INFLUENCE OF MATRIX COMPOSITION ON CREEP OF ALUMINIUM-BASED COMPOSITES

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ABSTRACT

Creep of pure aluminium, aluminium-magnesium solid solution and their composites reinforced with 20 vol. % of Saffil fibres was studied by compression testing and small punch testing at 623 K. For both types of test, two basic orientations of specimens were employed: (i) stress axis perpendicular to the random planar fibre plane and (ii) stress axis parallel to the fibre plane. The minimum creep rate and the minimum deflection rate were determined and their dependence on stress and force was found. The contributions of Mg atoms and of perpendicular and parallel fibres to creep resistance were evaluated. The results are discussed in terms of the threshold concept and of the strengthening coefficient and by means of the shear-lag models.

1. INTRODUCTION

Aluminium based composites exhibit many favourable characteristics that offer them a potential for use as structural materials for elevated temperature applications. An important role in improving the creep resistance is quite certainly played by the reinforcement. Nevertheless, the experimental results demonstrate that the creep of such metal matrix composites is controlled by the rate of deformation within the matrix alloy. A full understanding of creep behaviour thus needs a complex study of the influence of both the solution and precipitation strengthening in the matrix and the shape and geometry of reinforcement. An evaluation of creep mechanisms requires a close comparison between the creep behaviour of a composite and that of its unreinforced matrix alloy under similar experimental conditions. The results of some as yet published investigations lead to controversial conclusions about the effect of solution strengthening [1, 2]. The aim of the present paper is to compare creep behaviour of a set of aluminium-based alloys (pure aluminium and binary aluminium solid solution) prepared by an identical technology with and without reinforcement by short alumina fibres.

Two different techniques were used for creep testing: the tests were performed either in small punch mode or in compression. Both techniques require reduced volume of specimens in comparison with conventional tensile creep tests and thus the effect of reinforcement inhomogeneities can be partly diminished. Moreover, the small punch testing offers the possibility to test different orientations by tensile mode of straining. This possibility is not accessible by conventional tensile creep tests due to dimensional limitations of the composite preparation [3].

2. EXPERIMENTAL

For experiments, the aluminium alloys and their composites with approx. 20 vol. % of Saffil fibres were prepared by squeeze casting at the Department of Material Engineering and Technology, TU Clausthal-Zellerfeld, Germany. Fibre pre-form for the composite consisting of planar randomly distributed Saffil fibres was used. The fibres were supplied by ICI Chemicals & Polymers Ltd, Runcorn, Cheshire, UK. They contained 97% Al_2O_3 and 3% SiO_2 and their average diameter and length were 3 μm and up to 150 μm, respectively. The preforms of Saffil fibres had a shape of rectangular parallelepipeds with dimensions 70 x 70 x 20 mm. The dimensions of cast blocks were cca. 100 x 100 x 50 mm. The matrix was pure aluminium (99.99%) and aluminium with 5.5 wt. % Mg. The same technology was used to cast the blocks with and without Saffil fibres.

Cylinders of 8 mm in diameter were machined from the cast blocks. The slices 1.2 mm in thickness were spark cut from these cylinders for preparation of specimens for small punch tests. The slices were then thinned to plan-parallel discs by means of conventional procedures used for the preparation of surfaces for metallographic observation, i.e., by grinding and polishing (to 1200 grit), equally from both sides of the disc to a thickness of 0.5 mm. Only discs with uniform distribution of fibres were used for the testing.

Specimens for compression testing were prepared by cutting parallelepipeds 6 x 6 x 12 mm. Two basic possibilities of such cutting exist with respect to the orientation of the fibres: (i) the compression stress axis is perpendicular to the random planar fibre plane and (ii) the compression is parallel to the fibre plane. These possibilities correspond to the designation (i) CN and (ii) CP that was used in the analogical investigation of similar random planar composites [3]. The same possibilities were also considered in the preparation of specimens for the small punch testing: (i) the disc plane was either perpendicular to the fibre plane or (ii) the disc plane was parallel to the fibre plane. It is assumed that during the small punch test an equibiaxial tension dominates in the secondary stage of the test and so the orientations (i) and (ii) correspond to the same orientations in the compressive test.

