Non-Basal Slip in Magnesium-Lithium Alloy Single Crystals*

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Magnesium-lithium single crystals were stretched in the $[11\bar{2}0]$ direction to investigate the deformation behavior by non-basal slip. $\{11\bar{2}2\}\{1\bar{1}23\}$ second order pyramidal slip is activated in magnesium -3.5 at%, -7.5 at% and -10.6 at% lithium alloy single crystals, and its yield stress shows anomalous temperature dependence in the range from 77 K to 293 K. The yield stress due to the pyramidal slip decreases with addition of lithium. The deformation mode due to the pyramidal slip is investigated by the observation of slip bands. Narrow slip bands are formed at lower temperature just after yielding. The width of slip bands at yielding increases continuously with increasing temperature and covers the whole specimen surface at 293 K. The results of the observation by TEM showed that double cross slip of $(c+a)$ screw dislocations occur more frequently during deformation at 293 K than at 133 K. Many a and c edge dislocations are also observed in the crystals deformed at 293 K. The deformation mechanism of magnesium-lithium alloy is similar to that of cadmium.

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1. Introduction

It is important to understand the deformation mechanism of yielding and workhardening in metals to improve their plasticity. The deformation by slip in fcc and bcc metals has been studied in detail with experimental and theoretical approaches. In the case of hcp metals, such as magnesium, while their engineering importance has been risen recently, many fundamental problems remain open; *e.g.* identification of active slip systems, temperature and strain rate dependence of the flow stress and the influence of additional elements.

In hcp metals, (0001) basal slip and $(10\bar{1}0)$ prismatic slip systems are well known, but the total number of these independent slip systems is four. According to the von Mises requirement,¹⁾ another non-basal slip systems must be activated to deform the poly-crystalline materials. It has been reported that $\{11\bar{2}2\}\{1\bar{1}23\}$ second order pyramidal slip is activated in magnesium single crystals.^{2,3)} In that case the yield stress due to second order pyramidal slip shows anomalous or positive temperature dependence, and the yield stress at 293 K is more than one hundred times higher than that of basal slip. To improve plasticity of magnesium, it is necessary to increase the activity of such non-basal slip systems. In the present work, plastic deformation behavior due to the non-basal slip systems in magnesium-lithium single crystal is investigated.

2. Experimental Method

Three kinds of magnesium-lithium alloys, Mg-3.5 at%Li, -7.5 at%Li and -10.6 at%Li, are prepared from 99.9 mass% magnesium and 99 mass% lithium ingot. Two types of single crystals with different orientation were prepared from pure magnesium and above three kinds of magnesium-lithium alloys using the Bridgeman technique. Each single crystal has the thickness of 0.3, width of 3 and length of 30 mm, re-

Fig. 1 Orientation of A- and B-specimen relative to hcp unit cell. Second order pyramidal planes are hatched.

spectively. The geometrical directions of A-specimen and B-specimen are shown relative to the hcp unit cell in Fig. 1. The wide and narrow surfaces of A-specimen were parallel to (0001) and $(10\bar{1}0)$ crystal surfaces, and those of B-specimen were parallel to $(10\bar{1}0)$ and (0001) surfaces, respectively. Both tensile axes of A- and B-specimen were parallel to the $[11\bar{2}0]$ direction.

The specimens were annealed for 8 cycles in the range between 673 K and 723 K with a periodic time of 21.6 ks. Surface of each specimens were polished by the chemical solution ($C_2H_5OH : H_2O_2 : HNO_3 = 20 : 7 : 5$). These specimens were stretched with an Instron type tensile test machine in the temperature range from 77 K to 293 K at shear strain rates $\dot{\gamma} = 1.0 \times 10^{-4} s^{-1}$. Slip traces on surfaces of A- and B-specimens were observed with a Nomarsky type optical microscopy and dislocations in B-specimens were observed with a transmission microscopy (JEOL-2000FX).

