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Recrystallization behaviour of fine-grained magnesium alloy after hot deformation

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Abstract: Annealing behaviors of hot-deformed magnesium alloy AZ31 were studied at temperatures from 300 to 673 K by optical and SEM/EBSD metallographic observation. Temperature dependence of the average grain size(D) is categorized into three temperature regions, i.e. an incubation period for grain growth, rapid grain coarsening, and normal grain growth. The number of fine grains per unit area, however, is reduced remarkably even in incubation period. This leads to grain coarsening taking place continuously in the whole temperature regions. In contrast, the deformation texture scarcely changes even after full annealing at high temperatures. It is concluded that the annealing processes operating in hot-deformed magnesium alloy with continuous dynamic recrystallized grain structures can be mainly controlled by grain coarsening accompanied with no texture change, that is, continuous static recrystallization.

Key words: fine-grained magnesium alloy; annealing; continuous recrystallization; grain growth; texture

1 Introduction

Magnesium(Mg) is one of the lightest metals in practical use and is of growing interest because of its high specific strength and excellent technological properties[1]. Mg alloys show generally low cold-workability because of a few slip systems in the HCP lattice. One of possible methods breaking through the low ductility is to develop fine-grained structures in Mg alloys. Grain refinement could improve not only the plastic workability, but also the strength at ambient temperature [2-3]. Recently, severe plastic deformation by using equal channel angular extrusion[4-5], multi-directional forging(MDF)[6-7] etc. has been carried out on the Mg alloys to develop a fine-grained structure. The authors have studied thermo-mechanical processes and developed fine-grained structures with the grain size in submicrons by using MDF under decreasing temperature conditions and succeeded much improvement of the plastic workability and mechanical properties[8-10]. The texture control will also be important for increasing the ductility of deformed Mg alloys[11], because, for example, the basal plane becomes perpendicular to the forging direction in high strain during hot deformation[12]. Further improvement of the ductility of deformed Mg alloys can be obtained through the texture control. There have been a few reports on the annealing behaviors of fine-grained Mg alloys[13]. The annealing characteristics and the texture changes in a widely used Mg alloy, e.g. AZ31, have been almost unknown, as far as the authors know.

The present work aimed to investigate the annealing characteristic of a Mg alloy AZ31 after hot deformation. The structural changes during hot deformation and subsequent isochronal annealing were systematically studied at various reheating temperatures. Changes in the grain structure and the texture developed during and after hot deformation were analyzed in detail, and the mechanisms of annealing process were also discussed.

2 Experimental

The alloy used in this study was a commercial magnesium alloy, AZ31 (Al 2.68, Zn 0.75, Mn 0.68, Cu 0.001, Si 0.003, Fe 0.003, and balance Mg, in mass fraction, %). Cylindrical samples of 8 mm in diameter and 12 mm in height were machined from the rod

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parallel to the extrusion direction. The samples were annealed at 733 K for 2 h and then furnace cooled, leading to the evolution of equiaxed grains with an average size of $22 \ \mu m$.

Compression tests were carried out at constant true strain rates on a testing machine equipped with a water quenching apparatus, which made it possible to quench the samples within 1.5 s after deformation. The samples were deformed up to strains of 1.2 at 573 K and at true strain rates of 3×10^{-3} s⁻¹, followed by quenching in water. They were cut into plates with 2–3 mm in thickness parallel to the compression axis, and then annealed for 1 ks at temperatures ranging from 300 K to 673 K. Each plate was mechanically and electrolytically polished and then etched in a solution of 6% picric acid and 94% methanol. The microscructures were examined by using optical microscopy(OM) and orientation imaging microscopy(OIM). Crystallographical orientation and texture changes were examined by SEM/OIM.

3 Results and discussion

3.1 Optical microstructures

Fig.1 shows the microstructures evolved before and after annealing at various temperatures. It is seen that fine grains are not fully developed throughout the material even after deformation to ε =1.2 at 573 K (Fig.1(a)).

Upon annealing at $T \ge 473$ K, such strain induces fine grains to coarsen homogeneously with increase in reheating temperature. When $T \le 493$ K, some rather coarse grains still remain and are clearly distinguishable from surrounding fine grains (Fig.1(b)). After annealing at $T \ge 493$ K (Figs.1(c) and (d)), it is difficult to distinguish the coarse grains from the surrounding ones that coarsen homogeneously, finally leading to a fully development of an almost equiaxed grain structure.