For small punch testing, a constant load cantilever creep machine was adapted. During the test, a precise ceramic ball made of FRIALIT F99.7, 2.5 mm in diameter, is pushed with a constant force against a specimen supported by a 4-mm diameter receiving die (lower die). The disc specimen is clamped by an upper die. Central deflection was measured as the difference in the positions of the punch and lower die, using a linear variable differential transformer W2K from Hottinger-Baldwin Co. (Germany) and was continuously recorded with a PC. The technique is described in more detail elsewhere [4, 5].

Compressive creep tests were performed at constant stress on a special cantilever machine. The stress was maintained constant by means of modified Hofman’s principle [6]. Displacement during compression testing was measured as the difference between the loading plates of a compression cage.

The compressive tests, as well as small punch tests were performed at temperature 623 K. During the test, temperature was kept constant within ± 1 K. The tests were performed in protective argon atmosphere.

3. RESULTS & DISCUSSION

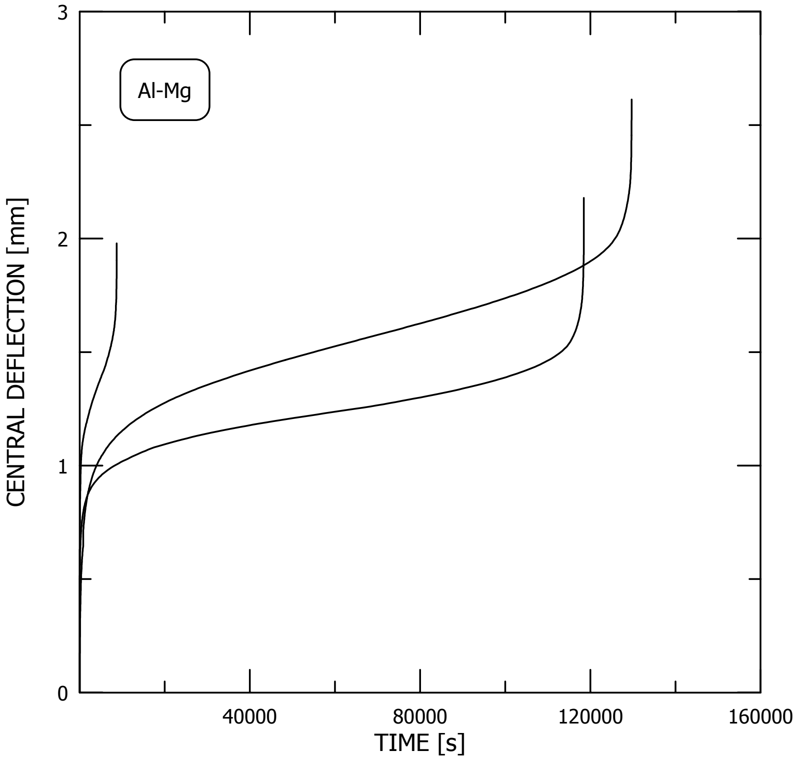
Examples of time dependence of the central deflection (in small punch tests) and of the strain (in compression creep test) are given in Figs. 1 and 2, respectively. A typical high temperature creep behaviour with decelerating primary stage and accelerating tertiary stage can be observed in both type of tests for all materials and orientations. In small punch tests, the behaviour of unreinforced and reinforced material differs mainly by the value of the maximum deflection observed at rupture. A significant difference is observed in the shape of the creep curves in compression tests. The decrease of the creep rate in the primary stage in reinforced composites is more pronounced than in matrix materials. The same behaviour in similar aluminium composites was attributed to load transfer to the fibres [2]. The difference in tertiary stage is even more evident: The acceleration of the creep rate is weak in unreinforced materials and it is very significant in composite materials, especially in materials with fibre plane parallel to the stress axis. In the latter case, the specimen splits into several fragments.

