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Acoustic emission study on the activity of slip and twin mechanisms during compression testing of magnesium single crystals

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ABSTRACT

Magnesium single crystals with various crystallographic orientations were uniaxially and channel-die compressed at room temperature (RT) and at a constant strain rate of $10^{-3}\ s^{-1}$ in order to obtain a comprehensive set of acoustic emission (AE) data, which can be applied in studies of twinning and dislocation processes in polycrystalline Mg alloys. Loading along the <11.2> axis led to a preferable activation of basal slip and it was accompanied by a low amplitude AE signal. Twinning was observed exclusively during compression along the <10.0> and <11.0> axis. The twin nucleation was associated with burst AE signals with high amplitudes.

1. Introduction

Plastic deformation of magnesium alloys is currently intensively studied because of increasing demand for light materials in the automotive and aerospace industry. Magnesium, with the hexagonal close packed (hcp) lattice and the *c*/*a* ratio close to the ideal value (1.624), exhibits different deformation behavior in comparison to materials with cubic lattice. The reason is mainly the limited number of slip systems available at room temperature (RT).

Numerous studies were recently performed on wrought Mg alloys, which show better mechanical properties in comparison to cast Mg alloys. The deformation behavior of wrought Mg alloys is strongly affected by a crystallographic texture, which is developed during manufacturing processes (extrusion, rolling, forging, etc.) [1,2].

It is known that plastic deformation in Mg proceeds mainly via activation of four slip systems (basal (00.1) <a>, prismatic (10.0) <a>, pyramidal π1 (10.1) <a>, and pyramidal π2 (11.2) <a+c>) according to their specific critical resolved shear stress (CRSS) [3,4]. According to the von Mises criterion for a homogeneous deformation of polycrystalline materials, at least five independent slip systems are required [5]. In this regard, an additional mechanism, mechanical twinning, is supposed to play an important role to maintain a ductile mechanical behavior of Mg alloys. Twinning modifies the original crystal lattice and the most common twinning mode, {10.2} extension twinning, is characterized by 86° misorientation with respect to the original lattice. Twinning itself can accommodate strain (to a certain degree). In addition, the twins make orientations of the lattice more favorable for the activation of the dislocation slip, thus providing additional strain.

Earlier studies [6,7] have also shown that plastic deformation of Mg and its alloys at RT, besides {10.2} extension twins, could proceed by {10.1} banding, which consists of {10.1} twinning followed by {10.2} twinning in the formed twin. A basal slip may be subsequently activated in the twinned material and, therefore, can enhance the ability of the material to accommodate a plastic strain.

The situation in polycrystalline wrought materials is more involved due to diverse grain orientations and grain-size effects, but the plastic deformation proceeds via the same mechanisms as in single crystals. For example, the anisotropy should be similar in strongly textured polycrystals and in single crystals, and the degree of anisotropy should depend on the strength of the texture [6,8]. An analogy between deformation curves for single-crystalline and polycrystalline Mg with a strong texture, with orientation similar to that of the single crystal, was indeed observed by Kelley and Hosford [6]. Their study was followed by the work of Graff et al. [9], where mechanical tests and numerical modeling were collated for understanding the mechanisms of dislocation gliding and deformation twinning in single- and polycrystalline Mg. They attempted to describe links between micro- and mesoscale processes. The influence of slip plane orientation and temperature on the deformation processes in Mg single crystals was discussed in Refs. [6,10–12].

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From those studies it became obvious that the deformation behavior of textured Mg and its alloys can be interpreted in terms of deformation modes observed in single crystals.

The activation of basal and non-basal slip and twinning in Mg single crystals with different orientations was studied recently [13,14]. Another experimental approach to the plasticity in Mg single crystals is based on spherical nanoindentation (i.e. a localized contact) [15–17]. The finite element simulation [15] indicates different spatial locations of the {10.2} extension twins for different indentation modes. Crystal plasticity analysis [17] suggests that indentation morphology results from the basal and $<a+c>$ pyramidal slip systems in the case of (00.1) indentation and from basal and twin systems in the case of (1-1.0) and (11.0) indentation. Multiple twinning and dynamic recrystallization processes during channel-die compression along the $<11.0>$ direction in the *c*-axis extension were studied by Molodov et al. [18] using X-ray diffraction, electron backscattered diffraction (EBSD), and theoretical calculations.

At the present level of understanding, it is essential to get more insight into individual mechanisms of deformation and their interference, all with respect to given orientations and related to specific stages of the deformation curve. Acoustic emission (AE) as in-situ technique has the possibility to perform studies concurrently with the deformation tests, which opens an avenue for such study. In general, the AE phenomenon allows to follow the dislocation motion and twinning in metallic materials. The AE technique is based on the detection of transient elastic waves, which are generated by a rapid release of energy due to sudden localized structure changes within the material [19]. During plastic deformation of conventional polycrystalline materials the AE response is characterized by a distinct peak close to the yield point, which is followed by a rapid decay of the AE activity [20–21]. The onset AE peak is explained in terms of rapid dislocation multiplication and movement at the beginning of plastic deformation. The subsequent decay of the AE activity is linked with shortening of moving dislocation lines and reduction of their flight distance, both due to increasing density of immobile dislocations.

