The Creep Resistance of Short-Fibre Reinforced Metal Matrix Composites

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Abstract. The creep resistance of two discontinuously reinforced with 20 vol.% alumina short-fibres magnesium composites were examined by performing a comparison between the creep properties of these composites and their magnesium matrix alloys AZ 91 and QE 22. It was found that the magnesium AZ 91 composite exhibits an improved creep resistance arising mainly from an efficient load transfer effect and the existence of a threshold stress, respectively. By contrast, the beneficial effect of reinforcement and the improved creep resistance of the QE 22 composite is significantly influenced by the creep loading conditions.

Keywords: Magnesium composites · Creep resistance · Reinforcement

1 Introduction

The creep resistance of magnesium alloys is rather limited at elevated temperatures. However, a marked improvement in the creep properties of magnesium monolithic alloys can potentially be achieved through the production of composite materials, where the matrices consist of conventional magnesium alloys which are strengthened through the introduction of non-metallic fibres or particulates to form metal matrix composites (MMCs) [1]. The most fundamental issue of the creep behaviour of these composites is the determination of the mechanism(s) by which the creep life of the composite is increased by reinforcing the creep matrix with less-creeping non-metallic short-fibres or particulates. Once the mechanism is clarified, one can design new MMC with higher creep resistance by tailoring constituent parameters of the matrix alloy and short fibre phases.

This work reports the experimental results obtained in an investigation of the high temperature creep behaviour of short-fibre reinforced AZ 91 and QE 22 matrix-based composites and their monolithic alloys. The objective of the present research is a further attempt to clarify the creep strengthening and creep resistance in short-fibre reinforced magnesium alloys.

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2 Experimental

All the experimental materials used in this work were fabricated at the Technical University of Clausthal, Germany. Short-fibre reinforced and unreinforced blocks of the common AZ 91 alloy (Mg-9 wt%Al-1 wt%Zn-0.3 wt%Mn) and the high strength silver-containing QE 22 alloy (Mg-2.5 wt%Ag-2.0 wt%Nd rich rare earths-0.6 wt%Zr) were processed by squeeze casting [2]. The fibre preform consisted of planar randomly distributed δ-alumina short fibres (Saffil Al_2O_3 fibres ~ 5 μm in diameter with varying lengths up to an estimated maximum of ~ 150 μm). The final fibre fraction after squeeze casting in both composites was about 20vol.%. For convenience, the composites are henceforth designated AZ 91 + Saffil and QE 22 + Saffil. All materials were subjected to a T6 heat treatment [2].

Flat creep specimens with a 25 mm gauge length and 3×3.2 mm^2 cross-section were machined from the blocks so that the longitudinal specimen axes parallel to the plane in which the long axes of the fibres were situated. Constant stress tensile creep tests were carried out at temperatures from 423 K to 523 K and at applied stresses from 20 to 200 MPa. The creep elongations were measured using a linear variable differential transducer (W2K from Hottinger-Baldwin Co., Germany) and continuously recorded digitally and computer-processed.

Metallographic and fractographic investigations were conducted after creep testing using scanning electron microscope Lyra 3 TESCAN.

3 Creep Strengthening of the Composite

At present it is generally accepted that creep deformation in metal matrix composites is controlled by flow in the matrix materials [2]. Creep strengthening of the magnesium composites may occur by either direct or indirect mechanisms [1] as it is illustrated in Fig. 1. Direct strengthening is due to a load transfer from the matrix to the reinforcements. Thus, load transfer is accompanied by a redistribution of stresses in the matrix and this reduces the effective stress for creep. Indirect strengthening occurs when the presence of the reinforcements or the process used to manufacture the composite influence the matrix microstructure which could modify the creep resistance. Potential microstructural effects include changes in the dislocation arrangements, accelerated ageing, microstructural decomposition, a matrix chemical compositional variation, and/or a reinforcement transformation. As a result, the microstructural changes in the matrix of the composite can retard and/or inhibit dislocation motion and lead to a threshold for creep that increases the creep resistance.