3. Results

Typical stress-strain curves of each alloy single crystals are shown in Fig. 2. The stress arrow-marked in the figure indicates the yield stress. Each curve after yielding has small

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Fig. 2 Typical normal stress-strain curves of Mg-Li alloys.

serrated region. In all alloys, flow stress increased with increasing temperature.

The temperature dependence of yield stress is shown in Fig. 3. The yield stress of three type of magnesium-lithium alloys increase with increasing temperature and shows anomalous temperature dependence in the range from 77 to 293 K. The solid line indicates the temperature dependence of yield stress in pure magnesium³⁾ as a reference. It is found that the yield stress decreases with addition of lithium and the yield stress of Mg-7.5 at%Li is about a half of that of pure magnesium. There is no difference in yields stress for A- and B-specimen in all alloys. The scatter in the stress values in Fig. 3 will be caused by the scatter of specimen size and shape. Since magnesium single crystals are easy to deform by basal slip, chemical polishing and sizing must be employed to avoid damages. Therefore, it is very difficult to make the size and the shape of each specimens uniformly with chemical polishing.

Figure 4 shows fine slip lines observed on a (0001) surface of Mg-3.5 at%Li A-specimens at 77 and 293 K. Both of the slip lines are perpendicular to the $[11\bar{2}0]$ tensile axis. Slip lines on a $(10\bar{1}0)$ surface of B-specimens are not observed. From these results the slip lines shown in Fig. 4 are corresponding to $\{11\bar{2}2\}\{11\bar{2}3\}$ second order pyramidal slip. These slip lines form narrow slip bands at 77 K, and the width of the slip bands at yielding becomes wider with increasing test temperature. At 293 K, shown in Fig. 4(b), slip lines are observed whole of (0001) surface after yielding. Figure 5 shows slip lines of Mg-10.6 at%Li. Slip lines of pyramidal slip became coarser than the case of Mg-3.5 at%Li.

It is also observed that the width of slip band formed at yielding becomes wider with applying strain. This result in-

Fig. 3 Temperature dependence of yield stress due to second order pyramidal slip.

Fig. 4 Slip bands due to secondary pyramidal slip observed on the (0001) surface of Mg-3.5 at%Li.

icates that the slip propagates to the next slip planes with increasing strain after yielding. This propagation of slip corresponds to small serrated region of stress-strain curves. This deformation mode is also observed in Mg-7.5 at%Li and -10.6 at%Li alloys. In this work, specimens are yield due to second order pyramidal slip and other type of slip lines were not found.

Figure 6 shows dislocations observed by transmission microscopy in Mg-7.5 at%Li B-specimens tested at 133 and 293 K. Figs. 6(a) and (b) show dislocation contrasts in 0002 and $11\bar{2}0$ diffraction, respectively. In hcp crystals, there are three type of perfect dislocations with Burgers vector, a , c and $(c + a)$. From relationship with $g \cdot b = 0$ (g : reciprocal lattice vector, b : Burgers vector) a and c dislocations

Fig. 5 Slip bands due to secondary pyramidal slip observed on the (0001) surface of Mg-10.6 at%Li.

Fig. 6 Long $(c+a)$ screw dislocations and short a and c edge dislocations observed in Mg-7.5 at%Li. (a) and (c) is 0002 diffraction and (b) and (d) is 1120 diffraction.

show contrast only in $11\bar{2}0$ and 0002 diffractions, respectively, and $(c+a)$ dislocations are found in both diffractions. Long bowed $(c+a)$ screw dislocations and short c edge dislocations are shown in Fig. 6(a) and a edge dislocations are shown in Fig. 6(b). At 293 K, shown in Figs. 6(c) and (d), there are many c dislocations and $(c+a)$ screw dislocations with many steps than the case of 133 K.

It is obviously found that a and c dislocations are not activated in $[11\bar{2}0]$ tensile. Moreover, $(c+a)$ screw dislocations are observed in conjunction with a and c dislocations. These results indicate that $(c+a)$ edge dislocation is unstable and it

decomposes into a and c dislocations in magnesium-lithium alloys. c dislocations do not move in hcp crystals, therefore, $(c+a)$ edge dislocation becomes immobile. Because of the result that these c and a dislocations are more frequently observed in specimens tested at 293 K than at 133 K, this decomposition process seems to be thermal activation process.

