EFFECT OF LOADING MODE AND ORIENTATION ON THE DEVELOPMENT OF DEFORMATION MECHANISMS IN THE ROLLED AZ31

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Abstract

The rolled sheet of AZ31 with the strong basal texture in ND direction was used for this study. Three different sample orientations (ND, 45, RD) were cut out and deformed in compression and tension. The acoustic emission (AE) was measured during the deformation and the deformed microstructure was studied by the electron backscatter diffraction. The advanced analysis of the AE measurements provides an insight to the active deformation mechanism. Extension twinning plays an important role in the deformation behavior. The higher yield stress can be observed when the texture is unfavorable oriented for twinning. Moreover, another twinning system has been observed to be active in such oriented samples.

Keywords: Magnesium, acoustic emission, mechanical testing, twinning, EBSD

1. INTRODUCTION

Magnesium alloys represent the lowest density structural metals (along with toxic beryllium) and, thus, is a highly interesting material for modern applications. Moreover, it is possible to get outstanding mechanical properties with biocompatibility and increased corrosion resistance by alloying of magnesium [1, 2]. The hexagonal close-packed structure causes complex deformation behavior of magnesium alloys, where the concurrent activity of several deformation mechanisms is necessary. The activity individual deformation mechanism is strongly dependent on the texture, alloying elements or temperature.

Generally, the slip system with the lowest critical shear stress is the $(0001)\langle 11\bar{2}0\rangle$ basal slip, followed by the $\{10\bar{1}0\}\langle 11\bar{2}0\rangle$ prismatic slip. Together they provide only 4 independent slip systems and neither of this system provides deformation in the $\langle c\rangle$ direction. To ensure compatibility of the plastic deformation, another deformation mechanism has to be activated. The possibilities are the $\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ 2nd order pyramidal slip which require high stress or temperature or deformation twinning [3]. Twinning is a polar mechanism which results in activation of twinning in different grains during compressive and tensile loading. The most common twinning system in magnesium alloys is extension twinning on the $\{10\bar{1}2\}$ twinning plane. Extension twinning means that it causes the elongation along the c-axis. Other twinning mechanisms observed during deformation of magnesium alloys are $\{11\bar{2}2\}$ extension twinning and $\{10\bar{1}1\}$ and $\{11\bar{2}1\}$ compression twinning [4].

The acoustic emission (AE) has been found as a powerful non-destructive technique for study of deformation mechanisms. It gives information from entire volume about the dynamic processes during plastic deformation or corrosion processes. The sources of AE have generally different characteristics [5], but the signal is modulated by the sample shape, microstructural characteristics or characteristics of the sensor. Together with the fact, that there is the concurrent activity of several sources of AE [6, 7] it make quite challenging task to separate the signal from different sources. The classic approach of evaluation of AE data, so called hit-based processing, is based on setting parameters, which define the AE event (threshold level, hit definition time, …) [8]. The system saves the parameters of the AE event (amplitude, duration, counts, energy, …) (**Figure 1**). In materials science, this approach can be successfully applied for general characterization, when the main goal is the investigation of the influence of the experimental and material parameters on the deformation behavior (e.g. [9, 10]).