The minimum deflection rate and the minimum creep rate can be evaluated from the plots of deflection vs. time and creep strain vs. time, respectively. The dependence of the minimum deflection rate $\dot{\delta}$ and the minimum creep rate $\dot{\varepsilon}$ on the applied force F and on the applied stress σ, respectively, is given in figures 3 to 6. Both dependences could be described by the power functions of the Norton type:

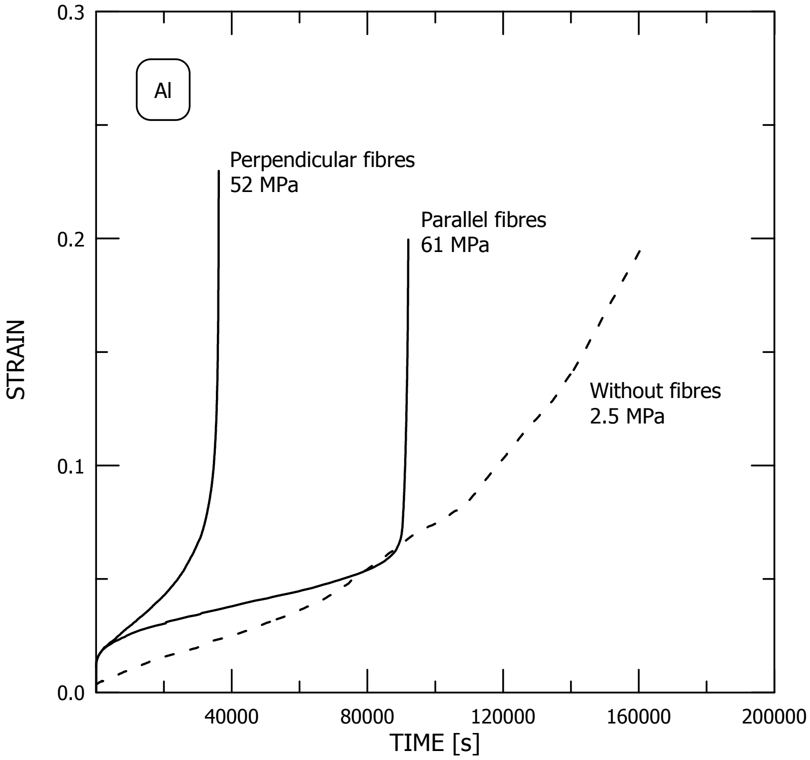
$$\dot{\delta} = A_{\mathrm{SP}} F^{p} \tag{1}$$

$$\dot{\varepsilon} = A_{\mathrm{CC}} \sigma^{n} \tag{2}$$

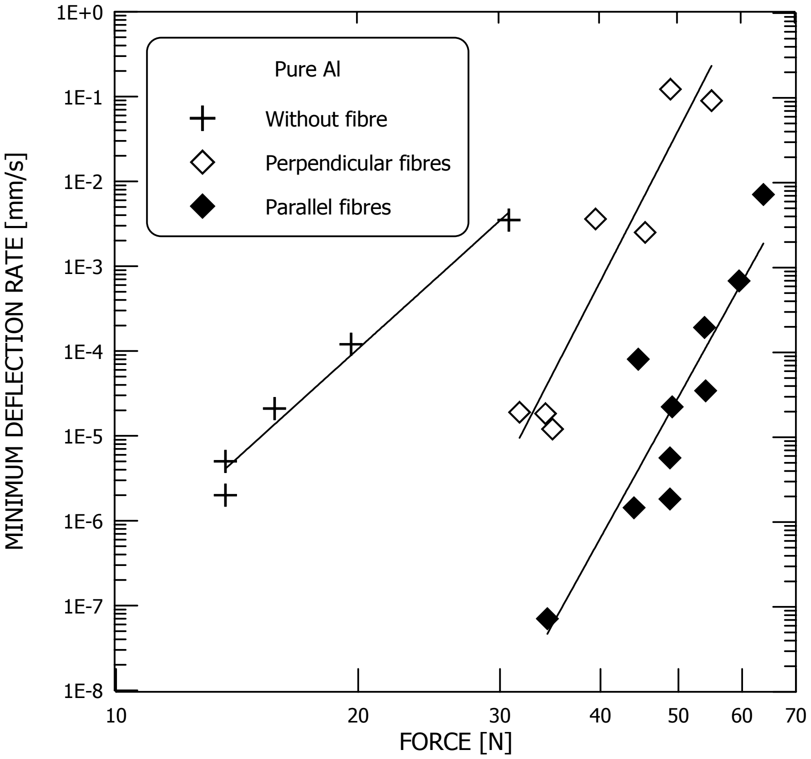
where A_{SP} and A_{CC} are temperature dependent constants and p and n are force and stress exponents, respectively. The values of exponents are given in Tables 1 and 2. The exponents follow approximately the same pattern in both tests. The exponents are appreciably greater in composites than in unreinforced matrices. The exponent of small punch test in Al-Mg alloy is in agreement with the value reported for tensile creep test in this type of solid solutions. The value of the same exponent in pure Al is probably influenced by swaying of the deflection rate that is caused by recrystallization. On the other hand, it is not clear why the value of the stress exponent in compression test of Al-Mg is greater than the value of exponent in pure aluminium.