To investigate effects of lithium addition, c/a ratio of Mg-7.5 at%Li alloy which shows lowest yield stress among three alloys was estimated from $(10\bar{1}0)$ diffraction pattern, c/a ratio of this alloy is 1.556 and this is smaller than pure magnesium 1.623.

4. Discussion

From above results, deformation modes by second order pyramidal slip in magnesium-lithium alloy single crystals are similar to that in cadmium.⁴⁾ Therefore, the deformation process by the pyramidal slip will be suggested as follows.

A dislocation source on $(11\bar{2}2)$ slip plane produced $(c+a)$ dislocation loops. $(c+a)$ edge of the loop move some distance and then stopped because of thermally activated immobilization, such as decomposition of $(c+a)$ to c and a . Because of this immobilization, the strain on the slip plane is suppressed with increasing temperature. To accept strain at a strain rate which is imposed by a tensile test machine, the activation of new sources on the other slip planes is needed. Then, a number of new dislocation must be nucleated and activated onto next slip planes by double cross slip of $(c+a)$ screw dislocations. The growth of slip bands which found by observations of slip bands and $(c+a)$ screw dislocation with many steps are the evidence of double cross slip of screw dislocations. In the higher temperature range, immobilization of $(c+a)$ edge dislocation becomes more frequently, then the growth velocity of slip bands increases due to the assistance of an increasing applied stress. Therefore, the yield stress of the pyramidal slip increase with increasing temperature.

There are two passible reasons for decreasing yield stress by lithium addition. One is suppressing the immobilization process and the other is emphasizing activation of double cross slip process. Coarse slip lines observed in the high lithium content alloy, shown in Fig. 5, indicate that dislocations move more long distance and the strain on each slip planes became larger than that of the pure magnesium, therefore, the former will be supported.

We already reported the core structure of $(c+a)$ edge dislocation by molecular dynamics simulation.⁵⁾ $(c+a)$ edge have two type of core structure, one is a perfect dislocation with extended core to a basal plane (Type A) and the other is consist of two partial dislocations (Type B). The core extension to a basal plane in Type A is small at 0 K, then the core change to Type B easily by applying stress and it move on $(11\bar{2}2)$ slip plane. At 293 K, the Type A core extends larger than the case of 0 K and does not move by applying stress. If the core structure of $(c+a)$ edge dislocation becomes a core with small extension core on basal plane by the change of c/a ratio due to lithium addition, the immobilization process is suppressed and the yield stress will decrease.

However, the yield stress of Mg-10.6 at%Li is higher than that of Mg-7.5 at%Li. We suppose that the double cross slip

of $(c + a)$ screw dislocation become hard gradually by increasing lithium addition, the yield stress will turn to increase in the range from 7.5 to 10.6 at%Li. However, there is no evidence to clarify this behavior, now. It is necessary to investigate more detail about these behavior.

5. Conclusions

[11 $\bar{2}$ 0] tensile test was carried with magnesium–3.5, –7.5 and 10.6 at% lithium single crystals in the range from 77 to 293 K. Results are summarized as follows:

(1) $\{11\bar{2}2\}\langle\bar{1}\bar{1}23\rangle$ second order pyramidal slip is activated in all magnesium alloy in the range from 77 to 293 K.

(2) Yield stress due to second order pyramidal slip increases with increasing temperature from 77 to 293 K.

(3) Yield stress due to second order pyramidal slip in magnesium single crystal decreases by addition of lithium.

(4) The deformation process due to second order pyramidal slip in magnesium-lithium alloys is similar to that of cadmium.

(5) It is suggested that decreasing yield stress of magnesium single crystal by lithium addition causes immobilization of $(c + a)$ edge dislocation suppressed by the change of c/a ratio affects to the core structure of $(c + a)$ edge dislocation.

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