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A SIMPLE PROCEDURE FOR ESTIMATING THRESHOLD STRESSES IN THE CREEP OF METAL MATRIX COMPOSITES

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Introduction

There is considerable evidence for the presence of a threshold stress in the high temperature creep of metal matrix composites [1-14], where the threshold stress is defined as a lower limiting stress below which no measurable strain rate can be achieved [15]. When a threshold stress is present, the steady-state creep rate, $\dot{\varepsilon}$, is expressed through a relationship of the form

$$\dot{\varepsilon} = \frac{ADGb}{kT}\left(\frac{\sigma - \sigma_0}{G}\right)^n \tag{1}$$

where D is the appropriate diffusion coefficient [= D_o exp (-Q/RT), where D_o is a frequency factor, Q is the activation energy, R is the gas constant and T is the absolute temperature], G is the shear modulus, **b** is the Burgers vector, k is Boltzmann's constant, σ is the applied stress, σ_0 is the threshold stress, n is the stress exponent and A is a dimensionless constant.

In practice, creep tests are conducted under conditions where the value of σ_0 is not known and it is a standard procedure to plot the experimental data in logarithmic coordinates as $\dot{\varepsilon}$ versus σ. When $\sigma_0 = 0$, all of the datum points lie along a line with a slope which defines the true stress exponent, n. However, when σ_0 is a reasonable fraction of the applied stress, the datum points fall along a line having a slope which continuously increases with decreasing applied stress, so that a small change in the applied stress in the low strain rate region leads to a very significant change in the measured strain rate. The approximate slope of this curve defines the apparent stress exponent, n_a.

This paper outlines a simple and reproducible procedure for estimating the value of σ_0. The following section examines the difficulties associated with the current method of estimating σ_0 and the subsequent section proposes a simple alternative.

Current Procedure for Estimating σ_0

In the presence of a threshold stress, 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 extrapolating linearly to zero strain rate [16]. However, a plot of this type requires, *a priori*, a judicious selection of the appropriate value of the true stress exponent, n. Analyses are generally undertaken using values of n of 3, 5, 7 or 8, where these values are taken to represent the processes of viscous glide [17,18], high temperature climb controlled by lattice self-diffusion [19], low temperature climb controlled by core diffusion [20] or a constant structure model controlled by lattice self-diffusion [8,21], respectively.

Numerous attempts have been made to identify the appropriate value of n by preparing separate plots for each of these values of n and then selecting the plot where all of the datum points fall most closely onto a straight, rather than a curved, line. However, it has been noted in several investigations that the experimental data extend over a rather limited range of strain rates so that a linear relationship can be achieved with at least two different values of n [5,10,11]. As a result of this problem, Čadek and Šustek [10] proposed that it was necessary to obtain experimental data over not less than five orders of magnitude of strain rate.

In addition to the problem of unambiguously establishing the best linear fit, there are two other deficiencies in this procedure. First, by choosing limited discrete values of n, such as 3 or 5, the possibility of a non-integer value of n is necessarily excluded. This exclusion may be important in interpreting the creep behavior of materials such as Al matrix composites where it is well established that pure Al exhibits a value of n ≈ 4.4 [22]. Second, the linear extrapolation method of plotting $\dot{\varepsilon}^{1/n}$ against σ requires an initial selection of the value of n and then uses this value to determine the corresponding magnitudes of σ_0. However, it is apparent that a more appropriate procedure should be based on determining the values of σ_0 using a method which is independent of n, and then taking these values of σ_0 to calculate n from a line of best fit in a logarithmic plot of $\dot{\varepsilon}$ versus $(\sigma - \sigma_0)$. In the following section, a simple method of estimating σ_0 is outlined which avoids the obvious deficiencies in the current procedure.

An Alternative Procedure for Estimating σ_0

In order to develop an alternative procedure for determining σ_0, it is first necessary to examine the creep data for selected experiments covering more than five orders of magnitude of strain rate where the presence and magnitude of the threshold stresses are well defined.