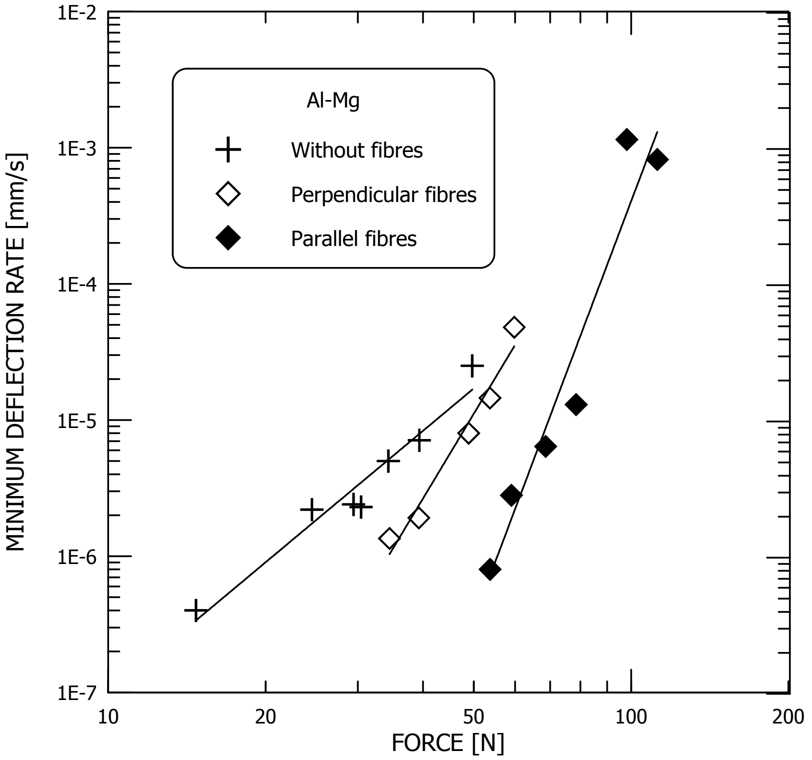
“**Fig. 1.** Examples of creep curves in small punch testing of Al-Mg materials.”



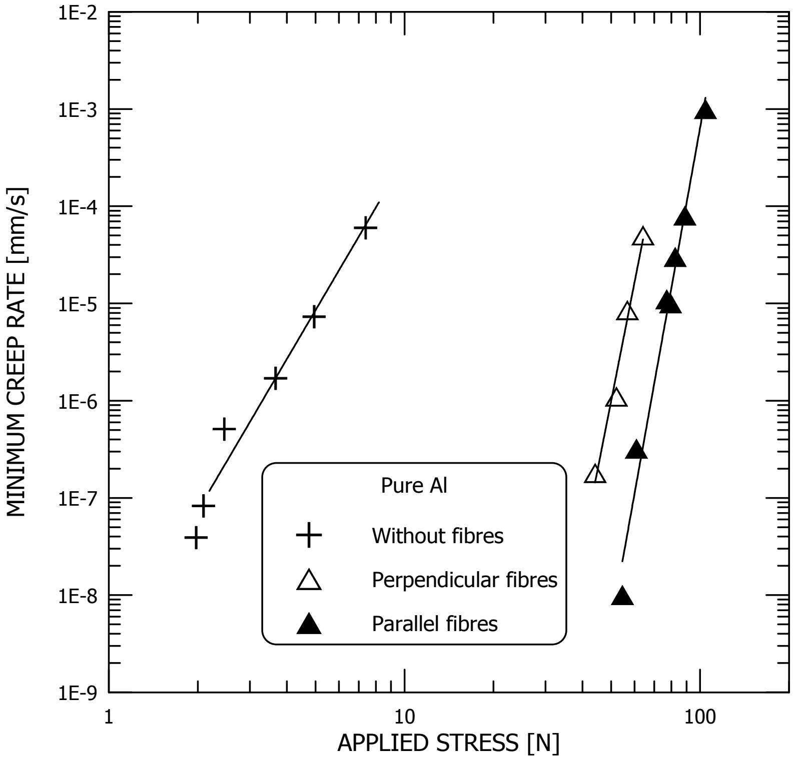
"**Fig. 2.** Examples of creep curves in compression testing of Al materials."



