BACK STRESSES IN CREEP OF 2024Al-SAFFIL FIBRE COMPOSITE

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ABSTRACT
The aim of the present paper is to compare creep behaviour of aluminium-based alloy (2024AA) prepared by an identical technology with and without reinforcement by short alumina fibres and with two different orientations of fibres. The observed behaviour is analyzed in terms of back stresses obtained by threshold stress approach from steady-state data or by the internal stress approach with the values of internal stress found by an analysis of primary creep data.

1. INTRODUCTION
The dependence of creep rate $\dot{\varepsilon}$ on applied stress σ is usually described by the power function of the Norton type:

$$\dot{\varepsilon} = A_C \sigma^n , \quad (1)$$

where A_C is temperature dependent constant and n is stress exponent. The values of n are taken as an indication of potential creep controlling mechanisms. When dislocation motion controls creep deformation of pure metals and single phase solid solutions, a value of n from 3 to 5 is expected: $n = 3$ is typical of Class I alloys, $n = 5$ of Class II alloys [1]. Values of n can be substantially greater in alloys reinforced with particles of secondary phases. The creep behaviour can be rationalized by the threshold stress concept [2]: the stress dependence of the creep rate is rewritten as

$$\dot{\varepsilon} = A'(\sigma - \sigma_{th})^{n'} , \quad (2)$$

where σ_{th} is the threshold stress. The value of n' should be close to the value of n observed in pure metals and single-phase solid solutions. However, the creep rates at accordingly adjusted stresses are faster in the matrix alloys than in the composites. There is the possibility that, through the process of load transfer, part of the external load is carried by the reinforcement and there is a consequent reduction in the effective stress acting on the material. The effective stress in the presence of load transfer, σ_{ef}, may be expressed in the form [2]

$$\sigma_{ef} = (1 - \alpha)\sigma - \sigma_{th} , \quad (3)$$

where α is the load transfer coefficient. There may be also a substructural strengthening within the matrix due to e.g. an increase in the dislocation density. This strengthening may be incorporated into the analysis through the introduction of an effective stress and described by the same formalism [2]. In spite of these sophisticated approaches, the physical nature of the threshold stress is not yet clear. The aim of the present contribution is to find the values of the threshold stress and to compare it with the internal stress acting against dislocation motion.

2. EXPERIMENTAL

For experiments, the aluminium alloy and its composite with approx. 20 vol. % of Saffil fibres were prepared by squeeze casting at the Zentrum für Funktionswerkstoffe gGmbH Clausthal, Germany. Fibre preforms for the composite consisting of planar randomly distributed Saffil fibres were used. The preforms were supplied by ICI Chemicals & Polymers Ltd, Runcorn, Cheshire, UK. The fibres 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 approx. 100 x 100 x 50 mm. The matrix was aluminium alloy AA2024. The matrix contained nominally 3.8-4.9 wt. % Cu, 1.2-1.8 wt. % Mg, 0.3-0.9 wt. % Mn and max 0.5 wt. % Si (bal. Al). The same technology was used to cast the blocks with and without Saffil fibres. Previously published results on pure Al and its fibre composite are used when necessary [3].

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 [4].

Uniaxial 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 [5]. Displacement during compression testing was measured as the difference between the loading plates of a compression cage. The tests were performed in protective argon atmosphere at temperature 623 K. During the test, temperature was kept constant within ± 1 K.

3. RESULTS

The minimum deflection rate and the minimum creep rate can be evaluated from the plots creep strain *vs*. time. The dependence of minimum creep rate $\dot{\varepsilon}$ on the applied stress σ is given in figure 1. The dependences could be described by the eq. (1). The values of exponent *n* are given in Table 1. The exponents are appreciably greater in composites than in unreinforced matrix.

The stress to cause the minimum creep rate equal to 10^{-7} 1/s can be used for the quantitative evaluation of the contributions of matrix strengthening (both solution and precipitation strengthening) and fibre strengthening. This criterion corresponds approximately to creep resistance evaluated by Mileiko [6] as the stress to cause 1 % creep strain in 100 h. The alloying of aluminium by 2024AA additions increases this stress by 30 MPa. The fibre reinforcement increases the stress by 82 MPa for perpendicular orientation of fibres and by approx. 110 MPa for parallel orientation (in comparison with unreinforced 2024AA alloy). These increments are about two times greater than in both pure aluminium and Al-Mg matrices (40 MPa for perpendicular orientation and approx. 56 MPa for parallel orientation).

