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Grain Refinement in Magnesium Alloy AZ31 during Hot Deformation

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Abstract. The deformation behavior and structure changes of magnesium alloy AZ31 were studied in compression at temperatures ranging from 523K to 673K and at a strain rate of 3×10^{-3} s^{-1}. They depend sensitively on deformation temperature. At high temperatures, grain fragmentation takes place due to frequent formation of kink bands initially at corrugated grain boundaries and then in grain interiors, followed by full development of new grains in high strain. At lower temperatures, in contrast, twinning takes place in rather coarse grains and kink bands are formed mainly in finer original ones in low strain. It is concluded that new grain evolution can be controlled by a deformation-induced continuous reaction resulting in grain fragmentation by kink bands, i.e. continuous dynamic recrystallization (cDRX). The latter is discussed comparing with conventional, i.e. discontinuous, DRX.

Introduction

Magnesium alloys have the lowest density among the commercially available structural metals and the several excellent specific properties [1]. However, they show generally low ductility because of few slip systems in hexagonal close-packed (HCP) lattice and so are categorized as hard plastic materials. On the other hand, it is widely accepted [2,3] that grain refinement may significantly improve the plastic workability of Mg alloys. For this reason, fine grain evolution and superplasticity in Mg alloys have been studied extensively. It has been reported in Mg alloys [4,5] that fine grain evolution may be result from continuous DRX including twinning DRX and rotation DRX at ambient to moderate temperatures, while conventional (i.e. discontinuous) DRX, including a nucleation of new grains and their large-scale growth, takes place during hot deformation. The reasons why the DRX mechanisms are changed by deformation condition and the mechanisms themselves are not fully understood.

The present work was aimed to study the effect of temperature on hot deformation and recrystallization process taking place in Mg alloy during hot deformation. The progress of new grain evolution was systematically investigated by using OIM measurements. The mechanisms of new grain evolution were discussed in detail.

Experimental Procedure

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, by mass%). The cylindrical samples of 8 mm in diameter and 12mm in height were prepared from the extruded rod parallel to extrusion direction. The samples, annealed at 733 K for 21.6 ks and then furnace cooled, had an equiaxed grain structure with an average grain size of about 90 μm.

Compression tests were carried out at constant true strain rates on a testing machine equipped with a water quenching apparatus to freeze instantaneous deformation structures. The samples

were deformed at temperatures ranging from 523K to 673K and mainly at a strain rate of 3 x 10^{-3} s^{-1}, followed by water quenching. Longitudinal section of deformed sample was mechanically polished and electropolished in a solution of nitric acid, glycerol and ethanol with a 1:3:6 volume ratio. The metallographic analysis was carried out using optical microscopy and scanning electron microscopy in corporate an orientation imaging microscopy (OIM) system.

Experimental Results and Discussion

Deformation Behaviors. Figure 1 shows a series of typical true stress-true strain (σ-ε) curves tested at 3 x 10^{-3} s^{-1} under various temperatures. The flow curves at high temperature show strain hardening and a single stress peak in relatively low strain, followed by strain softening and stead-state flow in high strain. It is remarkable to note in Fig. 1 that the shape of the flow curve at 573K is different from those at high temperature, i.e. a sharper peak stress following rapid strain hardening and then significant work softening. This suggests that deformation and structural mechanisms operating depend sensitively on temperature.

