Deformation Behavior of Magnesium Single Crystal in c-axis Compression and a-axis Tension

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Abstract. In general, deformation behavior of magnesium in compression is different from tensile. To investigate deformation behavior of magnesium single crystals by non-basal slips and twins, c-axis compression and a-axis tension tests were performed in the range of 77K-573K. The crystals were yielded by second order pyramidal slip, and the yield stress shows anomalous temperature dependence (increased with increasing temperature) between 203K and 293K. Yield stress of c-axis compression was bigger than that of a-axis tensile. In compression, fracture surface were $(11\bar{2}4)$ under 293K and were $\{30\bar{3}4\}$ above 373K, and fracture strain was smaller than the case of tension test. $\{10\bar{1}1\}$-$\{10\bar{1}2\}$ double twin were activated at higher temperature and the crystal, therefore, fractured along the twin interface.

Introduction

Recently, magnesium is interested as structured material because of its lowest density and high specific strength. However, it shows different deformation behavior of tensile and compression in rolled magnesium [1,2]. For this anisotropy, some problems occur in plastic forming. In magnesium, (0001) $<11\bar{2}0>$ basal slip is main slip system. However, von-Mises criterion cannot satisfy by the basal slip because it has only two independent slip systems. Therefore, non-basal slips and twins must occur in plastic deformation. In c-axis compression using magnesium single crystal [3-5], $\{11\bar{2}2\}<\bar{1}123>$ second order pyramidal (**c+a**) slip (SPCS) activated as non-basal slip and many kind of twins also occurred. We also reported that SPCS activated in a-axis tension under 293K[6]. In this study, detail deformation behavior after yielding was investigated.

Experimental Method

Magnesium single crystals were made by Bridgeman method from purity of 99.99% magnesium ingot. As shown in Fig.1, $[11\bar{2}0]$ (a-axis) tension and [0001] (c-axis) compression test specimens with (0001), $(10\bar{1}0)$ and $(1\bar{2}10)$ were prepared by chemical polish. The size of each specimen was 3x0.3x20 mm and 3×3×6 mm, respectively rectangular shape were made. These specimens were annealed for 8 cycles in the range between 673K and 723K with a periodic time of

Fig. 1 Shape and orientation of specimen.

21.6ks. Tension and compression test was carried in a temperature range from 77K to 573K at initial strain rates was 6.0×10^{-5}/s. After compression test, $(10\bar{1}0)$ and $(1\bar{2}10)$ surfaces of specimens were observed with a Nomarsky type optical microscopy and analyzed by EBSD method.
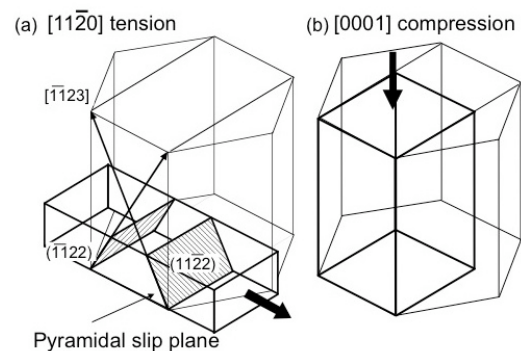
Results

Typical stress-strain curves of a-axis tension and c-axis compression are shown in Fig.2 and 3, respectively. Arrows in the figure indicate yield point and fracture point. In Fig.2, most of specimens were unloaded at about 1% strain before break to investigate deformation behavior. Under 293K, flow stress after yielding increased with increasing strain, while flow stress over 423K showed constant value. In case of c-axis compression, as shown in Fig.3, shape of stress-strain curves under 293K is similar to the case of a-axis tension. However, the specimen over 473K were fractured after yielding with small plastic strain.

Fig.2 Typical stress-strain curves in a-axis tensile.