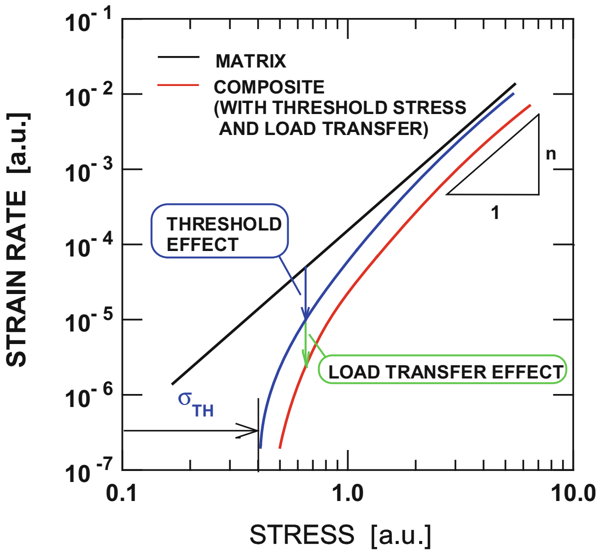


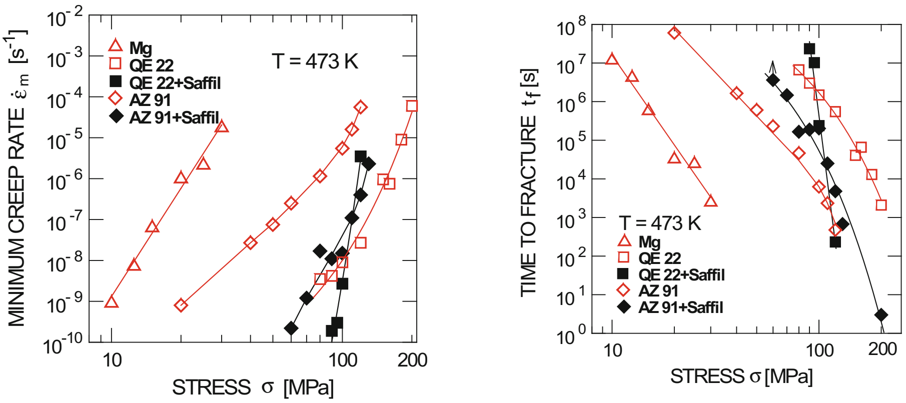
Fig. 1. A schematic illustration of the power law creep in conjunction with the effects of the threshold stress and load transfer.

4 Results and Discussion

4.1 Creep in Monolithic and Fibre-Reinforced AZ 91 and QE 22 Alloys

The most important creep data for the AZ 91 and QE 22 alloys and their composites at a testing temperature of 473 K are shown in Fig. 2, where the minimum creep $\dot{\varepsilon}_m$ rate $\dot{\varepsilon}_m$ and the time to fracture t_f are plotted against the applied tensile stress σ on a double logarithmic scale. Inspection of the creep data in Fig. 2(a) leads to two observations. First, the AZ 91 + Saffil composite exhibits an improved creep resistance (that means a substantial decrease of the minimum creep rate $\dot{\varepsilon}_m$), typically by >2 orders of magnitude in comparison with the monolithic alloy and, therefore, the trends of these plots are different because the unreinforced alloy exhibits a decreasing value of the true stress exponent of the creep rate $n = (\partial \ln\dot{\varepsilon}_m / \partial \ln\sigma)_T$ at the lower stresses, whereas the composite exhibits a higher value of n with decreasing stress. Second, the creep resistance of the QE 22 + Saffil composites is also somewhat better than that the unreinforced alloy but at the low stresses ($\sigma \leq 100$ MPa) only.

