A fundamental study of the high temperature deformation mechanisms of magnesium

Adrien Chapuis and Julian Driver
Ecole des Mines de Saint Etienne, Department of Material Science and Structures, UMR CNRS 5146, 158 Cours Faureil, 42023 Saint Etienne, France
driver@emse.fr

Abstract. Single crystals of Magnesium have been deformed in plane strain compression from room temperature to 450 °C. The deformed crystals have been analysed by EBSD to identify the operative twin variants and parent rotations for comparison with the expected systems. In parallel with these experiments, we have developed a crystal plasticity model based on Taylor principles and the Schmid law, to compute the activated systems together with the twin reorientations and the lattice rotations for large strains. The CRSS values are determined by an iterative procedure that best correlates the experimental data with the numerical simulations for each orientation. From the measured stress/strain data the CRSS for twinning and some slip systems are given over this wide temperature range.

1. Introduction
Since the 1960’s there have been very few basic studies of the fundamental mechanisms of plastic deformation in Mg despite their importance for controlling texture, anisotropy and ductility [1-3]. With the advent of modern EBSD it is now possible to follow local reorientations due to both slip and twinning and hence evaluate, with greater accuracy, their respective contributions to the crystal deformation. This paper describes a systematic study of the deformation of Mg crystals as a function of orientation and temperature using EBSD mapping.

Mg single crystals were compressed in a channel die at temperatures from 25 to 450°C. Overall, about 10 initial orientations have been studied, but here we limit the results to 3 significantly different cases. They correspond to the orientations (90 90 30) in which tensile twinning on {10-12} is expected, (0 90 30) where prismatic slip should occur, and the high symmetry (0 0 0) promoting multiple twinning. In parallel with the experiments, a crystal plasticity model has been developed to compute the crystal rotation due to slip and the amount and orientation of twins, as a function of the critical resolved shear stresses (CRSS) for the slip and twinning systems.

2. Experimental procedure
Pure magnesium single crystals were produced by directional controlled solidification in a mould under protective argon atmosphere in our laboratory. Samples were cut by spark cutting.

Plane strain compression tests were performed in a channel die at 25, 150, 250 350 and 450°C and a strain rate of 0.1 s⁻¹. The samples were lubricated with graphite and Teflon for high temperature tests. Just after deformation the samples were immediately quenched in cold water.
EBSD maps were made on a RD-ND plane, both to check the initial orientation and to analyze the lattice rotations and twins. In many cases the inclination of the twin plane on the RD-ND plane gives the twin variant with good accuracy, e.g. \{10-12\} twins have symmetrical variants of misorientation 8°, but the twin planes can have very different inclinations.

The lattice and twin orientations are given in Euler angles, using the Bunge convention taking the crystal basis as X along [10-10], Y along [-1-120] and Z along [0001].

3. Crystal plasticity analysis

The program describes the plastic deformation by slip and twinning of a rate insensitive material [4] under mixed boundary conditions. It maximizes the imposed external plastic work (1), under condition (2), where M is the generalized Schmidt factor.

\[
\dot{\epsilon}_\alpha = \sum_\alpha \sigma_\alpha \dot{\varepsilon}_\alpha \\
\text{CRSS} = \sum_\alpha \sigma_\alpha M_{\alpha} \geq 0
\]

36 systems are used as follows: 3 basal (0001)<-12-10>, 3 prismatic \{10-10\}<12-10>, 6 pyramidal I \{10-11\}<12-10> and 6 pyramidal II \{12-12\}<12-1-3> slip systems together with 6 tensile \{10-12\}<1011>, 6 compressive \{10-11\}<10-1-2> and 6 other compressive \{10-13\}<30-3-2> twinning systems. The orientations of the twinning planes with respect to the RD-ND plane of observation can then be compared with the corresponding experimental observations.

4. Results

4.1. Single crystals 90 90 30 (exact orientation 88 84 32)

Crystals were deformed over the temperature range 25-450°C (Figure 1). The EBSD map of crystal deformed at 350°C (figure 2) is color-coded so that [0001] along ND is red and <10-10> along ND is blue. All \{10-12\} tensile twin variants (noted A1 to A6) are observed and identified (Figure 3).

![Figure 1. Stress strain curves of (90 90 30) crystals at 5 temperatures](image1)

![Figure 2. EBSD map of crystal (90 90 30) deformed 0.096 at 350°C, and pole figure](image2)

![Figure 3a. EBSD map of crystal (90 90 30) deformed 0.04 at RT](image3a)

![Figure 3b. pole figure of crystal (90 90 30) deformed 0.04 at RT](image3b)

![Figure 3c. scheme of twin planes](image3c)
At all temperatures the dominant deformation mode is primary \{10-12\} tensile twinning; the two symmetrical twin variants in red dominate, but twins 2 and 3 seem to increase at high temperature.

4.2. Single crystals 0 90 30 (exact orientation 1 89 32)
This crystal is expected to undergo prismatic slip but, as also found by [2], at low temperature there is a superposition of tensile and compressive twinning. We analyzed (Figure 4) compressive \{10-11\} twins which double twinned into \{10-11\} \{10-12\} (noted b-a-) and which cut across \{10-12\} to form \{10-12\} \{10-13\} (noted a-c-). At temperatures higher than 300°C, prismatic slip is observed as the lattice rotates around $\bar{c}$ leading to a softer, stable, orientation close to 0 90 0 (Figure 5).

![Figure 4. EBSD map of crystal (0 90 30) deformed 0.083 at 150°C and pole figure](image)

![Figure 5. EBSD map of crystal (0 90 30) deformed 0.303 at 350°C and pole figure](image)

Crystals deformed at 250°C shows recrystallized compressive twins, but the parent part does not show any clear rotation, whereas crystals deformed at 350 and 450°C rotated by prismatic or pyramidal I slip, both giving the same rotation around TD.

4.3. Single crystals 0 0 0 (exact orientation 45 1 17)
At 25°C the crystal broke quickly, but in crystals deformed at 150°C and above (Figure 6), we found many twins that could be analyzed (Figures 7, 8) as \(-1103\)(0-112) double twinning (noted c1a5). On Figure 8c observed twins noted C are \{10-13\}; the usual \{10-11\} twins (noted B) are a little observed at low temperature. At 450°C a few twins were observed but deformation is mainly due to pyramidal II slip.

![Figure 6. Stress-strain curves of crystals (0 0 0)](image)

![Figure 7. EBSD map of crystal (0 0 0) deformed 0.082 at 150°C and pole figure](image)
We conclude that \{10-13\} \{10-12\} double twinning occurred at all temperature, whereas usually double twinning is reported on \{10-11\} \{10-12\}.

5. Discussion and conclusion

To estimate the CRSS from the flow stress of channel die experiments, we assume proportionality between the CRSS for activated slip or twinning systems and the calculated stress.

Figure 9 summarizes, for each orientation and various temperatures, the experimental yield stress at about 0.2% strain, and the evaluated CRSS.

For \{10-11\} twinning our result agree with those of Yoshinaga and Horiuchi [1] (empty points) who used uniaxial compression tests along \(\bar{c}\); other channel-die experiments [2-3] also fit quite well. In general the present systematic study of the temperature dependence of slip and twinning in pure Mg gives similar flow stress results to those of previous works, when available, but we have been able to estimate the CRSS values of many systems over a wide temperature range.

References

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