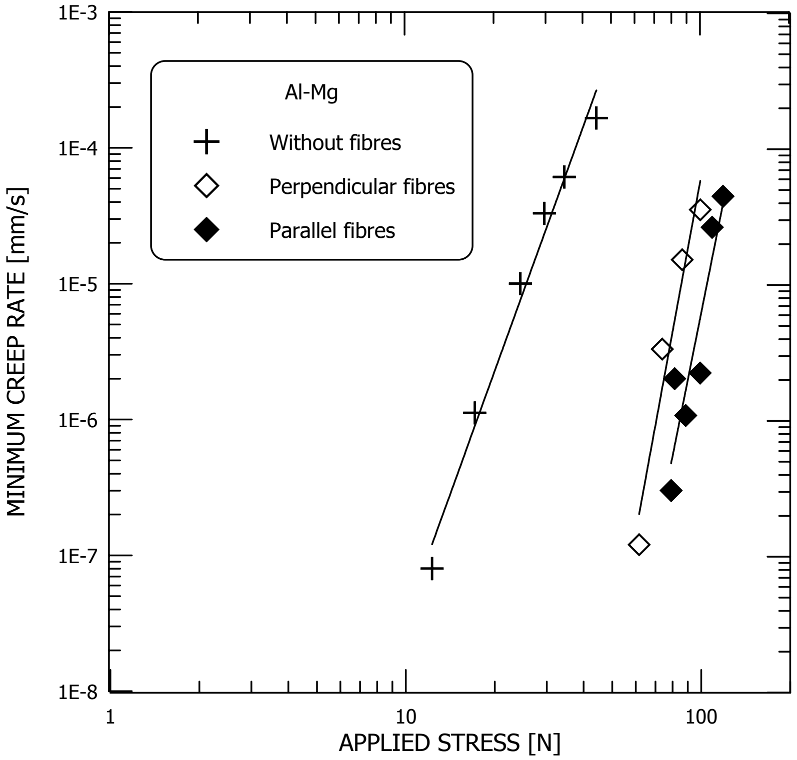
"**Fig. 3.** Force dependence of minimum deflection rate in Al materials."



“**Fig. 4.** Force dependence of minimum deflection rate in Al-Mg materials.”



“**Fig. 5.** Dependence of minimum creep rate on applied stress in Al materials.”



“**Fig. 6.** Dependence of minimum creep rate on applied stress in Al-Mg materials.”

“**Table 1.** Force Exponents in Small Punch Tests.”

Matrix	Without fibres	Perpendicular fibres	Parallel fibres
Al	8.57	18.39	17.13
Al-Mg	3.21	6.39	10.18

“**Table 2.** Stress Exponents in Compression Tests.”

Matrix	Without fibres	Perpendicular fibres	Parallel fibres
Al	5.18	15.43	16.98
Al-Mg	6.01	11.84	13.57

For the quantitative evaluation of the contributions of solution strengthening and fibre strengthening we can use the stress to cause the minimum creep rate equal to 10^{-7} 1/s. This criterion corresponds approximately to creep resistance evaluated by Mileiko [7] as the stress to cause 1 % creep strain in 100 h. The alloying of aluminium by magnesium increases this stress by 10 MPa. The fibre reinforcement increases the stress by 40 MPa for perpendicular orientation of fibres and by approx. 56 MPa for parallel orientation in both pure aluminium and Al-Mg matrices.