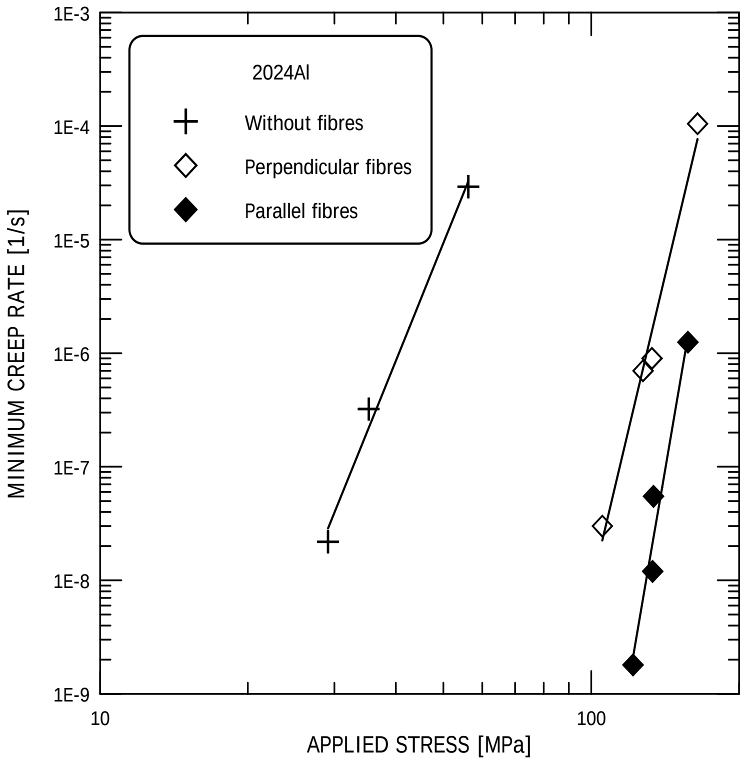

Fig. 1. Dependence of minimum creep rate on applied stress

The threshold stress σ_{th} and the load transfer coefficient α were evaluated from creep rates measured in composites with fibres using the values of parameter A_C and exponent n obtained in unreinforced alloy. The creep rates measured in 2024 alloy without Saffil fibres were evaluated with the values of A_C and n obtained in pure aluminium [3]. The results are given in Table 1.

Table 1: Summary of stress exponents, parameters of threshold stress approach and internal stresses

	Without fibres	Perpendicular fibres	Parallel fibres
Stress exponent	10.45	18.24	25.25
Load transfer coefficient	0.824	0.415	0.459
Threshold stress [MPa]	3.54	34.69	43.72
Apparent threshold stress [MPa]	20.11	59.3	80.8
Particle internal stress [MPa]	10.2	89.4	124.9

4. DISCUSSION

Another back-stress approach used in analysis of creep data is the internal stress concept [7]. It starts from the postulate that the dislocation motion is driven by a difference between the externally applied stress and an internal stress, resulting from resistance of the structure to dislocation motion. In composites, the internal stress is given by a superposition of two components: (i) due to the presence of dispersed particles and fibres and (ii) induced by long-range stress fields of neighbouring dislocations. Whereas for thermodynamically stable particles and fibres the former component is independent of strain, the latter changes with the increasing strain owing to the generation of new dislocations. During the creep test, the initial dislocation structure gradually develops towards its steady-state configuration. Simultaneously the internal stress also changes towards the steady-state value. Depending on its initial value, the internal stress can either increase or decrease during the test. The phenomenon manifests itself as a normal primary creep with a decelerating strain rate in the former case and as an inverse primary creep with an accelerating rate in the latter case. Let us assume that the time derivative of the internal stress is proportional to the difference between the steady-state value and the instantaneous value

$$\frac{\mathrm{d}\sigma_\mathrm{i}}{\mathrm{d}t} = K\left(\sigma_\mathrm{iS} - \sigma_\mathrm{i}\right), \tag{4}$$

where K is a constant. The effective stress dependence of the creep rate is usually described as in ref. 8

$$\dot{\varepsilon} = A\left(\sigma - \sigma_\mathrm{i}\right)^m . \tag{5}$$

Integrating the linearized (i.e. assuming that $m = 1$) equations (4) and (5) with the initial conditions t = 0, $\varepsilon = \varepsilon_0$, $\sigma_\mathrm{i} = \sigma_\mathrm{i0}$ we obtain the equation of creep curve in which the primary creep term is described by the relationship proposed by McVetty

$$\varepsilon = \varepsilon_0 + \varepsilon_1\left[1 - \exp\left(-t/\tau_1\right)\right] + \dot{\varepsilon}_\mathrm{S} t \ , \tag{6}$$

where ε_1 is the primary creep strain

$$\varepsilon_1 = A\left(\sigma_\mathrm{iS} - \sigma_\mathrm{i0}\right)/K = \dot{\varepsilon}_\mathrm{S}\tau_1 \frac{\sigma_\mathrm{iS} - \sigma_\mathrm{i0}}{\sigma - \sigma_\mathrm{iS}} \ , \tag{6a}$$

τ_1 is the relaxation time of primary creep

$$\tau_1 = 1/K \tag{6b}$$

and $\dot{\varepsilon}_\mathrm{S}$ is the steady-state creep rate

$$\dot{\varepsilon}_\mathrm{S} = A\left(\sigma - \sigma_\mathrm{iS}\right). \tag{6c}$$