3.2 Quantitative analysis of microstructures

Typical grain size distributions before and after annealing at 373–573 K are shown in Fig.2. The distribution at 373 K is almost similar to that for as-deformed state and shows a bimodal shape with two peaks at around 2 µm and 20 µm. The fine grains correspond to those newly developed by hot deformation and the coarser ones to the remained original grains. Upon annealing at $T \ge 473$ K, the relative frequency of fine grains rapidly decreases and the range of coarse grain sizes gradually increases with increase in temperature. With further annealing at $T \ge 573$ K, the grain size distribution is similar to a log-normal type with a single peak at around 15 µm (Fig.2(d)).

Fig.3 shows the changes in the average grain size (D) and the number of fine grains per unit area, N, less than 10 µm in diameter, with annealing temperature. D is hardly changed during annealing at T < 473 K. D increases rapidly at 473–523 K and then increases slowly with rising temperature. Such a grain size change looks like that occurring in conventional deformed cubic metals during annealing[14–15]. The annealing stage 1 may correspond to an incubation region for recrystallization and stages 2 and 3 the regions for recrystallization



Fig.1 Microstructures developed in AZ31 alloy deformed to ε = 1.2 at 573 K (a), followed by annealing for 1 ks at 473 K (b), 493 K (c) and 573 K (d)



Fig.2 Changes in grain size distribution of AZ31 alloy with annealing temperature: (a) As-deformed; (b) 373 K; (c) 473 K; (d) 573 K



Fig.3 Changes in average grain size and number of fine grains per unit area less than 10 μ m in diameter with annealing temperature

and normal grain growth, respectively. On the other hand, it is remarkable to note that N decreases clearly even at stage 1. This is in contrast with the result of the average grain size in Fig.3(a), i.e. there is no remarkable grain coarsening in this stage. It is concluded that grain growth starts to take place mainly in the fine-grained regions simultaneously just after annealing even at stage 1. Further annealing in the stage 2 leads to a rapid grain coarsening accompanied by a rapid decrease in N. Then the grain size distribution changes from a double peak to a single peak type, as shown in Fig.2(d). During annealing at stage 3, the average grain size gradually increases accompanied with a little decrease in N, suggesting the occurrence of normal grain growth.

Fig.4 shows the changes in the inverse pole figures for compression direction. It is remarkable to note that hot-deformed sample has a strong texture, in which the basal (0001) plane of the HCP lattice lies perpendicular to the compression axis (Fig.4(a)). Such basal texture exists stably even after full annealing at high temperatures (Figs.4(b) and 4(c)). It is concluded that strain-induced fine grains evolved in Mg alloys can grow remarkably and, in contrast, the deformation texture is scarcely changed with annealing.



Fig.4 Changes in inverse pole figures with annealing temperature deformed to ε =1.2 at 573 K (a), followed by annealing for 1 ks at 473 K (b) and 673 K (c)

Such annealing behaviors are in contrast with those for conventional deformed cubic metals, in which discontinuous recrystallization takes place accompanied with nucleation of new grains and their long range grain boundary migration. It is concluded, therefore, that annealing processes operating in hot-deformed Mg alloy are controlled mainly by grain coarsening accompanied with no texture change, that is, continuous static recrystallization(cSRX). It is interesting to note that dynamic evolution of new grains in Mg alloys results from continuous dynamic recrystallization(DRX) taking place during hot deformation[12] and continuous static recrystallization can subsequently operate in cDRXed grain structure during annealing.

4 Conclusions

1) A bimodal distribution of grain size in as-deformed AZ31 alloy changes to a single peak type after rapid grain coarsening taking place from medium to high temperature.

2) Temperature dependence of the grain size is categorized into three regions, i.e. an incubation period of grain growth, rapid grain coarsening and normal grain growth.

3) The number of fine grains per unit area, however, is reduced remarkably, which leads to continuous grain coarsening in the whole temperature regions.

4) The deformation texture with the basal plane (0001) perpendicular to the compression axis can exist stably at high temperature and so scarcely change even after full annealing.

5) The annealing processes operated in fine-grained Mg alloy are controlled mainly by grain growth accompanied with no texture change, that is continuous static recrystallization.

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