Figure 4 shows temperature dependence of yield stress σ_y in tension and compression. σ_y between 133K and 293K shows anomalous temperature dependence, and σ_y over 293K decreased with increasing temperature. Fracture stress in c-axis compression σ_B above 293K was also plotted in the figure. σ_B were drastically decreased and were almost same as σ_y of compression over 473K.

Fig.3 Typical stress-strain curves in c-axis compression.

Typical slip lines observed on (0001) in a-axis tension are shown in Fig.5. Slip lines normal to [11$\bar{2}$0] on (0001) correspond to SPCS. Since such slip lines were observed in all temperature range in tension test, magnesium would be deformed mainly by SPCS in a-axis tensile.

Figure 6 shows slip lines on (1$\bar{2}$10) in c-axis compression. Slip lines inclined about 39° to basal plane were also observed on (10$\bar{1}$0). These slip lines correspond to SPCS

Fig.4 Temperature dependence of yield stress.

by slip trace analysis. This type of slip lines was observed at yielding in the range of 77K to 473K.

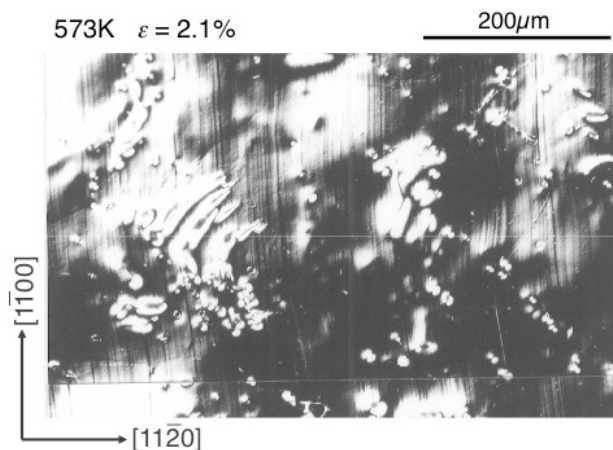Fig.5 Slip lines of second order pyramidal slip observed on a-axis tensile specimen.
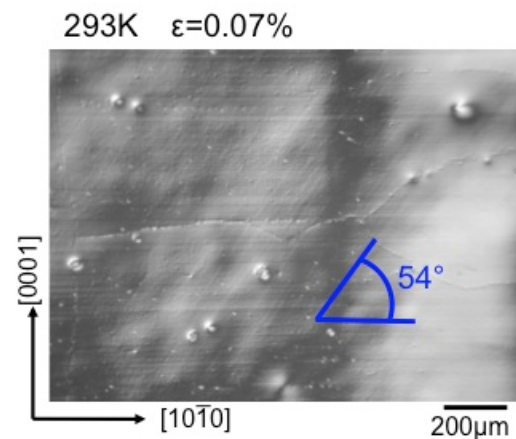

Fig.6 Slip lines of second order pyramidal slip observed on c-axis compression specimen.

