STUDY OF DEFORMATION MECHANISMS OF A MG-AL-SR ALLOY REINFORCED WITH SHORT SAFFIL® FIBERS

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Abstract

In-situ acoustic emission (AE) method has been applied to study of deformation processes of an AJ51 magnesium alloy reinforced with short Saffil® fibers. The analysis of parameters of AE signal revealed a significant difference in deformation mechanisms between the matrix alloy and the composite, respectively. It is shown that the AE technique is suitable for detection of fiber cracking onset.

Keywords: acoustic emission, magnesium composite, plastic deformation

1. INTRODUCTION

Magnesium based composites have been used in the engineering since the second half of the twentieth century. Magnesium is one of the lightest constructive materials used in industry and also has good strength-to-weight ratio and low thermal expansion coefficient. Therefore its alloys and composites are used mostly in aerospace, electronic packaging, recreational products, etc. Since the automotive industry enhanced the importance of decreasing fuel consumption due to environmental protection, started applying magnesium composites as car components [1]. Few disadvantages of magnesium, which makes barriers in its applicability, for example weak creep resistance, significant reduction of mechanical properties at higher temperatures (yield stress, tensile stress), could be reduced or eliminated using ceramic reinforcements [2]. On the other hand, composites exhibit low ductility and they are produced by more complicated and expensive techniques.

Generally fiber reinforced materials have highly anisotropic mechanical properties, which depend on the orientation of fibers. Deformation mechanisms ongoing during plastic deformation in the composite material due to the presence of short fibers are more complex compare to the alloys. The observed strengthening effects of reinforcement phase are the following [2]:

- load transfer from the matrix to fibers
- enhanced dislocation density due to geometrical and thermal mismatch between matrix and fibers
- contribution of the fibers to the Orowan strengthening
- residual thermal stresses arising during the fabrication process.

Mechanical properties also depend on several other factors such as length and diameter of reinforced fibers, distribution of fibers in the matrix, volume fraction of fibers and the matrix composition.

For the observation of correlation of the micro mechanisms with macroscopic deformation is very powerful method the acoustic emission (AE) measurement. It is an in-situ method for observing AE response of material to the applied stress and deformation. AE defined as elastic wave, arising from sudden energy release due to local dynamic changes in the structure of material caused by internal or external forces. The AE is capable to detect the acoustic signals originate in collective motion, annihilation or dislocation multiplication and twinning nucleation. The most important advantage of AE is in getting information about
microscopic processes from entire volume in real time. The main disadvantage of AE method is given by the lack of a general mathematical model, which could describe quantitatively the spread of elastic wave in inhomogeneous space. Consequently, additional experimental methods are required for proving the AE results, as e.g. (electron) microscopy.

The goal of the present work is investigation of micromechanisms of plastic deformation during compression tests of an AJ51 magnesium alloy reinforced with short Saffil® fibers.

2. EXPERIMENTAL

The AJ51 magnesium alloy with a nominal composition of Mg +5 wt.% Al +0.6 wt. % Sr reinforced with short Saffil® fibers δ-Al₂O₃ with volume fraction 20% was investigated. Material was prepared by squeeze casting, the preform consisting Al₂O₃ short fibers and a binder system was preheated to a temperature higher than the melt point of the alloy and then inserted into a preheated die (290°C to 360°C). Under high pressure the two stages were compacted to the metal matrix composite. The 120 μm mean length ceramic fibers with diameter between 3 and 5 μm were distributed homogenously in the matrix with parallel orientation to the loading direction. An unreinforced AJ51 alloy was also prepared by the same technique for comparison purposes. For compression uniaxial tests cylindrical specimens with length of 12 mm and diameter of 6 mm were used. The tests were performed in a temperature range of 20 – 300 °C and at an initial strain rate of 10⁻³ s⁻¹. The specimens were tested in as-cast condition.

Acoustic emission response of material was detected by computer-controlled PCI-2 system manufactured by Physical Acoustic Corporation (PAC) only at room temperature. The facility incorporated a Micro2006 transducer (fabricated by DAKEL-ZD Rpety) with a flat response between 50 and 650 kHz and a PAC 2/4/6 preamplifier giving a gain of 40 dB. The threshold level was set at 26 dB, directly above the peak values of the background noise. Specimens were prepared for the light microscope observation by polishing and after that were etched for 15-25 s in a solution of 20% acetic acid, 1% nitric acid, 60% ethylene-glycol and 19% water.

3. RESULTS AND DISCUSSION

The initial state of magnesium alloy and composite observed by light microscope is shown in Fig.1a and b. The average size of grains was determinate by linear intercept method.

![Fig. 1 Initial state of a) magnesium alloy b) magnesium composite (cross-section of the samples)]
In case of magnesium alloy the average grain size was determined as 110 μm, while in composite the grain size was 44 μm. As it can be seen in Fig. 1b the fibers are parallel with the normal of the micrograph, but the orientation is not perfect.

The results of compression tests are shown on figure 2. It is obvious that the reinforcing phase has significant influence on the mechanical properties. At room temperature the yield stress increased approximately four times and tensile stress two times owing to the fiber content. On the other hand the AJ51 alloy has notably larger ductility at room temperature than the composite.