As it was mentioned above, the internal stress in dispersion-strengthened systems is given by a superposition of components from particles and from dislocations [9]:

$$\sigma = \sigma_\mathrm{iP} + \sigma_\mathrm{iD} . \tag{7}$$

For the steady-state value of dislocation component of the internal stress, we obtain from the above relations

$$\sigma_{iDS} = \frac{\varepsilon_1(\sigma - \sigma_{iP}) + \dot{\varepsilon}_S \tau_1 \sigma_{iD0}}{\varepsilon_1 + \dot{\varepsilon}_S \tau_1}, \tag{8}$$

where σ_{iD0} is the initial value of dislocation induced internal stress. For single-phase alloys this equation reduces to the relation introduced by Ion *et al.* [10] provided that, as assumed in their paper, the initial dislocation internal stress can be neglected. Equation (8) does not enable to calculate the internal stresses σ_{iDS} or σ_{iP} directly from parameters of the creep curves. We suggest the following procedure to estimate these values: The dependence of $\varepsilon_1/(\varepsilon_1 + \dot{\varepsilon}_S \tau_1)$ *vs.* applied stress can be extrapolated to the level $\varepsilon_1/(\varepsilon_1 + \dot{\varepsilon}_S \tau_1) = 1$. At this level, the product $\dot{\varepsilon}_S \tau_1$ must be equal to zero and from equation (8) it follows that

$$\sigma_{iDS} = \sigma - \sigma_{iP}. \tag{9}$$

Thus, the effective stress is equal to zero at this level. It is generally accepted that there is no threshold stress for dislocation creep in single-phase materials. In other words, for zero effective stress the dislocation internal stress σ_{iDS} must be equal to zero. Therefore, the applied stress found by the above extrapolation is equal to the internal stress induced by the dispersed particles σ_{iP}. The procedure is illustrated in Fig. 2. With the exception of the composite with perpendicular fibres, linear extrapolation of the experimental data is quite plausible. The obtained values of the particle internal stress σ_{iP} are given in Table 1. They are not close to the threshold stress determined from the applied stress dependence of the steady-state creep rate. They can perhaps be compared with the apparent threshold stress defined by Li and Langdon [2] as

$$\sigma_{th}^{*} = \frac{\sigma_{th}}{1-\alpha}. \tag{10}$$

The values of the apparent threshold stress are given in Table 1. These values are again not quite in agreement with the values of the particle internal stress. The discrepancy may perhaps stem from used approximations, i.e. from the linearization of the effective stress dependence of the creep rate and due to neglecting of the initial dislocation internal stress. Nevertheless it is clear, that the estimated values of the particle internal stress follow qualitatively the same trends as the both threshold stress and the apparent threshold stress. It seems that the suggested method may contribute to deciphering of roles played by particular microstructure components and to elucidating the nature of the threshold stress.

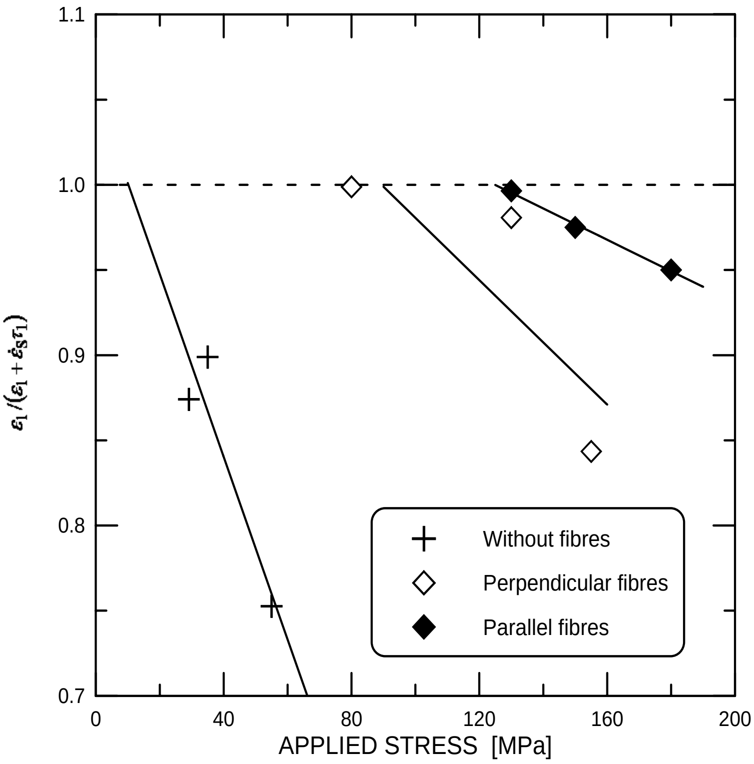

Fig. 2. Determination of the particle internal stress from creep curve parameters.

5. CONCLUSIONS

Creep of pure aluminium alloy 2024AA, and its composite reinforced with 20 vol. % of Saffil fibres was studied by compression testing at 623 K. From the results obtained in the present study the following conclusions can be drawn:

• Exponents that characterize stress 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 particle internal stress was determined from the parameters of the primary creep. This internal stress is substantially greater than the threshold stress and so the physical nature of this threshold stress remains unclear.

ACKNOWLEDGEMENTS

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