Figure 7 shows fracture path of c-axis compression. At 293K, the specimen yielded and deformed by SPCS about 1% with small amount of twins. After that, as shown in Fig.7(a), the specimen fractured along {11$\bar{2}$4}. Specimens under 293K were fractured as same manner in 293K. In contrast, as shown in Fig.7(b), the specimen tested over 473K were fractured along near to {30$\bar{3}$4}. Moreover, fracture behavior over 473K was different on test specimens. In a specimen of which σ_B was larger than 80MPa, many fine twins were formed along fracture plane, as shown in Fig.7(b). However, there are no twins in a specimen fractured under 80MPa. In such case, a very narrow twin was formed before break.
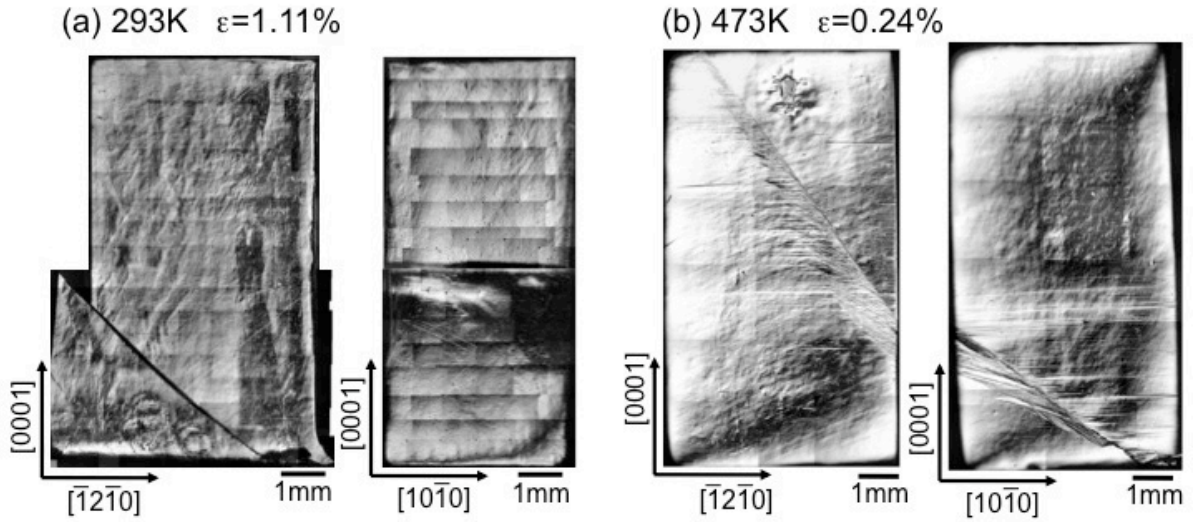

Fig. 7 Specimens fracture by c-axis compression at (a) 293K and (b) 473K.

Figure 8 shows a specimen yielded about 50MPa at 573K. A narrow twin inclined about 54° to [$\bar{1}$2$\bar{1}$0] was observed. IPF map by EBSD analysis (Fig.8(b)) indicates that a basal plane in the twin was rotated about 37° around [$\bar{2}$110]. Namely, the twin is {10$\bar{1}$1}-{10$\bar{1}$2} double twin[7]. This specimen fractured along this double twin with additional small strain.

Figure 9 shows a specimen yielded about 80MPa. A very narrow twin inclined about 54° and many fine twin inclined about 30° to [$\bar{1}$2$\bar{1}$0] were observed in Fig.9(a). By EBSD analysis, these twins were identified as {10$\bar{1}$1}-{10$\bar{1}$2} double twin and {10$\bar{1}$3} twin, respectively. This specimen was also fractured along the narrow double twin.

As shown in Fig.4, yield stress of a-axis tension and c-axis compression are different in spite of slip system at yielding same. To clarify the reason, effect of specimen size was examined at 293K. Figure 10 shows relation
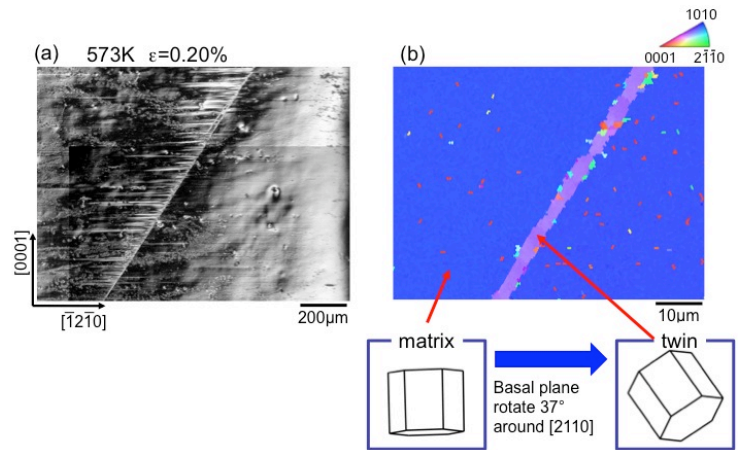

