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# Deformation processes in ZE41A cast magnesium alloy investigated by the acoustic emission technique

V. Satheeshkumar*, P.R. Lakshminarayanan

*Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar 608 002, Tamil Nadu, India*

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ABSTRACT

The acoustic emission (AE) technique is a very useful tool to detect the microplastic yielding occurring during macroscopic deformation. Cast ZE14A magnesium alloy was deformed in tension at temperatures between 20 and 350 °C and at a constant strain rate of 0.05 $s^{-1}$. Measurements of the AE during testing are presented and related to the microstructure of the sample material. AE count rates increase with increasing temperature from room temperature to a maximum at 330 °C. Above 330 °C temperatures count rate decrease. This behaviour is discussed with a view to the role of heat treatment, twinning and deformation mechanism.

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## 1. Introduction

Magnesium alloys combine favourable properties such as light weight with adequate castability and machinability. Mg-base alloys exhibit superior damping capacity and high thermal conductivity. The deformation behaviour of magnesium alloys has not been characterised to the same extent as for competing light metals like aluminium. Due to the hexagonal close packed lattice structure of magnesium, basal slip is the main slip mode. It is important to note that it has only three geometrical and two independent slip systems and therefore non-basal slip as well as twinning have to be active.

AE is used to describe a very low sound pulse which is emitted spontaneously when there is a relaxation of stress within the tested material. Strain waves which can be detected on the surface of the material by means of a sensitive piezoelectric transducer are generated. The phenomenon was investigated by Kaiser [1]. Tensile tests of magnesium alloys have shown that the materials do not behave in a linear-elastic manner even at stresses well below the macroscopic yield point. Careful analysis of the stress–strain curves shows that only the initial portion corresponding to stresses below 20 MPa (depending on grain size) exhibits true elastic behaviour. This micro-yielding is due to activation of basal slip in favourably oriented grains. This is also in accord with the recorded AE signals [2]. Twinning may also reorient the basal planes so that they become more favourably oriented for slip [3]. The process parameters significantly influence the microstructural evolution, e.g. in terms of grain size and grain size distribution of the material and, consequently, influence the mechanical properties of the resulting profile [4]. AE responds to collective dislocation motion and twinning and therefore yields information on the dynamic processes involved in plastic deformation of the material. To date, there are only limited results demonstrating the use of AE in monitoring the structural response and deformation of Mg-based alloys [5–10]. In all the cases deformation, twinning and dislocation glide were to be found the major source of AE. The objective of the paper is an AE study of the relation between the mechanism of tensile plastic deformation and twinning of ZE41A magnesium alloy.

## 2. Experimental procedure

The ZE41A cast magnesium alloy was used in this investigation. The chemical composition of the alloy is presented in Table 1. This alloy was heat treated in a muffle furnace by the solutioning at a temperature of 330 °C for 2 h to improve the strength and gives toughness and shock resistance. Artificial ageing was performed after solutioning treatment of magnesium alloy at 180 °C for 16 h, to improve hardness and strength [11].

Tensile specimens were machined from as cast and heat treated plates. The flat tensile test specimen conformed to standard specified in ASTM E8. The dimension of specimen was 150 mm × 20 mm with 6 mm in thickness. The tests were carried out in uniaxial tensile testing computer controlled servo hydraulic machine. Tests were carried out at room temperature at a strain rate of 0.05 $s^{-1}$.

Acoustic emission was continuously monitored during the tensile tests by using Pci/Disp AE platform acquisition system of physical acoustic corporation (PAC), with a frequency range (10 KHz–2.1 MHz). Ambient noise was filtered using a threshold of 40 dB. AE measurements were achieved by using resonant micro80 PAC sensor which have a large range of resonance (175 KHz–1 MHz), coupled on the faces of the samples with silicon grease. After installation of the transducer, a pencil lead break [12] procedure was used to simulate AE signals in the calibration of each test. In this test, a repeatable acoustic wave can be generated. When the lead breaks,

* Corresponding author. Tel.: +91 9994294220; fax: +91 144 239734/238275.
*E-mail address:* svsatheshk@hotmail.com (V. Satheeshkumar).