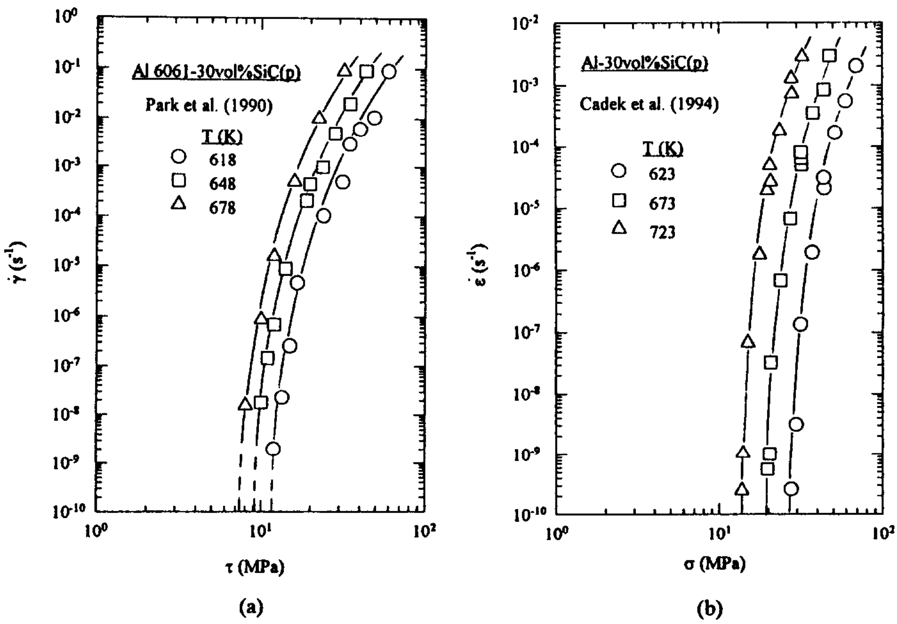

Figure 1. Shear strain rate versus shear stress for (a) Al 6061-30 vol % SiC(p) [2] and (b) Al-30 vol% SiC (p) [11,23].

Figures 1 (a) and (b) show experimental creep data for an Al 6061 alloy reinforced with 30 vol % SiC particulates [2,5] and pure Al reinforced with 30 vol % SiC particulates [11,23], respectively: for the first material, the experiments were conducted under double-shear conditions and the plot shows the steady-state shear strain rate, $\dot{\gamma}$, against the shear stress, τ. Both sets of data exhibit a pronounced curvature in the logarithmic plots of strain rate versus stress and this curvature extends over approximately seven orders of magnitude of strain rate.

These data were examined originally using the linear extrapolation procedure outlined in the preceding section and for both composites a line of best fit was obtained with n = 5. Table 1 summarizes the values reported for the threshold stresses, τ_0 and σ_0, in the analyses using n = 5 by Mohamed and co-workers [2,5] and Čadek *et al.* [11,23].

Close inspection of Figs 1 (a) and (b) shows that the curves through the individual datum points are almost vertical at a strain rate of 10^{-10} s^{-1}. In practice, this strain rate represents essentially the slowest rate which may be conveniently measured in laboratory experiments and it is equivalent to a strain of only ~1% after a testing time of 3 years. Since the extrapolated curves in Fig. 1 are almost vertical at this very low strain rate, the predicted stress levels for these rates must be very close to the threshold stresses. This suggests that it may be reasonable to arbitrarily define the threshold stress, for those sets of data where the plots of $\dot{\varepsilon}$ versus σ (or $\dot{\gamma}$ versus τ) appear to be essentially vertical at an extrapolated strain rate of 10^{-10} s^{-1}, as the stress level predicted by extrapolation at 10^{-10} s^{-1}. It is important to note, in addition, that a procedure of this type is valid only when the extrapolation takes place over a limited range of strain rates of the order of not more than approximately two orders of magnitude.

In order to check the use of this procedure, the stresses associated with a strain rate of 10^{-10} s^{-1} were read from the curves in Figs 1 (a) and (b) and the values are recorded in Table 1. Inspection shows that the predicted values are consistently within <5%, and generally to within ~1%, of the values estimated by the standard linear extrapolation method. This agreement therefore confirms the validity of this alternative procedure and it demonstrates also that, at least for these two materials, the true stress exponent is close to ~5.

Conclusion

A simple method is proposed for estimating the threshold stress in the creep of metal matrix composites for experimental data where it is possible to extrapolate, over a limited range of strain rates, the curved logarithmic plot of strain rate versus stress to give a vertical line at a strain rate of 10^{-10} s^{-1}. The stress level at this strain rate is used to define σ_0.

TABLE 1
Values Estimated for the Threshold Stresses Using Two Different Procedures

Al 6061-30 vol % SiC(p) [2,5]			Al-30 vol % SiC(p) [11,23]		
	τ_0 (MPa)			σ_0 (MPa)	
T (K)	Linear extrapolation (n = 5)	Stress at 10^{-10} s^{-1}	T (K)	Linear extrapolation (n = 5)	Stress at 10^{-10} s^{-1}
618	10.6	11.4	623	27.5	27.2
648	8.6	9.0	673	19.0	19.2
678	7.3	7.4	723	13.7	13.7

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