Figure 2(b) shows the variation of the time to fracture with the stress for the same specimens tested in Fig. 2(a). The results for AZ 91 alloy and its composite demonstrate the creep lifetimes of the composite are up to one order of magnitude longer than that for the monolithic alloy at low stresses, although this difference decreases with increasing applied stress so that ultimately there is very little difference at stresses $\sigma > 100$ MPa. By contrast, the creep life of the QE 22 + Saffil composite is markedly shorter than that of the unreinforced alloy at stresses > 100 MPa.



(a) (b)

Fig. 2. Stress dependences of (a) minimum creep rate and (b) time to fracture for the monolithic magnesium alloys and their short-fibre composites.

In conclusion, it was found that the presence of reinforcement leads to a substantial decrease in the overall ductility of the monolithic alloys. Thus, the values of the strain to fracture ε_f in both composites were only ≈1–2%. By contrast, the strains to fracture in the monolithic alloys were significantly higher, typically up to 15% in the AZ 91 alloy and up to 30% in the QE 22 alloy.

Despite the general similarity of the creep behaviour of both composites, the presence of the same composition and amount of a short-fibre reinforcement in the unreinforced AZ 91 and QE 22 alloys results in a significantly different improvement of the creep resistance of composite by comparison with the matrix alloy. Thus, it will only be appropriate here to analyse differences that can be inferred from a comparison between the creep strengthening mechanisms of both composites and the unreinforced alloys (Fig. 1).

4.2 Direct Strengthening Due to a Load Transfer

As already shown in Fig. 2(a), the presence of short fibre reinforcement could lead to a reduced creep rate in both composites. Such effect can arise when significant load transfer partitions the external load between the matrix and the reinforcement. In the presence of load transfer, the creep data may be successfully reconciled by putting the ratios of the minimum creep rates of the composite and the rates of the matrix alloy at the same loading conditions, equal to a factor given by $(1 - \alpha)^n$, where α is a load transfer coefficient having values lying within the range from 0 (no load transfer) to 1 (full-load transfer). Thus, the values of α inferred from the data for the unreinforced AZ 91 and its composite in Fig. 2(a) using $n = 3$ are within the range of 0.8 to 0.9. The predicted values α are in reasonable agreement with the theoretical prediction according to an analytical treatment based on a modified shear-lag model. Unfortunately, values of the load transfer coefficient α, for the QE 22 composite cannot be rigorously obtained due to insufficient creep data inferred from this study. The indicative experimentally estimated values of α, for which the rate of the composite $\dot{\varepsilon}_c < \dot{\varepsilon}_m$ were found to be 0.11 and 0.26 for 423 and 523 K, respectively.

4.3 Indirect Strengthening Due to a Threshold Stress σ_0

Having only a small number of experimental points it was appropriate to make use of the procedure in which it is possible to estimate the magnitude of σ_0 by plotting the data on linear axes as $(\dot{\varepsilon})^{1/n}$ against σ and linearly extrapolating the data to give the threshold stresses at a zero strain rate. A plot of this type requires, a priori, a judicious selection of the appropriate value of the true stress exponent, *n*. Figure 3 shows the determination of the threshold stress for the unreinforced AZ 91 alloy (Fig. 3(a)) and its composite (Fig. 3(b)) in double linear coordinates. Detailed inspection of the individual plots shows that a true stress exponent of 3 yields the best linear fit – Fig. 3(b). The finding of $n = 3$ provides support for adopting the suggestion that the AZ 91 composite exhibits creep behaviour which is consistent with the behaviour anticipated for magnesium solid solution alloys. Similar results for QE 22 alloy and its composite show that, while no threshold stress was found in the case of monolithic QE 22 alloy, the values of the threshold stress of the composite at 473 K and 523 K were estimated as 22 MPa and 18 MPa, respectively.