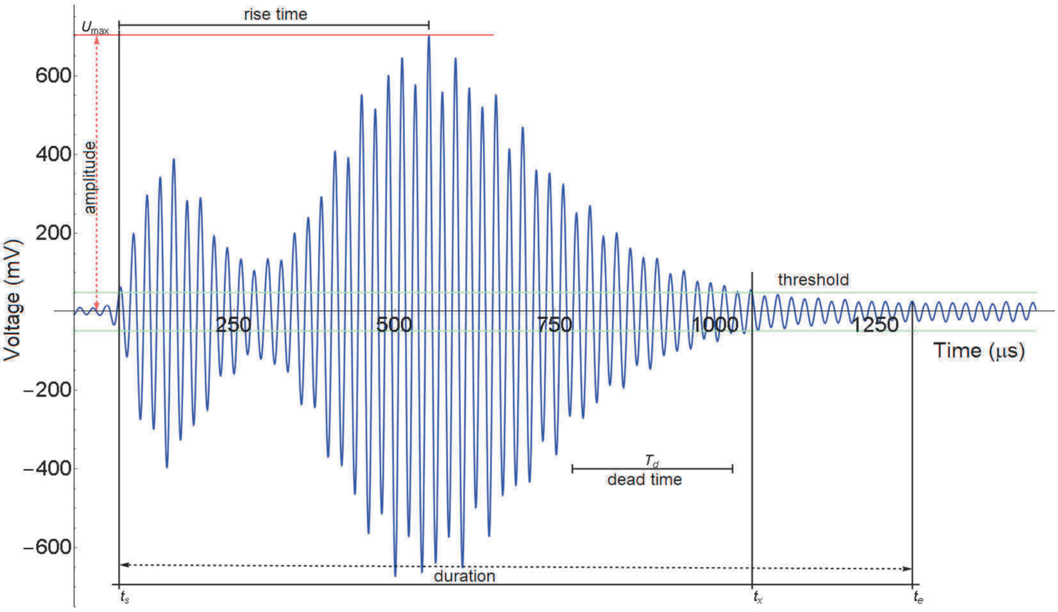

Figure 1 Parametrization of AE signal

In our work we applied the algorithm of Pomponi and Vinogradov [11, 12] - ASK analysis. Data are sectioned into consecutive individual realizations (“frames”) with length in order of μs and the power spectral density (PSD) function G(ω) is calculated for each frame computing the discrete Fourier transformation. PSD functions are compared together and the discrimination between the signals coming from different sources is done on the statistical basis.

2. MATERIAL AND EXPERIMENTAL METHODS

The deformation tests were performed on rolled AZ31 sheet. The coordinate system related to the sheet is the rolling direction (RD), normal direction (ND) - out of the sheet plane and transverse direction (TD). The sheet has a strong basal texture in ND (**Figure 2**). For deformation tests, samples of 10x6.5x6.5 mm^3 were cut out from the billets. The size of the samples for tensile test was limited by the thickness of the sheet, which was 15mm. That allowed us to cut the samples with the dimensions of the active area 9x4x1.5 mm^3. The samples were cut in the RD, 45° and ND (**Figure 2**). Texture in RD is favorable oriented for prismatic slip, the 45° samples are favorable oriented for basal slip and the samples in ND orientation are oriented favorably for the 2nd order pyramidal slip. Owing to the polar character of twinning different sample orientation are favorably oriented for twinning during tensile and compressive loading. Texture in RD is favorable oriented for twinning in compression while samples in ND direction are favorable oriented for twinning in tension [13].

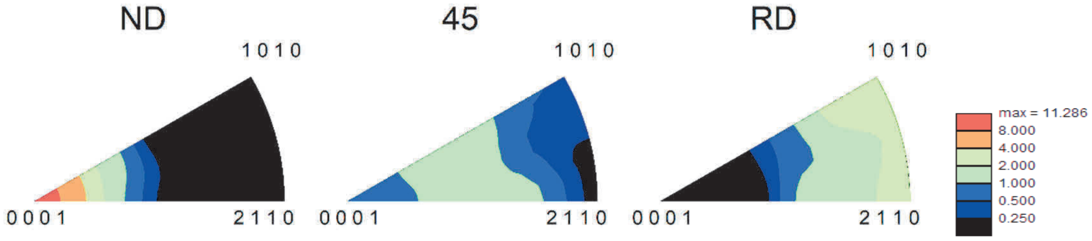

Figure 2 Inverse pole figure of samples cut in ND,45 and RD

The samples were deformed at the deformation rate 10^{-3} s^{-1}. Concurrently with the deformation tests the AE was recorded. The AE was measured by the PCI-2 device from Physical Acoustics Corporation. Piezoelectric wideband PAC PICO AE sensor was used in order to record the broad AE signal spectra needed for the analyses. The signal was recorded with a sampling rate of 5 MHz and the signal was preamplified by a PAC 2/4/6 preamplifier (40 dB gain).

The microstructure of deformed samples was investigated by scanning electron microscope (SEM) ZEISS Auriga Compact equipped with EDAX electron backscatter diffraction (EBSD) camera.

3. RESULTS

The deformation curves with AE response are shown at the **Figure 3** and the yield stresses and maximal stresses are in **Table 1**. The yield stress of RD and 45 samples is the same and significantly higher for ND sample in compression. Also the shape of RD and 45 curves exhibits the S-shape which is typical for the $\{10\bar{1}2\}$ extension twinning, while the curve of the sample in ND has a convex shape. The tensile test exhibits opposite evolution, the lowest yield stress is for ND sample and the highest for RD sample. These results are consistent with the suitability of the orientation of the texture for twinning. These results are consistent with the AE results. Energy of the AE is higher for twin nucleation than for the dislocation slip[7] and the energy of measured AE is the highest for samples favorably oriented for twinning.

