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Mechanical and microstructural observations during compression creep of a short fiber reinforced AlMg metal matrix composite

J. Olbricht[a,*], A. Yawny[b], M.L. Young[a], G. Eggeler[a]

[a] Ruhr-Universität Bochum, Institut für Werkstoffe, Universitätsstr. 150, 44801 Bochum, Germany
[b] Centro Atómico Bariloche, CNEA-CONICET, 8400 S. C. de Bariloche, Argentina

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ABSTRACT

The constant load compression creep behavior of a short fiber reinforced aluminium-5 wt.% magnesium alloy (AlMg5) containing 15 vol.% Al_2O_3 fibers (Saffil) was investigated. Creep of the matrix alloy and the metal matrix composite (MMC) was studied at 300 °C and 500 °C. Stresses ranging from 10 MPa to 120 MPa result in minimum creep rates between 10^{-9} s^{-1} and 10^{-3} s^{-1}. MMC creep is characterized by an initial decrease of the creep rate before a distinct creep rate minimum is reached, while the matrix alloy shows increasing primary creep rates at 500 °C. It is difficult to rationalize the stress dependence of the minimum creep rates by a simple Norton law, because the stress exponent n is not always constant. The orientation of Al_2O_3 fibers with respect to the loading axis is found to affect minimum creep rates. Fiber breakage represents an important damage mechanism. Fiber agglomerates are observed in the initial microstructure which may well affect the entire process of creep.

1. Introduction

Reinforcing aluminium alloys with short ceramic fibers significantly increases their creep resistance [1–4]. Short fiber reinforced Al metal matrix composites (MMCs) can withstand temperatures which exceed half of the melting point of the matrix alloy (in K) [5–7]. Mechanical loading in this temperature range results in time-dependent plastic deformation.

Creep testing of short fiber reinforced Al-MMCs under uniaxial and multiaxial loading conditions revealed that the presence of fibers alters the stress and temperature dependences of creep [2,6–8]. Stress exponents and apparent activation energies of creep in the MMCs differ significantly from those of the respective matrix alloys, indicating a general change in the mechanism of creep. Moreover, under creep conditions, MMCs generally show a strong initial decrease of the creep rate followed by a distinct creep rate minimum. Subsequently, a continuous increase of the deformation rate is observed [2,7,8]. A micromechanical scenario suggested by Dlouhy et al. [9] rationalizes this creep curve shape as well as the stress and temperature dependences of creep on the basis of three coupled elementary processes: (i) loading of fibers by dislocations, (ii) movement of dislocations to the fiber ends and annihilation of dislocation loops at these sites (time-dependent recovery), and (iii) fiber breakage with a related increase in recovery intensity due to a shortening of the recovery path.

Kausträter et al. [7] showed that the general shape of the Al-MMC creep curves is independent on whether a class I (alloy type, aluminium-5 wt.% magnesium alloy (AlMg5) [7]) or class II (metal type, AlZn11Mg0.2 [7]) matrix alloy is considered. Within the limited range of creep rates investigated in Ref. [7], the stress σ and temperature T dependence of the creep rate minima of matrix materials and MMCs correlated well with a simple Norton power law [10]:

$$\dot{\varepsilon}_{\min}(\sigma, T) = C_1 \sigma^n \exp\left(\frac{-Q_{\mathrm{app}}}{kT}\right) \quad (1)$$

where $\dot{\varepsilon}_{\min}$ is the minimum creep rate, C_1 is a material constant, k is the Boltzmann constant, n is the creep stress exponent, and Q_{app} is the apparent activation energy of creep. Simple metallic systems usually exhibit a power law type of creep behavior in lower stress ranges, where diffusion assisted dislocation climb governs dynamic recovery. It is generally accepted that diffusional creep at low loads yields stress exponents close to one, while significantly higher stress exponents are observed at higher stresses [10]. Thus, even simple systems exhibit a creep behavior, which is characterized by a stress exponent that gradually increases from low to high values. Power law descriptions of creep represent useful engineering approaches within a limited range of stresses.

MMCs represent complex engineering materials, where deviations from simple power-law dependencies are frequently observed. The effect of fibers on creep were examined on the basis

* Corresponding author. Tel.: +49 234 32 28982; fax: +49 234 32 14235.
E-mail address: juergen.olbricht@rub.de (J. Olbricht).

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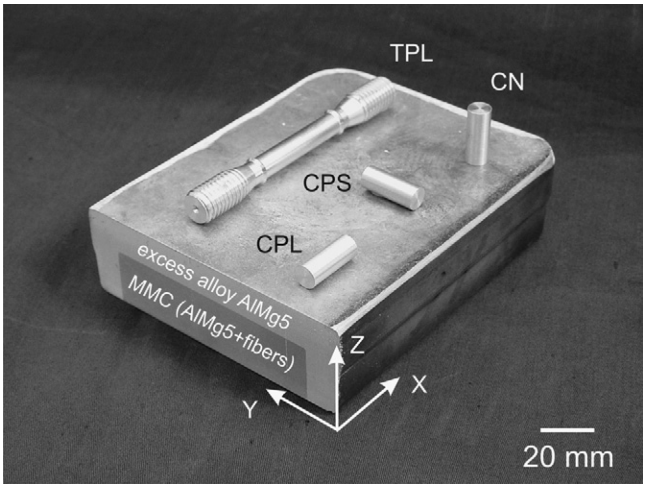

Fig. 1. AlMg5-block obtained by squeeze casting. The dark rectangular region in the lower part of the block represents the fiber reinforced MMC (AlMg5 + fibers). The image shows the specimen geometries and orientations considered in the present study.