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**Table 1**
Chemical composition (wt%) of ZE41A cast magnesium alloy.

| Cu | Si | Zn | Zr | Fe | TRE | Ni | Mn | Al | Ni | Mg |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.002 | 0.003 | 3.80 | 0.60 | 0.004 | 1.18 | 0.002 | 0.008 | 0.006 | 0.002 | Bal |

there is a sudden release of stress on the surface of the sample causing an acoustic wave. For the microstructural studies using an optical microscope were made after deformation as a function of strain and temperature. Undeformed parts from the heads of the specimens and deformed parts of the tensile specimens were used. The employed etchant was 4.2 g picric + 10 ml distilled water + 10 ml acetic acid + 70 ml ethanol with etching time as high as 30 s.

## 3. Results

The engineering stress–strain curves corresponding AE count rates are shown in Fig. 1(a–c) for tensile test at various conditions. In all cases an increase of the AE count rates up to a characteristic peak in observed near the macroscopic yield point, which is followed by a decrease. According to the present observation, AE count rates decreases above the temperature of 330 °C. Both the yield stress and the tensile strength decreases with increasing temperature above 330 °C. The maximum AE count rates achieved in solutioning at 330 °C for 2 h with ageing of 180 °C for 15 h specimen.

The microstructure of the specimens after testing consists of a large number of twins from room temperature up to 330 °C. Extensive twinning was found almost in all areas of the specimen implying that twinning is a prevalent mechanism of deformation at low strains. Several families of almost parallel twins with a high density of dislocations passing through several grains and intersecting each other were observed so called compound twinning [13]. A much higher number of twins were found in the specimen deformed at room temperature and deformed at 330 °C (Fig. 2(a) and (b)) 60 percentages of twins are more as compared to that of deformed at 350 °C (Fig. 2(c)).

Macroscopic tensile fracture appearance is shown in Fig. 3. In the specimen fracture occurred macroscopically in the direction perpendicular to the specimen axis. The fracture surfaces of tensile test specimens were examined using a scanning electron microscope. Fig. 4(a) and (b) shows the SEM fractographs of specimens, which revealed features of brittle fracture, with cleavage and quasi-cleavage as the principal fracture modes, these images show a typical interdendritic morphology in the shrinkage void that is locally distributed among the quasi-cleavage fractured surfaces, with the entrapped holes formed by gas evolution. These figures also show that the fractured morphology of solution treated ZE41A alloy, which is made up of fine facets due to the fracture of $Mg_{17}Al_{12}$ precipitate and the quasi-cleavage fracture. Also, these images show that the quasi-cleavage fractured area increases as the grain size of solution treated alloys increases. Similar observation was made by Lun Sin et al. [14] for magnesium alloy.

## 4. Discussion

The AE count rate is proportional to the density of moving dislocations [15] and also to their free mean path [16]. The density of obstacles for the dislocation motion, e.g. forest or sessile dislocations and dislocation walls, increases with increasing strain. Thus, the mean free path of moving dislocations decreases and the AE activity drops. Furthermore, above 330 °C, the AE count rate decreases. The decrease of the AE count rate in subsequent stages of plastic deformation correlates with the formation of dislocation walls. The amount of twins decreases significantly with respect to the increase of temperature. This effect can be associated with the activation of additional deformation mechanisms [17] like prismatic {a} slip and, more important, second order pyramidal {c + a} slip, because the CRSS (critical resolved shear stress) of these slip