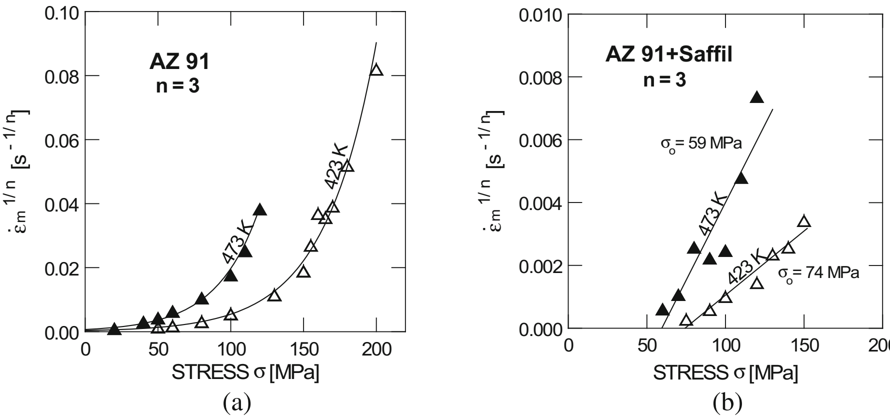


Fig. 3. Procedure for determining the threshold stress σ_0 with its estimated values: (a) AZ 91 alloy (no threshold stress), (b) AZ 91 composite.

It was mentioned earlier, that indirect strengthening may be caused by the microstructural changes in the material. In our previous studies [2] we found that the threshold stress values are closely connected with the development of a continuous precipitate morphology of $Mg_{17}(Al, Zn)_{12}$ particles. Further, it was observed that the fibres in the QE 22 composite can act as nucleation centre in the precipitation process, promoting precipitation of Al_2Nd, $Mg(Al)_{12}Nd$ and Mg_3Ag phases.

4.4 Matrix/Reinforcement Bonding

The creep behaviour of the composites may be substantially influenced by the matrix/fibre interfaces. Weak matrix/reinforcement bonding may lead to inferior creep properties of the composite. Thorough fractographic investigations of the AZ 91 composite did not reveal either substantial creep fibre cracking and breaking or any substantial debonding at the interfaces between the fibres and the matrix due to creep. By contrast, and intensive debonding was revealed at the fracture surfaces at the QE 22 composite. Thus, in the limit of zero interface strength, where no stress can be transmitted to the fibres, the composite may be weaker than the matrix alone. Detailed fractographic investigation revealed enhanced precipitation of secondary phases at the interfaces in the AZ 91 composite, which can favourably affect the strength of the matrix/fibre interface and thus the creep behaviour of the composite (Fig. 4).

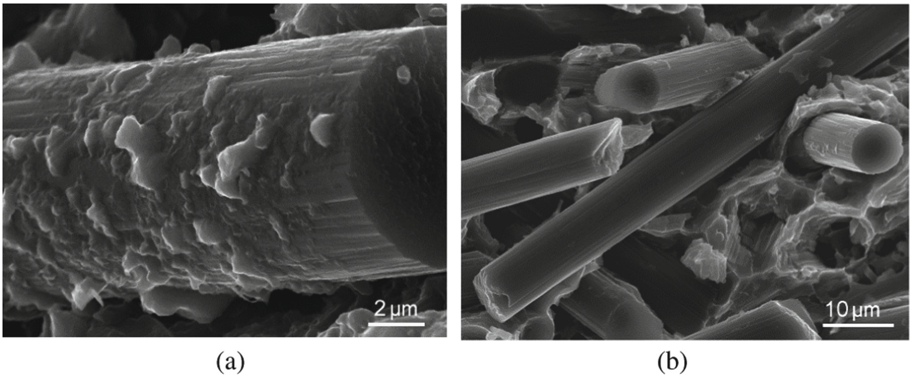


Fig. 4. Creep fracture surface: (a) good interface bonding due to an occurrence of precipitates at the fibre surface (AZ 91 composite), (b) weak cohesion of the interface due to clean fibre surface (QE 22 composite).

5 Conclusions

Creep strengthening in the composite arises mainly from the load transfer and the existence of a threshold stress. The load transfer occurs by plastic deformation of the matrix being limited by the intact bond of the fibre and enhanced precipitation of secondary phases.

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