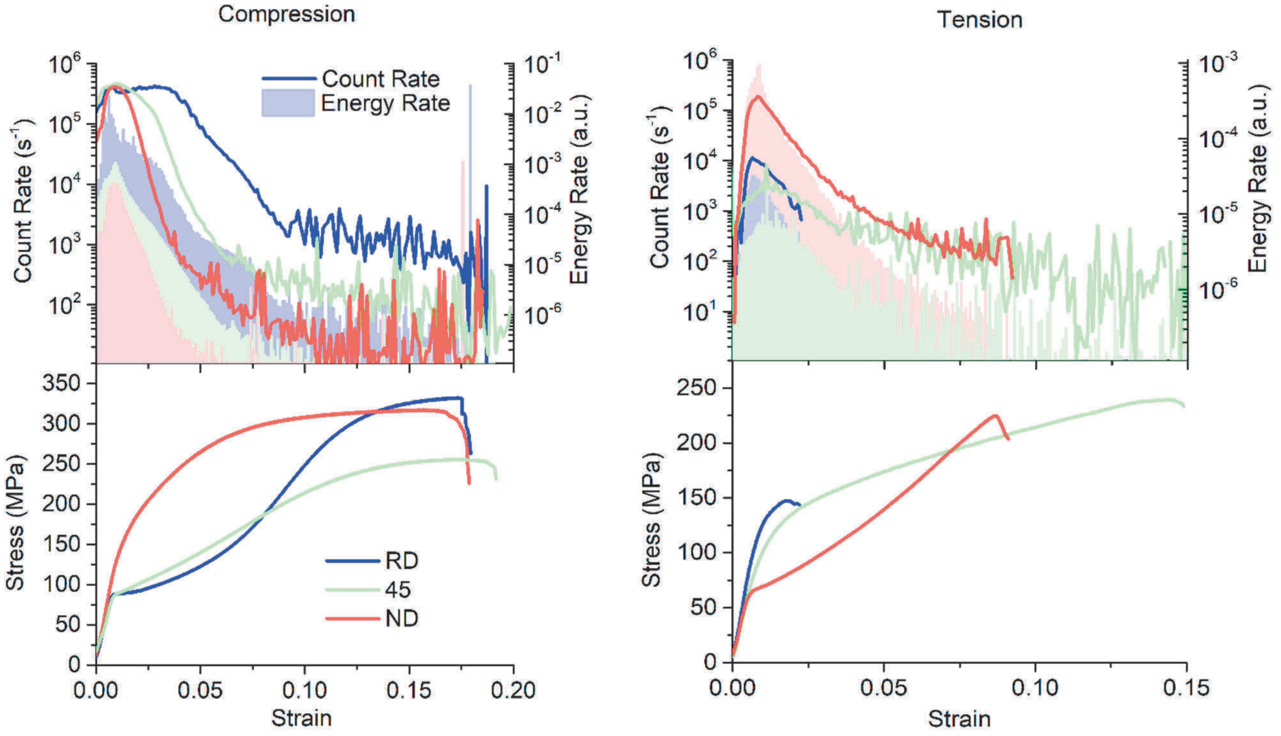

Figure 3 Deformation curves with the AE count rate and energy

Table 1 Yield stress and maximal stress for all orientations during tensile and compressive deformation

	RD		45		ND	
	σ_{02} (MPa)	σ_{max} (MPa)	σ_{02} (MPa)	σ_{max} (MPa)	σ_{02} (MPa)	σ_{max} (MPa)
Tension	125	147[1]	94	239	66	224
Compression	88	332	88	256	149	317

[1] The RD sample broke in the head, therefore, the maximal stress value is not representative

The ASK analysis was done on the AE data from the compression tests to evaluate the active deformation mechanisms. The activity of twinning cluster is shown at **Figure 4**. The results confirm the increasing activity of twinning with the increasing deviation of the basal texture out of the loading direction. The twin nucleation is a dominant source of AE for the RD sample up to the 6% of deformation. This result is consistent with the fact that the twin can accommodate up to the 6.4% of deformation. Twin nucleation is dominant mainly around the yield point for the 45 sample. On contrary, although the twinning is present in ND sample it is not dominant deformation mechanism during the deformation because only few grains favorably oriented for twinning are present.