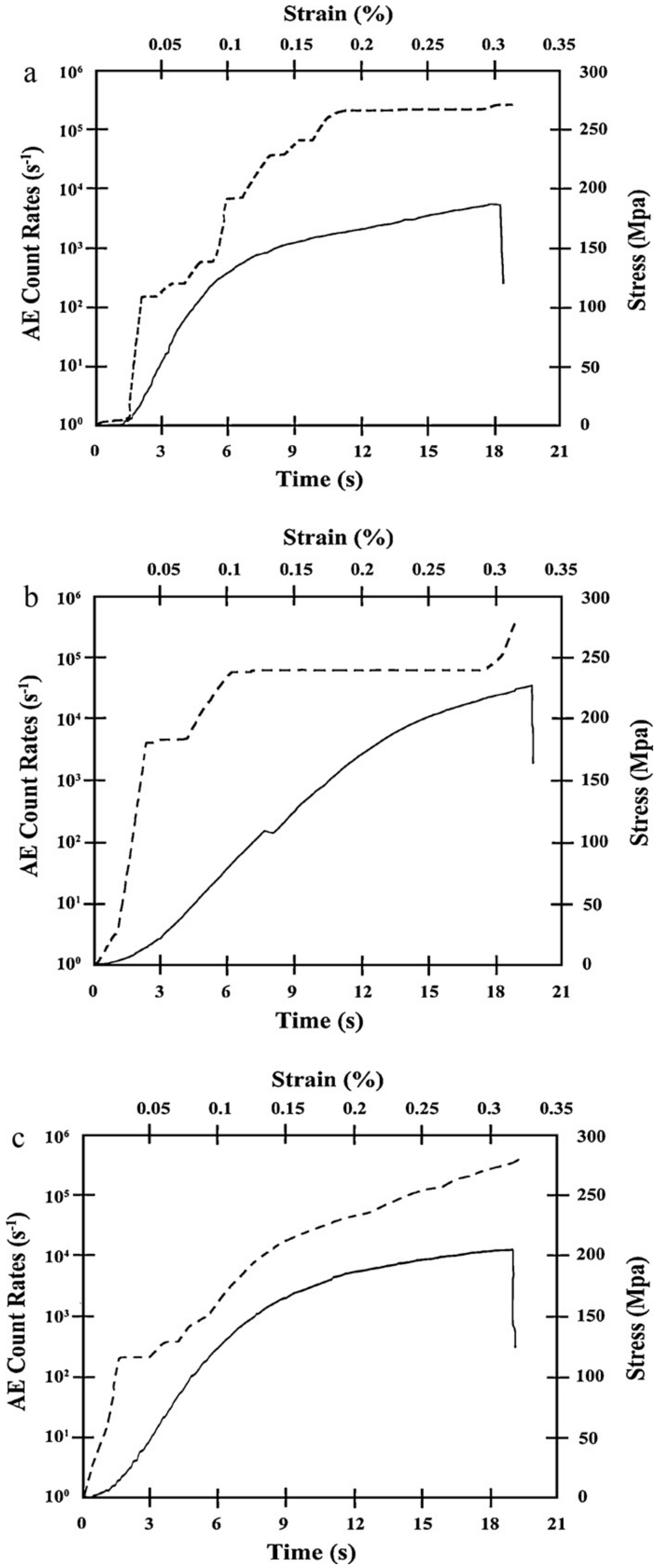


**Fig. 1.** Stress–strain curve (solid line) and AE count rates (dotted line) in tensile tests for ZE41A at room temperature and a constant strain rate of 0.05 $s^{-1}$ at: (a) room temperature, (b) 330 °C and (c) 350 °C.

