontal extruder with rated extrusion pressure 20 MPa. The samples were φ80 mm × 150 mm cylinders, which were firstly deformed into φ50 mm cylinders in diameter using routine forward extrusion. And then deformed samples went through into four change channels which were the change channel angular extrusion to form four bars with φ10 mm in diameter, and finally the four bars were deformed by equal channel angular extrusion. The total extrusion ratio is 16 : 1, and the angle of each corner is 90°. Both the die and the extruder were preheated to the extrusion temperature. Then the samples were put into the container and kept for 30 min at the same temperature of the die. As for lubrication, the graphite was used. Extrusion experiments were carried out at 623 K, 673 K and 723 K respectively, with a velocity of 2 mm/min. Finally, as-extruded sample extruded at 623 K was annealed at 623 K for 2 h.
Microstructures of the samples were examined using optical microscopy (OM). The mean grain size from the optical micrographs was determined by the following procedures presented in ASTM standard E112-95. The Vickers hardness ($H_v$) was measured using a digital micro-hardness tester HXD-1000TM/LCD at a load of 0.98 N for 20s. Both the compressive and tensile directions were aligned parallel to the extrusion direction, which were carried out by electronic universal testing machine CMT-5150 at room temperature. X-ray diffraction was used to analyze the texture evolution parallel to the ED–TD plane. A D/Max-1200X diffractometry with copper target operated at 40 kV and 30 mA was applied. Fracture morphology was observed by TECSAN-VEGAI1 scanning electron microscope (SEM).

3. Results and Discussion

3.1 Optical micro-structure and macro-texture

Figure 2 presents the optical microstructures of Mg alloy AZ31 of different processing states. Figure 2(a) shows the microstructure of as-cast homogenization before compound channel extrusion. The average grain size of the AZ31 alloy provided in the form of cast ingots is approximately 150 μm. After homogenization, the grain size grew up to 200~240 μm. The coarse microstructure after this combined channels extrusion process has been greatly improved since the original grains are replaced by newly generated equiaxed fine grains (Figs. 2(b), (c), (d)), where the ED–TD plane is observed. The mean grain sizes of the AZ31 samples deformed at 623 K, 673 K and 723 K are determined to be 4, 11 and 16 μm, respectively (Fig. 3). Therefore, grains of Mg alloy AZ31 have been refined obviously. After the annealing process for the extrusion parts, the grains re-grew into 30 μm, as illustrated in Fig. 2(e).

The Mg alloys are prone to dynamic recrystallization by hot extrusion process.\(^{21}\) With the increase of the extrusion temperature, the grain size became larger. The size of the grains obtained at 723 K is two times larger than that of the grains extruded at 623 K (Figs. 2(b), (d)), which indicates that the extrusion temperature is an important factor in controlling the microstructure of Mg alloys AZ31. We should note that this new type of severe plastic extrusion process retains the advantages both ECAE and CCAE\(^{22}\) on grain refinement at the same extrusion temperature, for example, the grain was refined to 9 μm under five passes by ECAE and we can get grain size to 23 μm by one-pass CCAE, but we can make grain fine to about 4 μm after one-pass this process at 623 K.

As can be seen from Fig. 4, the strongest and the second strongest XRD diffraction peak of homogenized Mg alloys are (1011) and (1010), respectively. After as-extrusion, the strongest diffraction peak appears at (0002) after XRD scanning from the ED-TD planes. The intensity of crystal plane’s diffraction reflects the relative number of the distribution of crystal planes, which are parallel to the surface. So the crystal planes corresponding to the strongest diffraction peak are the preferred and the most powerful crystal planes. Figure 4 clearly shows that the as-extruded sample has a preferred orientation along the extrusion direction, and there is a fiber texture (0002) of basal plane. For the as-extruded Mg alloy after annealing, the strongest peak remains the (0002), but the intensity decreases obviously.

3.2 Micro-hardness and mechanical properties

As seen in Fig. 5, the hardness and compressive properties of as-extruded Mg alloy AZ31 are better than those of the original homogeneous state. Micro-hardness and compressive strength are greatly improved after extrusion, but the total strain-to-fracture declines a little compared to the homogeneous state. In regard to the effect on the total strain-to-fracture, the theoretical strain-to-fracture decreases with the extrusion temperature and the grain size increases gradually. But at the same time, strain-to-fracture has a certain relationship with the uniformity of structural stress and heat stress. The structural stress is rather high owing to the less homogeneous structure, thus it’s more easily to generate pileup of dislocation and stress concentration, which lead to the overall plasticity and toughness decrease. Therefore, we find that the grain size of as-extruded Mg alloy AZ31 was fined hugely in Fig. 3, but the total strain-to-fracture showed little change due to the structural and thermal stress. Although the grains of annealed Mg alloy AZ31 re-grew, total strain-to-fracture was excellent due to complete recrystallization and homogeneous structure. As above discussion, two factors affect the strain-to-fracture, total strain-to-fracture of Mg alloy AZ31 extruded at different temperature changed slightly during this process.

We further investigate the mechanical properties have a strong dependence on the texture. Fiber texture (0002) makes property of as-extruded weak. As to as-extruded Mg alloy after annealing, the strongest peak remains the (0002), but the intensity decreases obviously, which was not in favor of microstructure and mechanical properties. In short, the fine grains make strength, ductility and toughness of Mg alloy AZ31 improved greatly. Compared with available studies on hot extrusion, the yield strength and the UCS of Mg alloy through this as-extrusion process at 623 K are 160 MPa and 396 MPa higher than previously reported 130 MPa (yield...
Fig. 2 Optical microstructures of Mg alloy AZ31 at different processing states: (a) homogenized at 673 K for 14 h, (b) (c) (d) extruded at 623 K, 673 K, 723 K parallel to the ED–TD plane, (d) annealed at 623 K for 2 h.

