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Effect of the fiber orientation on the deformation mechanisms of magnesium-alloy based composite

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A B S T R A C T

The influence of the orientation of the fiber reinforcement on the deformation mechanisms of Mg–Al–Ca alloy-based composite has been investigated *in-situ* using acoustic emission and neutron diffraction methods. Results indicate that the twinned volume is the smallest, when the fibers plane is perpendicular to the loading direction. Residual thermal stresses having a tensile character are present in the as-received composites, which gradually vanishing during compressive straining. The load transfer from the matrix to fiber has been found more effective for specimens with fiber planes aligned with the loading direction, which is in agreement with the theoretical shear-lag model.

1. Introduction

Magnesium-based metal matrix composites (MMC) have been successfully used in many engineering applications. Enhanced mechanical properties including high strength, stiffness and good creep resistance in the combination with a excellent specific strength (strength-to-weight ratio) make the usage of these materials class popular, especially in the transportation industry where the weight reducing belongs to the most important tasks [1]. There is a wide range of reinforcement shapes, as *e.g.* (nano) particles, whiskers, nanotubes or fibers. In the case, when short fibers are used, the mechanical performance of the MMC is influenced by many parameters, including fibers aspect ratio, volume content of fibers and their orientation with respect to the loading direction. The quality of the matrix-fiber interface determines further the application field: strong interface results in a high strength composite, whereas weaker bonding between the phases of the composite can enhance the toughness [2]. Thus, understanding the influence of these parameters on the mechanical properties is of the key importance. The impact of short ceramic fibers on the stress necessary for plastic deformation of Mg alloy based MMC has been reported in several studies [3,4]. Several hardening and softening mechanisms are active during the straining of MMCs. The main strengthening mechanisms arising owing to the presence of ceramic fibers in the metallic matrix are:

i. Load transfer from the matrix to fibers maintained with the shear stresses at the interface [5].
ii. Increased dislocation density due to the thermal and geometrical mismatch [6].
iii. Hall-Petch strengthening – increase of the grain boundary area in composites.
iv. Residual thermal stresses [7].

The Orowan strengthening has been found less significant in composites containing 10–25 vol% of fibers [8,9].

The non-destructive *in-situ* methods of acoustic emission (AE) and neutron diffraction (ND) rank among the most powerful and reliable experimental techniques for investigation of deformation processes operating in Mg composites [10]. The main advantage of both methods is that they gain experimental data from a large volume of the specimen. The AE is an elastic wave arising from sudden energy release due to local dynamic changes in the microstructure caused by the internal or external forces. Consequently, the AE technique is capable to detect acoustic signals originating from the processes connected with plastic deformation of composites such as collective dislocation motion, deformation twinning or fiber cracking [11].

The main advantage of the ND method is the large penetration depth of thermal neutrons. This technique is sensitive to the lattice parameters changes and also to the texture formation during the plastic deformation. Hence, the lattice strains for both matrix and the reinforcing phase and twinned volume in the matrix can be evaluated from the ND experimental data [12,13].

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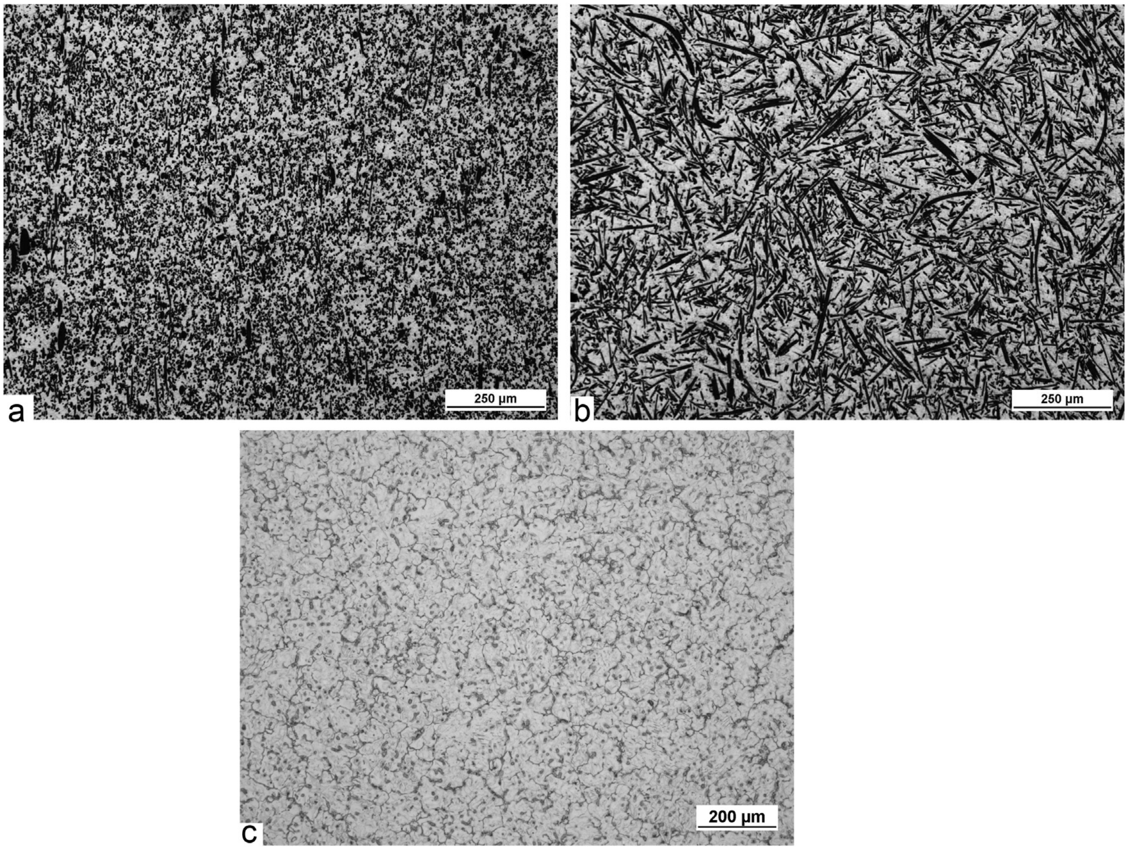