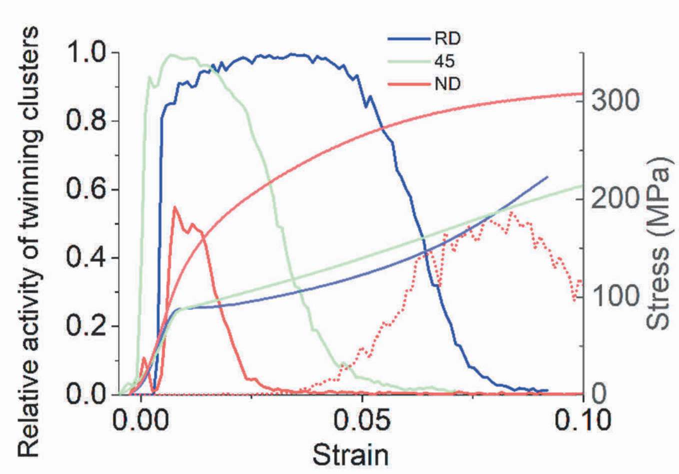

Figure 4 The activity of the nucleation of twining obtained from the ASK analysis of the AE signal

The deformation curves of samples favorably oriented for twinning are shown at **Figure 5**. It is possible to observe lower yield stress for the tensile sample. This can be caused by the number of nucleated twin variants during the deformation. It was shown, that the ideally oriented grains nucleate more twin variants in tension than in compression, which provides more straining possibilities and, therefore, makes the plastic deformation easier [13-15]. On contrary, the hardening is higher for tensile test than for compression at the early stage of plastic deformation. The more twins that are nucleated in tension cause that their growth is limited and nucleation of new twins is necessary. These twins are smaller and therefore the AE signal is decreasing during the deformation [13]. The results of AE during the compression test suggest that the twins nucleate continuously up to the 5% of deformation which is inconsistent with the measurement on non-textured samples where the nucleation of twins was observed only around the yield point and it was followed by the twin growth [13].

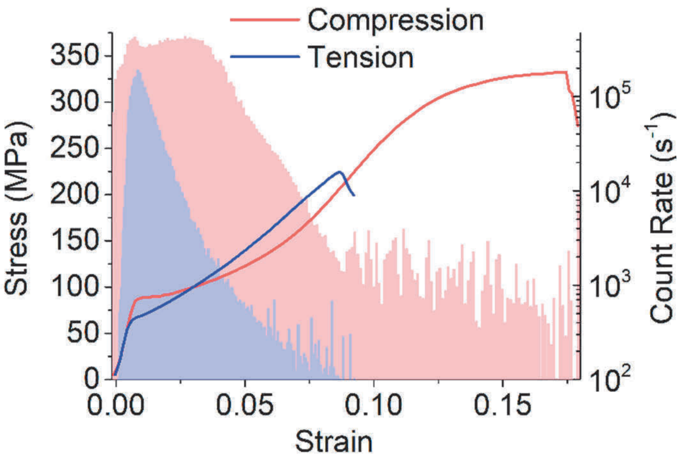

Figure 5 The comparison of samples favorably oriented for twinning in compression (RD) and tension (ND)

The detailed observation of microstructure confirms above mentioned results. The samples were deformed to 1% of plastic deformation in compression and examined by the optical microscopy and EBSD (**Figure 6**). **Figure 6a** shows that samples deformed in the RD create the bands of deformed and undeformed grains. The EBSD of the deformed band (**Figure 6b**) shows that the deformation is caused mainly by twinning. Twins causes complex stress field around them. When they reach the grain boundary, they create the stress field in the neighboring grain which causes the twin nucleation there [16]. As a result, the twins penetrate through the grain boundaries to the neighboring grains and creating the deformation band. The band become wider by the nucleation of twins in undeformed grains. This explains the difference from the non-textured samples.