Fig. 3 Average grain sizes of Mg alloy AZ31 at different processing states. (A-annealed at 623 K for 2 h, H-homogenized at 673 K for 14 h and as-extruded at 623 K, 673 K, 723 K).

Fig. 4 The XRD pattern of Mg alloy AZ31 at different processing states: homogenized at 673 K for 14 h, as-extruded at 623 K and annealed at 623 K for 2 h.
3.3 Effect of compound channel extrusion on tensile-compression asymmetry

Figure 6 shows the axial tension and compression stress-strain curves at room temperature of homogenized at 673 K for 15 h, as-extruded at 623 K and annealed 623 K for 2 h Mg alloy AZ31. According to Fig. 6(a), the tensile yield strength at homogenized state is about 95 MPa, and this sample ruptures as strain reaches 14.9% with the tensile strength being approximately 211 MPa. However, the compressive yield strength is relatively low, about 42 MPa. The alloy yields under low stress and ruptures when strain reaches 18.5% with the compressive strength being 270 MPa. The experiment suggests that homogenized Mg alloy has nature of tensile and compressive asymmetry with the value of $\sigma_{yc}/\sigma_{ys}$ being 0.44 ($\sigma_{yc}$ and $\sigma_{ys}$ represent the compressive yield strength and the tensile yield strength respectively). In a similar way, we can observe that Mg alloy AZ31 exhibited tensile and compressive asymmetry at as-extruded and annealed state, where the value of $\sigma_{yc}/\sigma_{ys}$ is 0.76 and 0.65, respectively. But the asymmetry was improved when being extruded through this process.

Figure 3 shows the grain size of the homogenized state is 20 times larger than that at 623 K as-extruded state indicating the tensile and compressive asymmetry of Mg alloy AZ31 at as-extruded state improved.25 In addition, the existence of texture has significant effect on the tensile and compressive asymmetry. According to Fig. 6, during the extrusion process, fiber texture {[0002]} formed on the basal plane along the direction of extrusion greatly influences the tension-compression asymmetry of Mg alloy AZ31. For the Mg alloy AZ31 with texture on the basal plane in as-extruded condition, the tensile yield strength is decided by the density of basal texture. Higher texture density will cause more difficulties in deformation and greater yield strength. When the alloy is compressed, orientation factors causing slip is also zero, while twinning strain at the time is the largest. So in this case, deformation is very much likely to happen through twinning mode, and the tension force along the axis c is easy to form the tension twinning {[1012]} (CRSS of which is extremely low). So the tensile yield strength is higher than the compressive yield strength. When being annealed, the Mg alloy AZ31 has relatively larger average gain size, but the texture intensity decreases obviously. So the annealing process does not have tremendous influence on the tensile and compressive asymmetry. On the whole, the new compound channel extrusion process improves this nature of the Mg alloy AZ31.

3.4 Fracture behavior

Figure 7(a)–(d) shows SEM fractography of Mg alloy AZ31 under different conditions, including are homogenized and as-extruded Mg alloy micro-fracture morphology of the tensile and compressive tests. The tensile fracture of homogenized sample exhibits complete dissociation characteristics (Fig. 7(a)). There are a large number of river patterns and cleavage terraces in SEM picture. The micro-fracture (Fig. 7(b)) of compressive fracture is similar to that of tensile fracture. We can observe cleavage planes and cleavage terraces (as pointed by the arrows in the Fig. 7(b)), but the river pattern is not very clear. The tensile fracture of the as-extruded sample is shown in the Fig. 7(c), which has dimples and displays the characteristics of the resembling microvoid coalescence. So the plasticity is improved significantly. However, it still exhibits the characteristic of brittleness. So
the tensile fracture of the as-extruded sample belongs to quasi-cleavage fracture. The compressive fracture of the as-extruded sample is of the typical transcrystalline fracture, in which a few cracks and elongated micro-cavities can be observed. In short, as-extruded alloy exhibits more plastic before rupture compared to the homogenized state. Thus people also regard the compressive fracture of the extruded alloy as quasi-cleavage fracture. From the above analysis, a conclusion can be made that the tensile and compressive fracture of the homogenized Mg alloy AZ31 belong to cleavage fractures, while that of the as-extruded alloy fall into the quasi-cleavage fracture of the brittle-to-ductile associative form.

4. Conclusions

We have applied a compound channel extrusion technique to Mg alloy AZ31 and investigated in details the microstructure evolution and mechanical properties. Mg alloy AZ31 exhibits uniform fine microstructure and excellent mechanical properties using this new process. Simultaneously, tension-compression asymmetry was greatly improved. Because of grain refinement, fracture of the as-extruded sample turned into quasi-cleavage fracture, which contains brittleness and ductility. In addition, this technology is developed and designed basing on the previous ECAE and CCAE, we find that single-pass compound channel extrusion can acquire better mechanical properties and continuous production compared to that obtained from the multi-pass ECAE and single-pass CCAE. Therefore, considering the shape of material, the production efficiency and the cost, this technique is worth exploring.

Acknowledgements

This work was supported in part by the National 973 Major Project of China, “The Key Fundamental Problem of Processing and Preparation for High Performance Magnesium Alloy”, under Grant No. 2007CB613700 and in part by the Fundamental Research Funds for the Central Universities (CDXS10131154) and a Distinguished PhD award from Ministry of Education of China. One of the authors (Zeng Wen) thanks the Chinese Scholarship Council (CSC) project (LJC20093012) for scholarship support.

REFERENCES

Microstructure and Mechanical Properties of Magnesium Alloy AZ31 Processed by Compound Channel Extrusion

1199–1207.