4. DISCUSSION

For an interpretation of high values of creep exponents in metal matrix composites, the threshold concept is frequently used [8, 9]. According to this concept, the creep rate is given by

$$\dot{\varepsilon} = A_{\mathrm{CC}}[(1-\alpha)\sigma - \sigma_0]^n \tag{3}$$

where σ_0 is the threshold stress, α the load transfer coefficient (α=0 in an absence of load transfer) and parameter A_{CC} and exponent n have the same values as observed in unreinforced matrices. We can apply this approach to the results of compression creep tests and evaluate the load transfer coefficient and the threshold stress by means of the least square method. The results are given in Table 3. The load transfer coefficient is approximately independent of specimen orientation and it is greater in Al-matrix composites than in Al-Mg composites, which is quite reasonable. The threshold stress is dependent on both the specimen orientation and the matrix composition. Such dependence can also be expected. On the other hand, a physical nature of the threshold stress and its proper interpretation is not yet clear. Equation (3) is predicted e.g. by McLean [10] for continuous elastic fibres embedded in plastic matrix with

$$\alpha = 1 - \frac{1}{\left[1 + \frac{E_{\mathrm{f}} V_{\mathrm{f}}}{E_{\mathrm{M}}(1-V_{\mathrm{f}})}\right]^{1/n} (1 - V_{\mathrm{f}})} \tag{4}$$

$$\sigma_0 = \varepsilon_{\mathrm{c}} E_{\mathrm{f}} V_{\mathrm{f}} (1-\alpha) \tag{5}$$

where V_{f} is the volume fraction of fibres and E_{m} and E_{f} are elastic moduli of the matrix and of fibres, respectively. The threshold stress in eq. (5) is proportional to creep strain ε_{c}. We can assess the creep strain corresponding to the experimental parameters σ_0 and α from Tab. 3 as ranging from 0.0006 to 0.0009 and thus far below creep strain for which the minimum creep rate was observed (~0.02).

"**Table 3.** Parameters of the Threshold-Stress Approach in Compression Tests."

Matrix	Perpendicular fibres		Parallel fibres	
	Load transfer α	Threshold stress [MPa]	Load transfer α	Threshold stress [MPa]
Al	0.76	8.52	0.79	10.9
Al-Mg	0.47	19.6	0.49	27.4

Another group of theories [11, 12] suggests to include the effect of fibres directly into the applied stress function as a strengthening coefficient λ

$$\dot{\varepsilon} = A_{\mathrm{CC}} \left(\frac{\sigma}{\lambda}\right)^n \tag{6}$$

The parameters A_{CC} and n should have again the same values as in unreinforced matrix material. The equation fails in explaining the stress exponents in composites. An estimate of λ

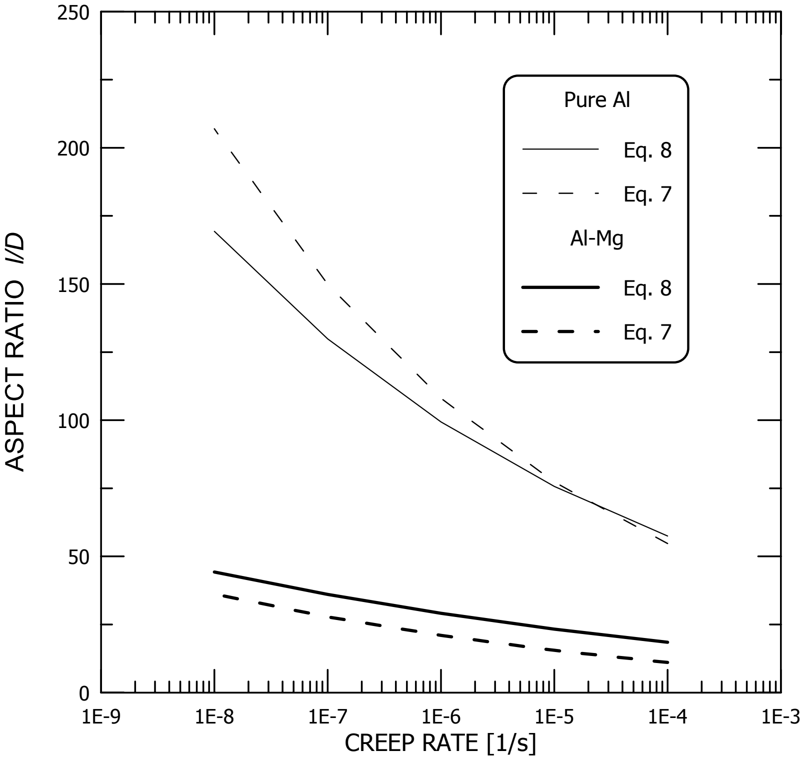
$$\lambda = 1 + 2\left(2 + \frac{l}{D}\right) V_{\mathrm{f}}^{3/2} \tag{7}$$