Fig. 8 (a) A narrow twin observed before break and (b) IPF map.
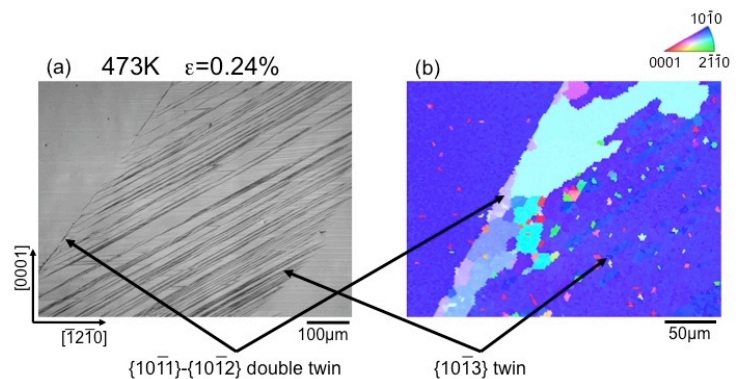

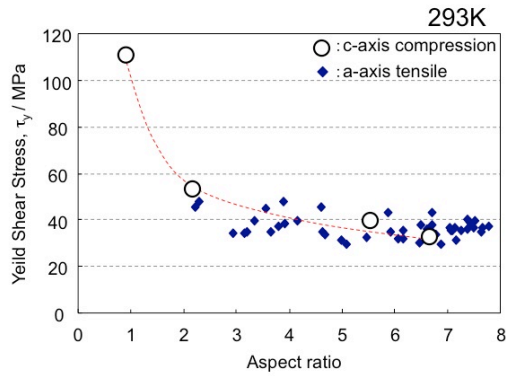Fig.9 (a) Fine twins formed near a narrow twin and (b) IPF map.

Fig. 10 Relation between aspect ratio of specimen and yield stress due to SPCS.

ship between aspect ratio (length / width of specimen) and shear yield stress of SPCS in tension and compression. The both yield stress decreased with increasing aspect ratio and both plots shows good agreement. This result indicates that yield stress in single crystal strongly depends on specimen size ratio and scarcely depends on loading direction.

Discussion

In pure magnesium single crystal, SPCS is main non-basal slip system in a-axis tension and c-axis compression. In this study, applying strain in tension test was limited under 1%, however, we already reported that the specimen elongated up to 3.5% at 293K [8]. In contrast, plastic strain in c-axis compression was under 1% and decreased with increasing temperature. As shown in Fig.7, fracture behavior over 473K was changed by activation $\{10\bar{1}1\}$-$\{10\bar{1}2\}$ double twin. Ando and Koike[9] discussed that the double twin will cause cracking in AZ31, because shear strain by $\{10\bar{1}1\}$ twin which active in c-axis compression cancels by $\{10\bar{1}2\}$ twin and then stress concentration would occur by slip within the twin. In this study, it is shown that a critical stress for the double twin have strongly temperature dependence and it becomes lower than the CRSS of SPCS over 473K, therefore, ductility in c-axis compress decreased at higher temperature.

Summary

Results of magnesium single crystals in a-axis tension and c-axis compression are summarized as follows: In a-axis tension, the crystal yielded due to $\{11\bar{2}2\}<\bar{1}\bar{1}23>$ second order pyramidal slip (SPCS) in the range from 77 to 573K. In c-axis compression, the crystal yielded due to SPCS in the range from 77 to 473K. Yield stress due to SPCS increased with increasing temperature from 133 to 293K and decreased over 293K. In c-axis compression, fracture surface in the range from 77 to 293K and over 473K were $\{11\bar{2}4\}$ and $\{30\bar{3}4\}$, respectively. Plastic strain in c-axis compression decreased with increasing temperature by increasing activity of $\{10\bar{1}1\}$-$\{10\bar{1}2\}$ double twin. Yield stress due to second order pyramidal slip strongly depended on aspect ratio of specimen.

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