Fig. 1. Light micrograph of AX61 alloy reinforced with short Saffil fibers: (a) fibers plane parallel; (b) perpendicular to the loading axis and (c) the unreinforced alloy.

Despite a relatively high number of published papers dealing with microstructure and mechanical properties of MMCs based on magnesium alloys, the physical basis of the deformation processes operating in these composites is not known enough. The objective of the present study – following from this fact – is to reveal the main features of the deformation processes taking place in an Mg–Al–Ca alloy reinforced with short alumina (Saffil®) fibers. The load transfer mechanism from the matrix alloy to the fibers is discussed in details.

2. Experimental

AX61 magnesium alloy with a nominal composition of Mg-6 wt% Al-1 wt% Ca was reinforced with 25 vol% short Saffil® fibers (δ-Al_2O_3). The material was prepared by squeeze casting technique. The preform consisting of Al_2O_3 short fibers showing a 2D planar isotropic fiber distribution and a binder system (containing Al_2O_3 and starch) were preheated to 1000 °C, inserted into a preheated die (300–360 °C) and then infiltrated by the liquid alloy using two-stage application of the pressure. The mean fibers length and fibers diameter (measured after squeeze casting) were ~78 μm and ~3 μm, respectively. Owing to the two stage pressure application the resulting composite exhibited no pores or voids. Specimens for deformation tests were cut from the bulk with two orientations with respect to the fibers plane: (i) with the fibers plane parallel and (ii) perpendicular to the longest sample axis which is identical with the loading direction. Samples were not thermally treated. The specimens having dimension $20 \times 10 \times 10$ mm^3 were deformed in compression at room temperature with an initial strain rate of 10^{-3} s^{-1}. In addition, samples made from the matrix alloy samples without any reinforcement were also investigated.

The AE response of samples was detected by a computer-controlled PCI-2 system manufactured by Physical Acoustic Corporation (PAC). 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.

The *in-situ* neutron diffraction tests were performed at the SALSA instrument in the Laue-Langevin Institute (ILL), Grenoble. The wavelength of the neutron beam was $\lambda = 1.7$ Å. The irradiated gauge volume was approximately $10 \times 10 \times 10$ mm^3. Thanks to the relatively large gauge volume the surface effects may be neglected. During the compression testing the loading was stopped for 3 min at predetermined strain levels in order to record the diffraction pattern. Owing to the angular range of the detector (10°) only two "Mg-peaks" (0002) and $\{10\bar{1}1\}$ and one "fiber-peak" (321) were recorded. The elastic lattice strains were calculated using the Bragg's law, which gives the relation between the scattering angle (θ) and lattice spacing (d) as follows

$$2d \sin\theta = \lambda \tag{1}$$

The relative lattice strain (e) is then given by differentiating of the Bragg's equation:

$$e = \frac{d - d_0}{d_0} = -(\cot\theta)(\theta - \theta_0) \tag{2}$$

In the present work, we considered d_0 and θ_0 as the lattice spacing and the Bragg angle of the corresponding lattice planes in the unloaded unreinforced alloy. The lattice micro-strains of the magnesium matrix were evaluated from the diffraction peaks (0002) and $\{10\bar{1}1\}$ as a function of the macroscopic stress levels.