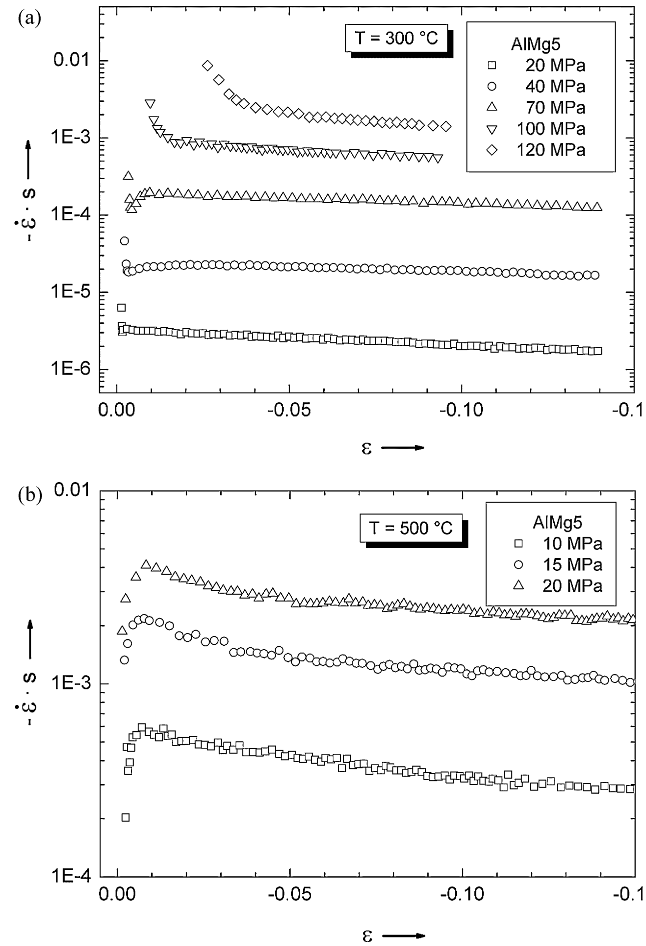

Fig. 2. Creep behavior of the non-reinforced AlMg5 matrix alloy at (a) 300 °C and (b) 500 °C.

of phenomenological back-stress (temperature-dependent threshold stresses) and load transfer concepts [4,11,12]. However, these approaches do not provide insight into the underlying microstructural deformation processes as pointed out in Refs. [7,13].

The main objective of the present study is to compare the compression creep properties of AlMg5 (a type I alloy) and the corresponding MMC in an extended temperature and stress parameter field (300–500 °C, 10–120 MPa). The results allow for comparison of the creep behavior of the reinforced and non-reinforced alloy under similar stress-temperature conditions. Furthermore, the importance of creep anisotropy in the MMC due to preferentially oriented fibers is investigated. Microstructural investigations before and after creep allow for identification of features which may have an impact on creep behavior. Lastly, the initial distribution of fibers in the microstructure and the accumulation of fiber damage during creep with a special focus on fiber clusters were examined.

2. Material and experimental procedures

Experiments were performed using a binary AlMg5 (wt.%) solid solution alloy and the corresponding MMC, which was produced by pressure infiltration of this same alloy into fiber preforms with 15 vol.% of Saffil (Al_2O_3) fibers. Creep properties of this alloy and the corresponding MMC were determined and compared. Details about the alloy composition, fiber preforms, suppliers, and squeeze casting procedures have been reported in Refs. [14,15].

Cylindrical compression creep specimens of 8 mm in diameter and a height of 20 mm were taken from the squeeze cast block as shown in Fig. 1 by spark erosion machining. The non-reinforced specimens were obtained from the upper part of the block (alloy). The MMC specimens were obtained from the lower reinforced part of the block (dark contrast representing the infiltrated fiber preform). The MMC exhibits a random planar fiber texture with the random planar fiber plane parallel to the *X*–*Y* plane defined in Fig. 1 [15]. The different types of creep specimens shown in Fig. 1 are referred to as CN (*c*ompression *n*ormal to random planar fiber plane), CPS (*c*ompression *p*arallel to *s*hort transverse direction of the fiber plane) and CPL (*c*ompression *p*arallel to *l*ong transverse direction of the fiber plane). The tensile specimens (TPL) were used for creep experiments in a previous study [7] and are not considered here. Compression creep testing was chosen for two reasons. Firstly, it allows to study the deformation behavior up to much higher strains. In tensile testing under similar conditions rupture occurs at strains of 2% [7]. On the other hand, the smaller volume of material required for compression creep specimens allows to perform more creep experiments for one MMC cast block. This allows detailed studies, including the orientation dependence of creep rate.

Creep tests were performed at temperatures of 300 °C and 500 °C under constant load conditions following the procedures described elsewhere [16].

Metallographic cross-sections for microstructural investigations were prepared following standard procedures, involving grinding and subsequent polishing with diamond and oxide-dispersion suspensions.

3. Results and discussion

3.1. Creep behavior of the matrix alloy

In order to compare with the AlMg5 MMC, the creep properties of the AlMg5 matrix alloy at 300 °C and 500 °C were examined first, see Fig. 2. The 300 °C experiments show decreasing primary creep rates and nearly constant secondary creep rates. Similar primary creep regimes for AlMg5 have been reported in Dragone et al. [1]. Unlike the 300 °C experiments, the 500 °C experiments exhibit typical alloy type I creep behavior of AlMg5, where early creep rates increase due to an increase of the density of mobile dislocations [17].