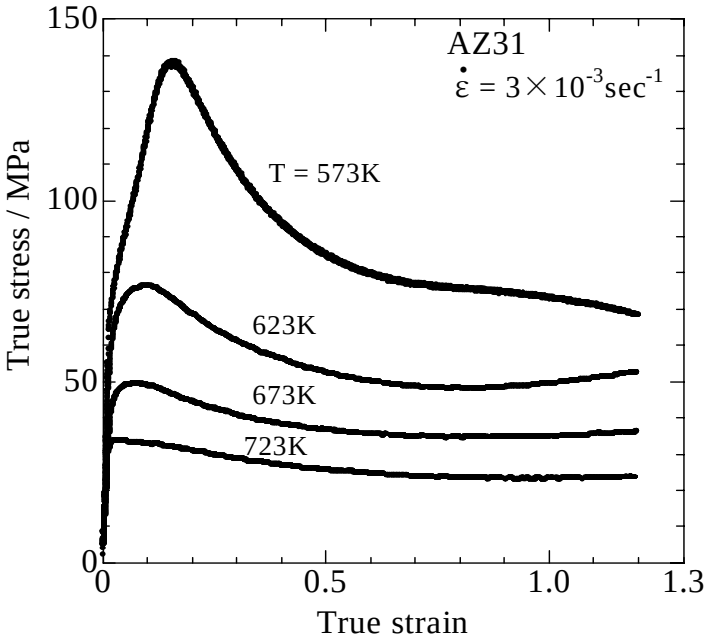

Fig. 1 Typical true stress-true strain curves of AZ31 alloy deformed at 3 x $10^{-3}s^{-1}$ and at various temperatures.

Optical microstructures. Typical microstructures developed during deformation at 573K and 673K are shown in Fig. 2. During deformation at 573K, twins are evolved frequently in grain interiors (Fig. 2a) accompanied with new grain formation along corrugated grain boundaries in low strain (Fig. 2c), where a sharp stress peak following rapid strain hardening appears (Fig. 1). New fine grains are not fully developed throughout the whole microstructure even at high strain (Fig. 2e). At 673K, in contrast, deformation bands, called as kink bands [6,7] or transition bands indicated by T, are evolved roughly perpendicular to the compression axis in some grain interiors and fine grains are developed in colony along corrugated grain boundaries and at triple junctions (Figs. 2b and 2d). Further straining to around 0.8 leads to almost full evolution of new grains with an average size of 8 μm, as shown in Fig. 2f.

OIM Observations. Fig. 3 shows a series of OIM micrographs for the exactly same place of a specimen deformed to strains of 0.06 and 0.11 at 523K. Orientation difference (θ) between neighboring grid points, $\theta > 2^\circ$, $\theta > 15^\circ$ are delineated by thin and bold black lines, and $\{10\bar{1}2\}$ twin boundaries are by bold white lines, respectively. It can be clearly seen in Fig. 3 that deformation twins are evolved in grain interiors accompanied with the orientation rotation toward <0001> direction. The basal planes became, therefore, perpendicular to the compression axis. It can be seen here that $\{10\bar{1}2\}$ twins are frequently developed at around $\pm45^\circ$ to the compression axis in coarse grain interiors and some of them continuously grow in their transverse direction (Fig. 3a). With further straining to ε = 0.11 (Fig. 3b), they continue to grow until impingement and finally most of the original grains are replaced by twinned grains at around a peak strain. The boundaries between twins and their neighbors disappear during progress of twinning. It should be noted, therefore, that twinning does not contribute to any grain fragmentation, which will be described below.