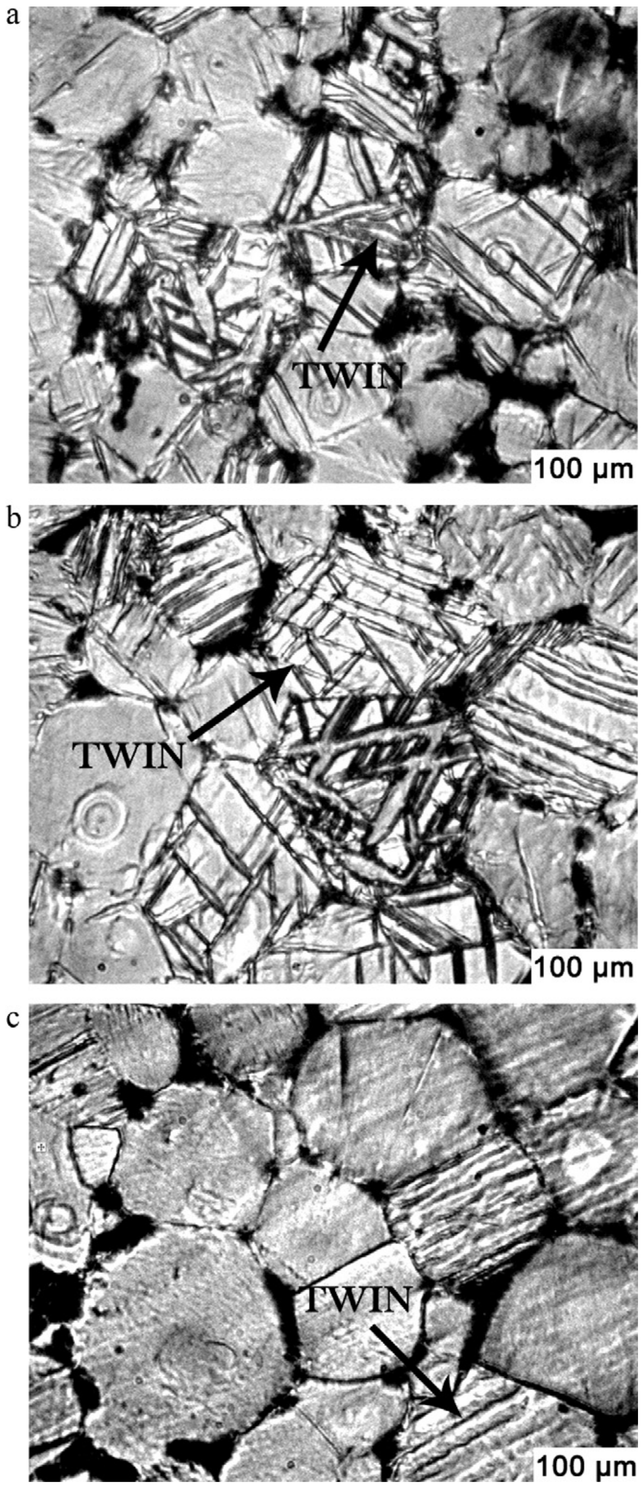


**Fig. 2.** Micrographs from longitudinal sections of the deformed samples after testing: (a) room temperature, (b) 330 °C and (c) 350 °C.