It is therefore obvious that each active deformation mechanism will show a specific AE signature. For instance, the activation of multiple slip leading to fast formation of strong barriers to dislocation motion is characterised by a very rapid decrease of the AE activity [22–24].

The AE signatures belonging to various slip systems and twinning can effectively be studied during plastic deformation of single crystals, where specific conditions can be controlled by proper orientation of compressive or tensile axis with respect to the single crystal orientation.

Results of AE measurements during mechanical testing on single crystals of various metals (Al, Zn, Fe, Cd, Ti, etc.) can be found e.g. in [19,25–28]. However, except [28], we are not aware of any AE study on Mg single crystals.

The performance of existing AE instrumentation and improved processing of large amount of AE data open new opportunities for detailed studies of the dynamics of deformation mechanisms in Mg single crystals. The results can be subsequently applicable for the interpretation of complex deformation behavior in wrought Mg alloys.

The main aim of the present paper is to obtain a comprehensive set of AE data on uniaxial and plane strain compression tests of Mg single crystals. These data, so far unavailable, will be used as a reference to the results of previous studies of twinning and dislocation processes in polycrystalline Mg alloys with respect to their chemical composition, technological processes, and deformation conditions [19–24,29–32]. They will provide vital background information for all future experiments in this field.

2. Experimental

Mg single crystals of commercial purity (99.95%) were grown by a modified vertical Bridgman technique using specially oriented monocrystalline seeds (c-axis parallel to the growth direction or 45° tilted).

The cutting of the specimens ($5 \times 6 \times 10$ mm^3) for deformation tests was performed by spark erosion. The orientation of specimens was determined by means of X-ray diffraction (Panalytical X-ray diffractometer, CuKα radiation).

Uniaxial and channel-die (Fig. 1) compression tests were performed at RT in universal testing machines Instron 5882 and Zwick Z50 at a constant strain rate of 10^{-3} s^{-1}. The texture after channel-die compression tests of single crystals was determined by X-ray diffraction in order to deduce the twinning activity.

Mg single-crystalline specimens were uniaxially compressed in four different directions (Fig. 2). Compression along the $<11.2>$ axis yields a set of AE data for crystallographic orientation which specifically favors the basal slip. For other orientations, compression was applied along the *c*-, $<10.0>$, and $<11.0>$ axis.

The channel-die compression tests were performed on Mg single crystals in three different crystallographic directions with a suppression of the material flow in the specific direction (Fig. 2b–d). This test was not performed for the first orientation (compression along the $<11.2>$ axis), because constraining to one flow direction does not mean any change for the deformation mechanism (basal slip). Therefore the AE data from the uniaxial compression test are sufficient for the AE analysis for this orientation.

For the next orientation (Fig. 2b), the stress was applied perpendicular to the basal planes with the flow possible in the $<11.0>$ direction, i.e. the material flow in the $<10.0>$ direction was impossible.

During compression perpendicular to the prismatic (10.0) and (11.0) planes (Fig. 2c and d) the constraint directions were chosen in order to allow material flow in the $<00.1>$ direction.

A computer controlled PCI-2 (Physical Acoustic Corporation) device was used to monitor the AE activity, based on a continuous storage of AE signals with 2 MHz sampling frequency. A miniaturized MST8S (Dakel-ZD Rpety, Czech Republic) piezoelectric transducer with a diameter of 3 mm and flat response in a frequency band from 100 to 600 kHz was used. The sensor was glued to the holder as close as possible to the specimen. A preamplifier with a gain of 40 dB was used. The full scale of the A/D converter was ± 10 V giving the total gain of 100 dB. The background noise during the tests did not exceed 1 mV (≈ 20 dB). With respect to this value, the threshold level of detection was set to 26 dB and a

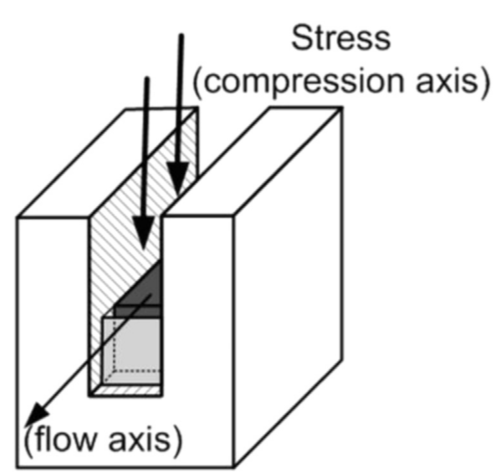

Fig. 1. Scheme of channel-die compression experiment.