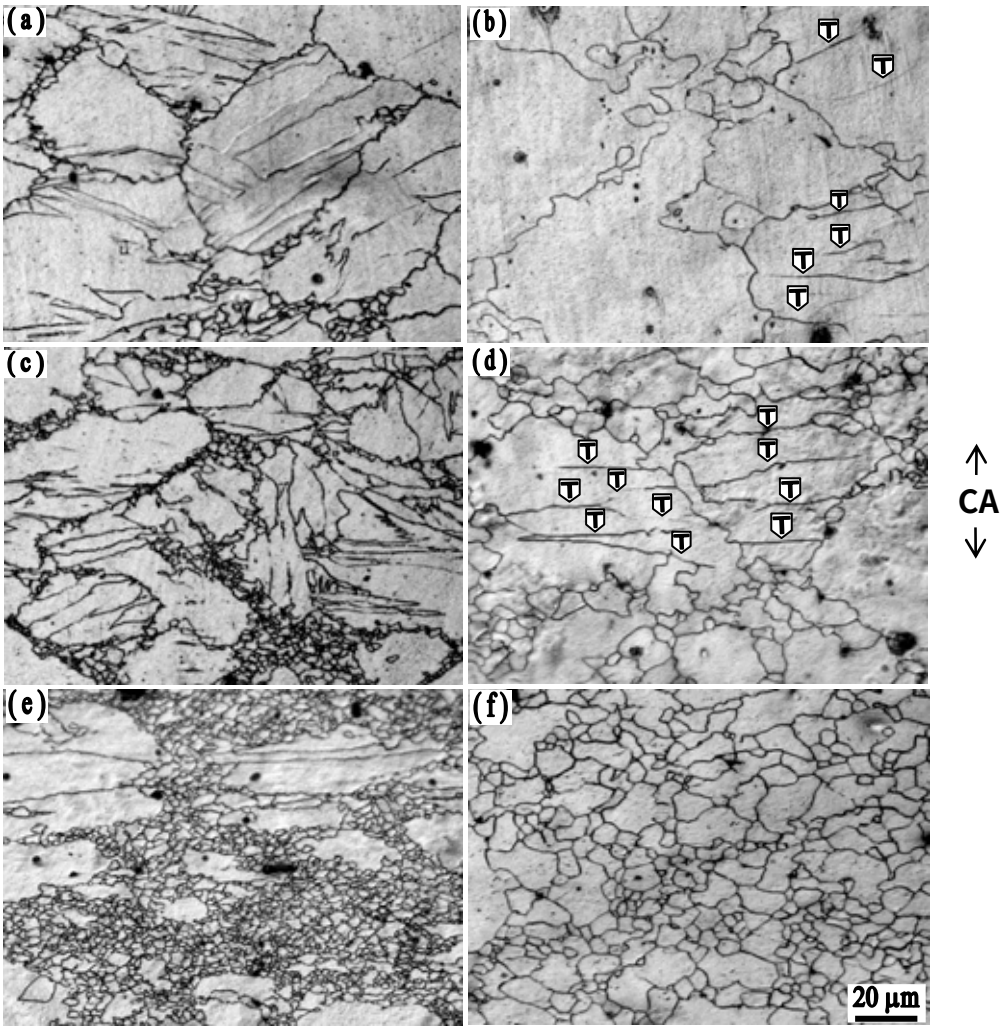

Fig. 2 Optical microstructures of AZ31 alloy deformed to various strains at 573 K (a, c, e) and 673K (b, d, f) and at 3 x $10^{-3}s^{-1}$, followed by water quenching. T represents the boundaries of kink band. (a), (b) ε = 0.15, (c), (d) ε = 0.3, (e), (f) ε = 0.8.