(*l* and *D* are length and diameter of fibres, respectively) is quite good for composites with fibre plane parallel to stress axis, especially for composite with Al-Mg matrix (see below).

The mechanical behaviour of discontinuous fibre composites is frequently described by means of the shear-lag models [13, 14]. One version of these models leads to eq. (6) with the strengthening coefficient [14]

$$\lambda = \left(\frac{2}{3}\right)^{\frac{1}{n}} \left(\frac{n}{2n+1}\right) \left[\left(\frac{2\sqrt{3}V_\mathrm{f}}{\pi}\right)^{-\frac{1}{2}} - 1 \right]^{-\frac{1}{n}} V_\mathrm{f} \left(\frac{l}{D}\right)^{\frac{n+1}{n}} + 1 - V_\mathrm{f} \tag{8}$$

The predicted stress exponents are again smaller than the experimental ones. This deficiency can perhaps be overcome by taking the breakage of the fibres into account. We can find the strengthening coefficient by comparing the creep rates of the matrix and the corresponding composite and calculate the necessary aspect ratio *l/D* from eqs. (7) and (8), respectively. The results are given in Fig. 7. The decrease of the aspect ratio or, in other words, the decrease of the fibre length with the increasing creep rate is in agreement with the expectance. The breakage of fibres is explicitly taken into account in some modifications of the shear-lag models [7, 15, 16]. Applicability of these modifications is critically sensitive to the knowledge of necessary additional materials characteristics, e.g. the boundary factor [15] or the coefficient of continuity of the fibre/matrix interface [7]. Very good agreement can be obtained for the Mileiko theory [7] with the coefficient of continuity equal to 0.065 in aluminium and 0.1 in Al-Mg composites, respectively.



“**Fig. 7.** Dependence of calculated aspect ratio on creep rate.”

The shear-lag models enable also to obtain insight into the dependence of creep properties on the orientation of specimens. Ryu and Hong [17] proposed to consider the effective aspect ratio that depends on the fibre orientation with respect to stress axis: for fibres perpendicular to stress axis the effective aspect ratio is

$$S_{\mathrm{ef}} = \left(\frac{3\pi - 4}{3\pi}\right)\left(1 + \frac{D}{l}\right) \tag{9}$$

(The effective aspect ratio for parallel fibres is equal to *l/D*.) They calculated the strengthening coefficient on the base of load transfer equation [18] as

$$\lambda = \frac{1 + 0.5 * S_{\mathrm{ef}} V_{\mathrm{f}}}{1 - V_{\mathrm{f}}} \tag{10}$$

We get from eq. (10) the strengthening coefficient for parallel orientation ranging from 5 for *l/D*=30 to 7.5 for *l/D*=50. This is in very good agreement with the data for compression creep in Al-Mg composite. The calculated strengthening coefficient for perpendicular fibres is not very sensitive to the aspect ratio *l/D* and it is equal approx. to 1.32. This is substantially less than observed in compression creep experiments in both types of matrices.

5. CONCLUSIONS

Creep of pure aluminium, aluminium-magnesium solid solution and their composites reinforced with 20 vol. % of Saffil fibres was studied by compression testing and small punch testing at 623 K. From the results obtained in the present study the following conclusions can be drawn:

- Exponents that characterize stress and force dependence of creep rate in reinforced materials are substantially higher than those in unreinforced matrices.

- The results can be phenomenologically described by the equation of the threshold stress concept. The physical nature of this threshold stress remains unclear.

- The shear-lag models can explain the observed creep behaviour. More effort is necessary to explain different strengthening coefficients in different matrices.

- The behaviour of composites with fibre plane perpendicular to the stress axis cannot be explained in terms of the effective aspect ratio.

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