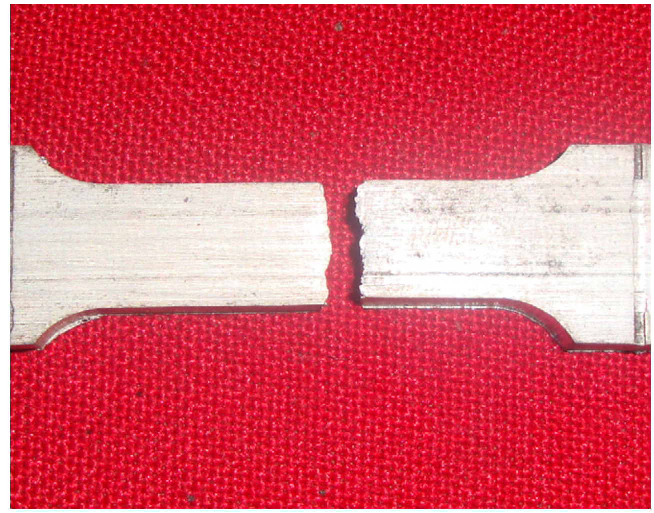

**Fig. 3.** Fractured sample of tensile test specimen.

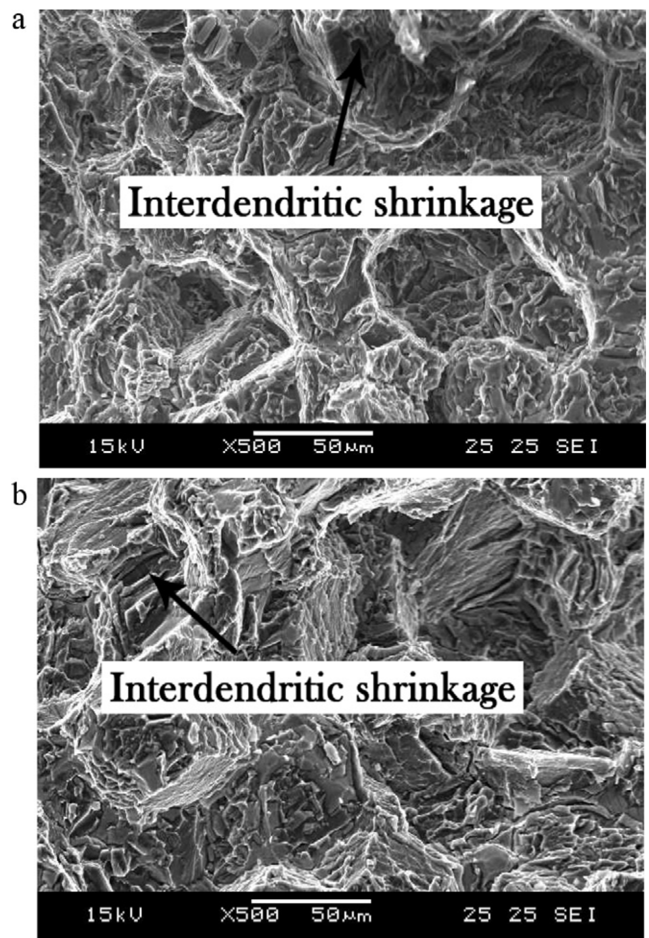


**Fig. 4.** SEM fractograph of the fracture surface of a tensile test specimens showing (a) and (b) cleavage features.

modes were strongly dependent on temperature [18] while CRSS at room temperature for these slip modes is about 100 times larger than that for basal slip [19], it is rapidly decrease with increasing temperature. We can understand that above 330 °C the activation of non-basal slip system is more favourable than twinning. At this point it is worthwhile to repeat that {c + a} pyramidal slip is the only slip mode that contributes to the macroscopic strain along the *c*-axis of the hcp-structure, as well as twinning does.

Both the additional possibility to activate {c + a} slip as well as the beginning of dynamic recrystallization do not contribute to ht AE count rates. With a decreasing amount of twins, a decrease in the number of AE counts should occur. The AE activity during deformation of pure Zinc polycrystals which also have a hcp lattice structure increased significantly with the grain size which is related to larger twins in a coarse-grained microstructure. This corresponds to the present study where the resulting microstructure after deformation shows at least more and/or larger twins in the microstructure. This effect is found in the material.

## 5. Conclusions

Twinning plays a major role as a deformation mechanism in the range at temperatures between 20 and 350 °C as observed in a microstructural analysis. It was also found during tensile testing the AE count rate that a finer grain size leads to an overall decrease in the AE count rate. It was discussed that dislocation glide and twinning are the most important sources for AE and therefore concluded that these deformation mechanisms are reduced in their activity.

Above 330 °C dynamic recrystallization occurs and twins are not visible. A softening of the materials also occurs. The AE count rate decrease again which is convenient with the start of the dynamic recrystallization as well as other slip modes being active such as (c + a) pyramidal slip.

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