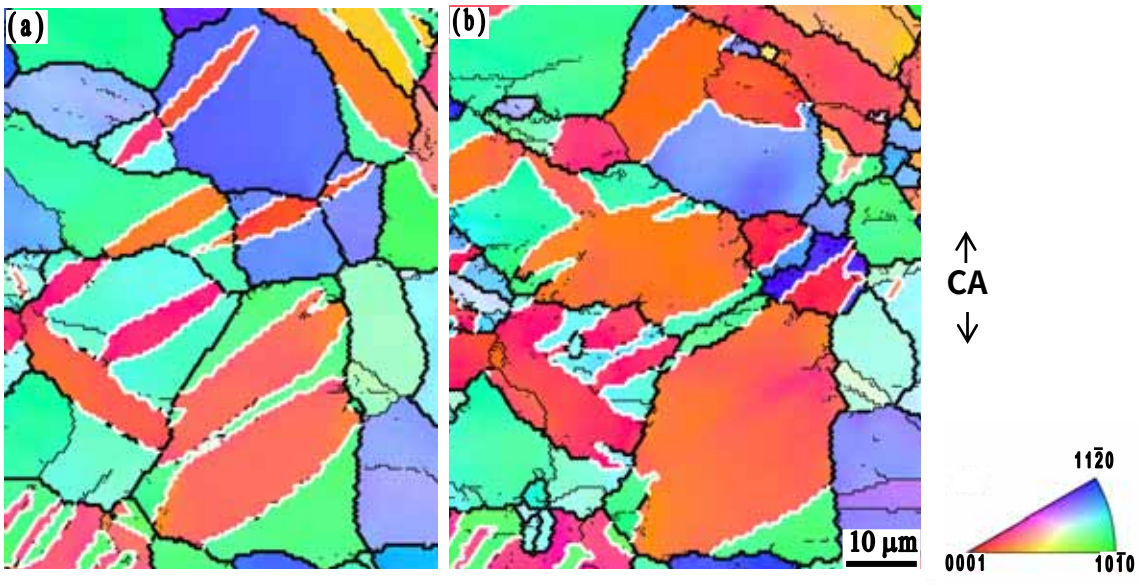

Fig. 3 OIM maps for the same place of AZ31 alloy deformed to various strains at 523K and at 3 x 10^{-3} s^{-1}. (a) ε = 0.06, (b) ε = 0.11

In contrast, no twins were developed even at ε = 0.15 at 673K, as shown in Fig. 4a. The grain boundaries are frequently serrated and several dislocation boundaries with low to medium angle misorientations are frequently developed in grain interiors. These boundaries are considered to correspond exactly to those of the kink bands in Figs. 2b and 2d. It should be added that the average grain size newly evolved is similar to minimum spacing of the kink bands in Fig. 4. Namely, there are quite few extra places for long distance growth of each DRX grain. It has been discussed in detail in elsewhere [7-9] that further deformation to moderate strains leads to increase in the misorientaion angle and the number of kink bands. The regions fragmented by kink bands are bounded by high angle boundaries in high strain, finally resulting in evolution *in-situ* of new grains assisted by dynamic recovery and also grain boundary sliding [7]. These results in the Mg alloy are, however, not the same as those of conventional DRX taking place in not only Mg alloy [4,5], but also cubic metals [10].

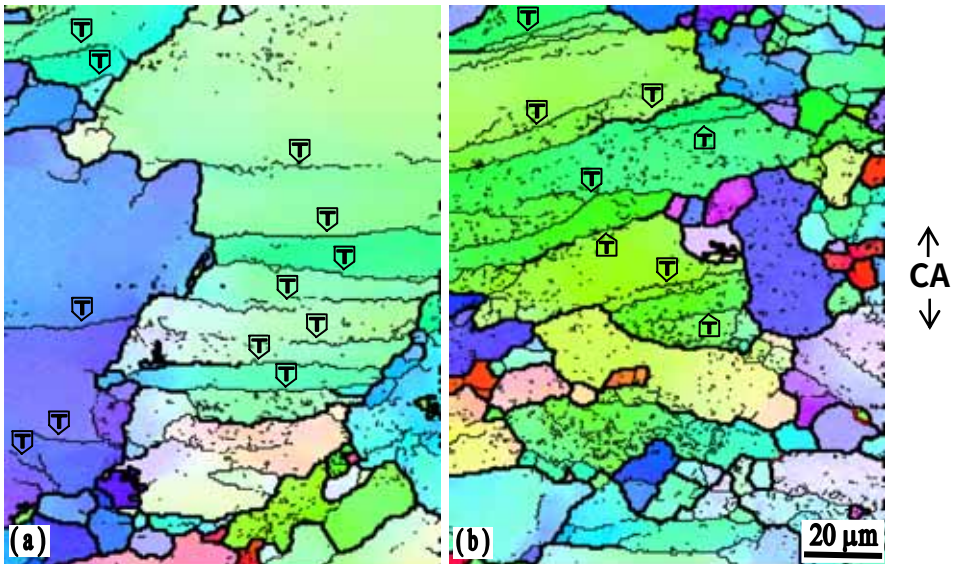

Fig. 4 Typical OIM maps of AZ31 alloy deformed to various strains at 673K and at 3 x 10^{-3} s^{-1}. (a) ε = 0.15, (b) ε = 0.3.