![Deformation curves at different temperatures for a) magnesium alloy b) AJ51 composite](image)

**Fig. 2** Deformation curves at different temperatures for a) magnesium alloy b) AJ51 composite

AJ51 alloy and composite show small changes up to 100 °C in the mechanical properties. From 200 °C significant degradation of mechanical properties in both cases were revealed. This behavior could be explained by activation of non-basal slip systems [3]. In case of composite the onset of softening at high temperature occurs at very small deformation.

The possible strengthening mechanisms, which were shown in headwords in the introduction, were discussed in detail in paper of Trojanova [3]. The calculated values of the following mechanisms are shown in the table 1: load transfer from the matrix to the fibers $\Delta \sigma_{LT}$; the stress increment $\Delta \sigma_{D}$ originated in the increased dislocation density due to both internal thermal stresses and geometrical mismatch between matrix and composite; Orowan strengthening $\Delta \sigma_{OR}$; stress increment caused by grain size refinement $\Delta \sigma_{GS}$ and average residual stress in matrix $\langle \sigma_m \rangle_{\text{max}}$.

**Tab. 1** Contributions of various strengthening mechanisms to the yield stress of the composite at room temperature

<table>
<thead>
<tr>
<th>$\sigma_{02}$ alloy [MPa]</th>
<th>$\Delta \sigma_{LT}$ [MPa]</th>
<th>$\Delta \sigma_{D}$ [MPa]</th>
<th>$\Delta \sigma_{OR}$ [MPa]</th>
<th>$\Delta \sigma_{GS}$ [MPa]</th>
<th>$\langle \sigma_m \rangle_{\text{max}}$ [MPa]</th>
<th>$\sigma_{\text{tot}}$ [MPa]</th>
<th>$\sigma_{\text{exp}}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>129</td>
<td>59</td>
<td>3</td>
<td>16</td>
<td>24</td>
<td>314</td>
<td>341</td>
</tr>
</tbody>
</table>

The AE measurements show notably differences between AJ51 alloy (Fig. 3a) and composite (Fig. 3b). In case of alloy there is a single peak in the strain dependence of the AE count rate, whereas for composite two regions with larger count rate were observed. The first peak in both types could come from the same types of sources: nucleation of $10\overline{1}2 \langle 10\overline{1}1 \rangle$ twins and the collective dislocation motion, respectively.
Fig. 3 Count rate during deformation with amplitude of each counts in case of a) AJ51 alloy b) composite

The disappearance of AE signals after the first peak has two reasons. The first is that above a certain strain level (in our case above approx. 2% of strain) instead of twin nucleation rapid twin growth takes place, in order to accommodate the plastic deformation. Twin growth contrary to the twin nucleation does not emit detectable AE signals. Mean velocity of twin growth is in order of $10^{-3}$ ms$^{-1}$ [4-5], which causes that the released energy is not large enough to make AE signals with measurable amplitude. The second reason of disappearing signals is the increasing number of obstacles for dislocation motion. The new twin boundaries are impenetrable for basal dislocations [6], which decrease the main free path of dislocation. This hinders the collective motion of dislocations and consequently the parameters of AE signal decrease. As it is obvious from Fig. 3, the amplitudes of AE signals are also different: the amplitudes are higher for the unreinforced alloy. This fact could be explained also with density of obstacles and different mean free path length. In composite the grain size is three times smaller and grain boundaries with phase boundaries between fibers and matrix make impenetrable obstacles for dislocations [7-8].

The peak frequency of AE signals were calculated by means of Fast Fourier Transformation (FFT). The results are presented in Figs 4a and b. There are two main frequency domains: 130 to 180 kHz and from 370 to 450 kHz. Based on paper of Li and Enoki [9] we referred higher frequencies to twin nucleation and the lower frequencies to collective dislocation motion respectively.

Fig. 4 True stress and Peak frequency dependence on strain for a) alloy b) composite at room temperature
It is obvious from Fig. 4 that the twin nucleation is less frequent in composite than that in alloy. The reason for that is most probably the smaller grain size and large internal stresses in composite, whose hinder the twin nucleation [7-8].

**Fig. 5** The characteristic AE frequencies of several deformation mechanisms

In the figure 4b appearance of a new very tight frequency range from 100 to 110 kHz can be observed, which can be connected with the onset of fibers cracking [11,12]. Above approximately 6% of strain the fibers can’t carry more loads and are start to break.

In the Fig. 5 the characteristic frequencies of different deformation mechanisms are summarized.

The micrographs of the deformed specimens are presented in Fig. 5. The presence of twins in alloy is obvious (Fig. 5a) that is an additional proof of the correctness of the above mentioned explanation of AE frequency analysis. On the other hand, there are only few twins in the composite (Fig 5b) in agreement with the low number of signals in “twin frequency” range.

**Fig. 6** – Optical micrographs of the unreinforced (matrix) alloy (a) and composite (b) specimens deformed to fracture.

4. CONCLUSIONS

The deformation mechanisms of AJ51 magnesium alloy and composite were investigated during monotonic compression tests. The main results of the work are the following:

- The fiber reinforcement has a prosperous impact on mechanical properties: both yield and maximum stress increases at room temperature.
- Frequency analysis of the AE signal allows distinguishing among the particular deformation mechanisms – characteristic frequencies of collective dislocation, twinning and fiber cracking were identified.
- The twin nucleation in composite is limited owing to the smaller grain size and large internal stresses
ACKNOWLEDGEMENTS

The authors are grateful for the financial support of the Czech Science Foundation under the contract P108/12/J018. GF acknowledges the support form the Grant Agency of Charles University under contract Nr. 676112

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