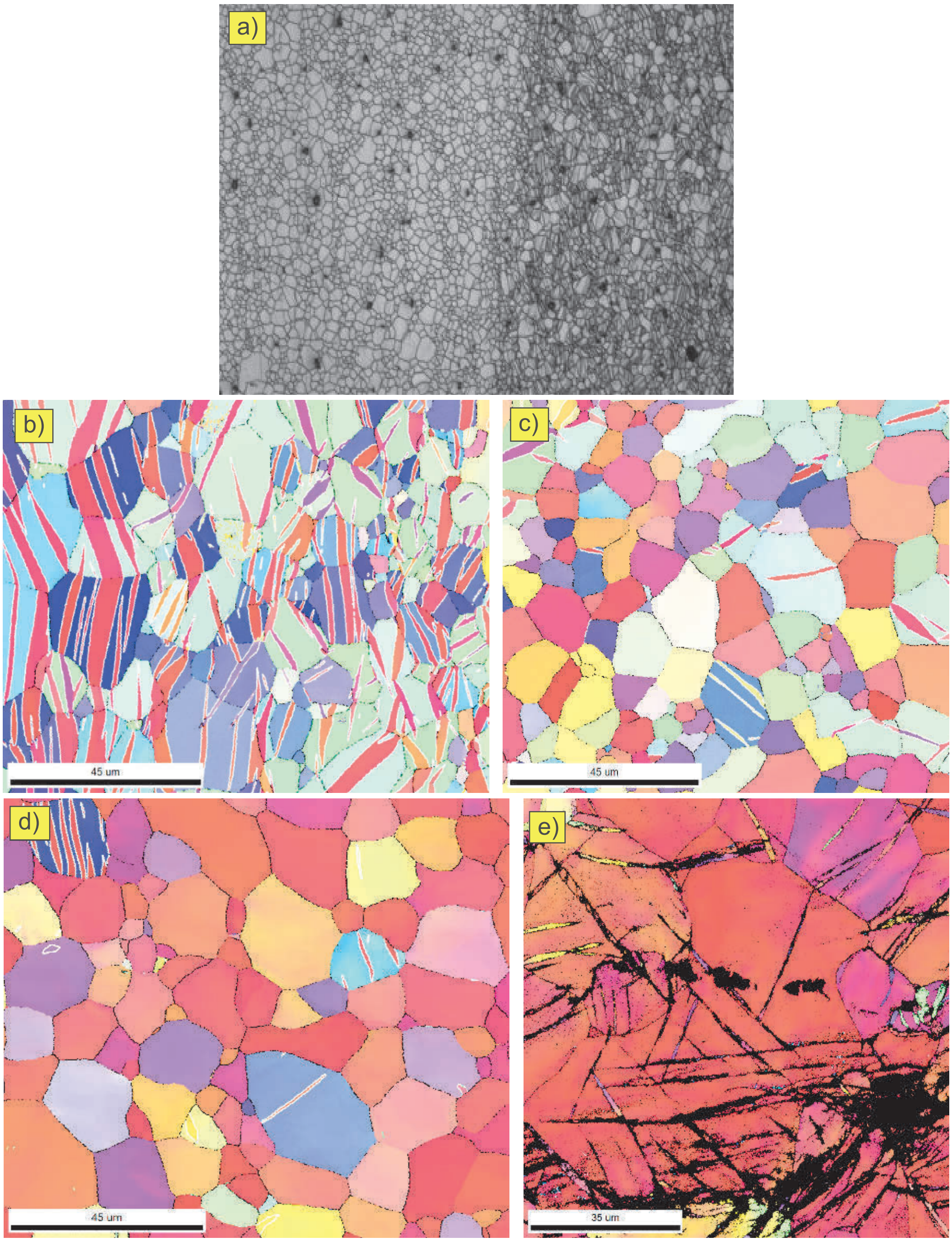

Figure 6 Microstructure of a, b) RD, c) 45, d) ND samples deformed in compression to 1% plastic strain and e) ND sample deformed up to the fracture.

Samples 45 (**Figure 6c**) and ND (**Figure 6d**) exhibits significantly smaller amount of twins, which is consistent with the results in **Figure 4**. All this twins are $\{10\bar{1}2\}$ extension twins. The microstructure of ND sample deformed to the fracture (**Figure 6e**) shows another type of twinning. It was analyzed as double twinning. First the $\{10\bar{1}1\}$ compression twins are formed then the twins undergo the $\{10\bar{1}2\}$ extension twinning. This is consistent with the presence of another AE cluster in the **Figure 4** for the deformation in ND direction. This cluster is connected to the double twinning.

4. CONCLUSION

The deformation test and the microstructural analysis show the different evolution of twinning as a result of orientation and loading direction. The yield stress of the material significantly depends on the suitability of orientation for twinning. Twinning is presented in all the samples but its role differs a lot. For the compression in the RD, twinning is the main deformation mechanism up to 6% of strain and the deformation has character of bands. Sample oriented in direction 45° also presents significant twinning activity; however, it is limited around the yield point. Twinning in the ND is limited to small number of grains around the yield point. Another twinning system $\{10\bar{1}1\}$ compression twinning is active at higher stresses and it is followed by the $\{10\bar{1}2\}$ twinning.

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