Quantitative Analysis of Microstructures. Fig. 5 shows strain dependence of the misorientation distribution of the boundaries of (sub)grain, twinning and kink band evolved at 573K. The distribution was measured in a unit area of 80 x 80 μm, which is smaller then the initial grain size. It is seen in Fig. 5a that most boundaries developed at ε = 0.06 exhibit twin relationship of 87°<1$\bar{2}$10>, although a small fraction of low angle boundaries is detected. The latter should be related to those of kink bands and/or deformation bands. With further deformation, the fraction of twinned boundaries rapidly decreases and, in contrast, that of medium to high angle ones increases (Figs. 5b and 5c). Finally the distribution changes from bimodal shape to a single peak type with an average misorientation of 25 ° in high strain (Fig. 5d).

Fig. 6 shows strain dependence of the average misorientation (θ_{av}) in Fig. 5 and the volume fraction of new grains (X_v) for the Mg alloy deformed at 573K and 673K. θ_{av} was evaluated only in the regions of new fine grains and also excluded the θ of twin boundaries. θ_{av} start to increase before a peak strain and rise rapidly during work softening, finally approaching a saturation value, which depends on temperature. X_v was measured from Fig.2. X_v also start to increase at around a peak strain and then increase gradually with deformation within the strain range investigated. Such behaviors of θ_{av} and X_v are considered to correspond to the shape of the flow curve and the development of an equiaxed new grain structure in high strain.

The kinetics of new grain evolution is lowered by temperature drop as usual. This retardation is considered to be due to not only decrease in temperature, but also a different deformation

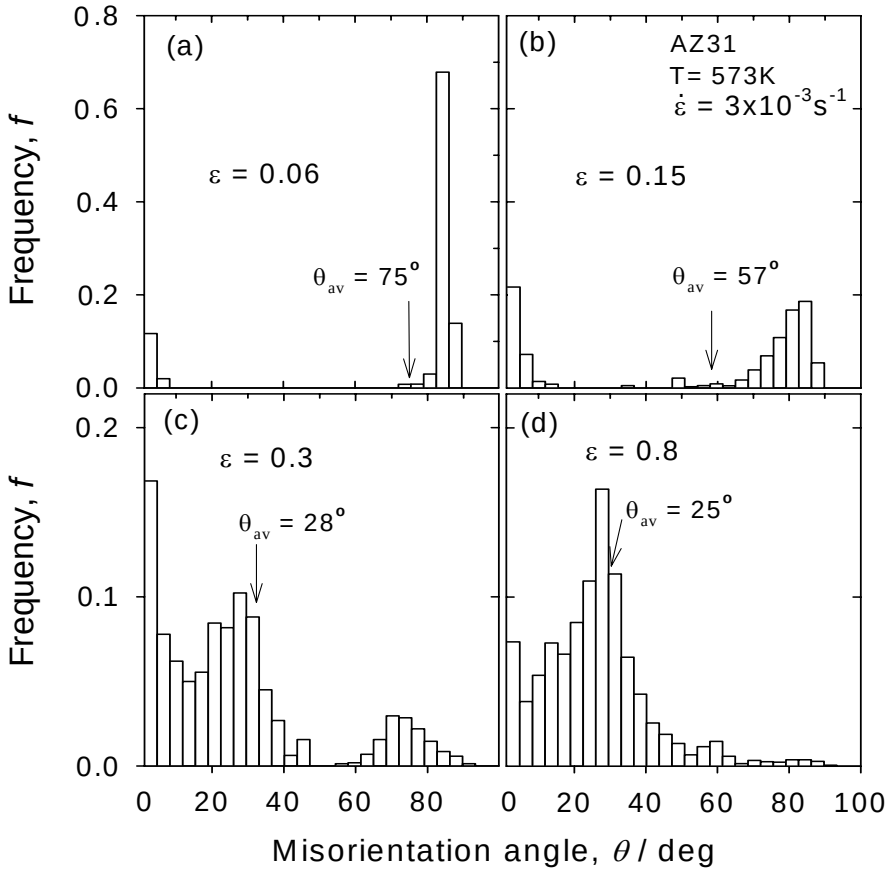

Fig. 5 Changes in the misorientation distributions of dislocation and (sub)grain boundaries developed in an unit area of 80 x 80 μm, which is roughly within an initial grain interior.

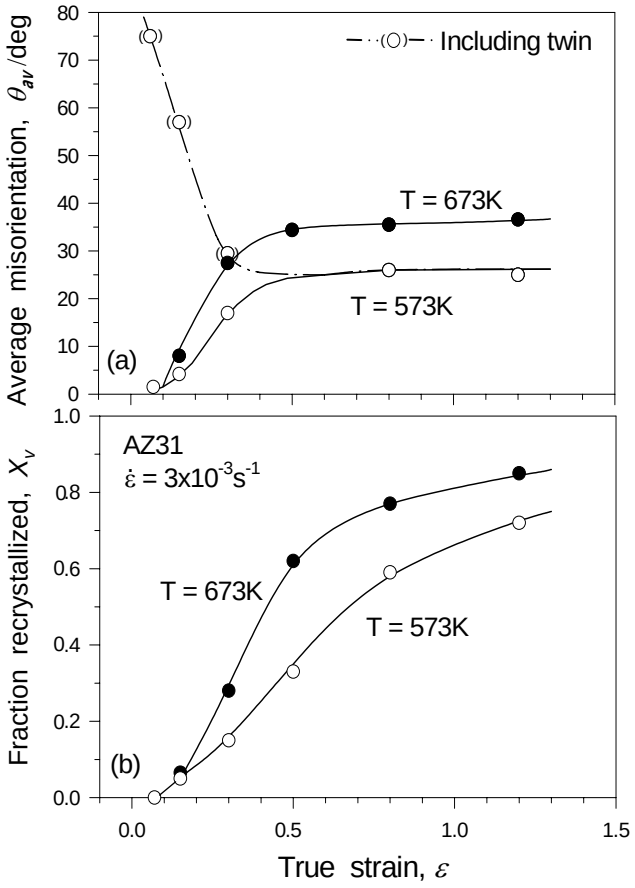

Fig.6 Strain dependence of (a) the average misorientation of dislocation and (sub)grain boundaries, θ_{av}, and (b) the volume fraction dynamically recrystallized, X_v, of AZ31 alloy deformed at 573K and 673K and at 3 x $10^{-3}s^{-1}$.

mechanism operating at lower temperature, i.e. twinning. Kink bands followed by new grains are scarcely developed in the twinned grain interiors. It is obvious that new grains are not fully developed even under a steady state flow. Such a result has not been reported in conventional DRX of cubic metals [11,12]. When original grains are surrounded by fine grains, kink bands may be hardly developed in the remained original grains, because constrained deformation by surrounding grains can be relaxed by operation of grain boundary sliding and dynamic recovery in the surrounding fine grained region. It can be concluded, therefore, that evolution of new grains in the present Mg alloy can result from a series of deformation-induced continuous reactions, that is essentially similar to continuous DRX.

Summary

Dynamic grain refinement taking place in an AZ31 Mg alloy was studied in compression at 523K-673K and at 3×10^{-3} s^{-1}. The main results are summarized as follows.

(1) The deformation behaviors depend clearly on temperature. The curve at lower temperature region shows a rapid strain hardening followed by a significant work softening.
(2) Lower temperature deformation leads to twin evolved frequently in coarse grain interiors accompanied with rapid strain hardening.
(3) At higher temperature, kink bands are evolved first at grain boundaries and then in grain interiors at relatively low strains. The misorientation and the number of boundaries of kink band rapidly increase with deformation, finally followed by the evolution *in-situ* of new grains with high angle boundaries in high strain.
(4) Grain refinement taking place during warm or hot deformation results from a series of deformation-induced continuous reactions, that is essentially similar to continuous dynamic recrystallization.

Acknowledgments

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