LOAD TRANSFER EFFECT IN THE TRUE THRESHOLD CREEP BEHAVIOUR

JOSEF ČADEK[1]*, KVĚTA KUCHAŘOVÁ[1]

An analysis is presented showing that the true threshold stress in creep of dispersion-strengthened metal can be increased significantly introducing a mechanically strong discontinuous reinforcement that impedes plastic flow in dispersion strengthened matrix.

Key words: dispersion strengthening, true threshold stress, reinforcement strengthening, load transfer

PŘENOS ZATÍŽENÍ PŘI CREEPU VYKAZUJÍCÍM SKUTEČNÉ PRAHOVÉ CHOVÁNÍ

Je ukázáno, že skutečné prahové napětí při creepu disperzně zpevněného kovu může být podstatně zvýšeno zavedením mechanicky tuhé diskontinuální výztuže, která omezuje plastický tok disperzně zpevněné matrice.

1. Introduction

The minimum (or steady-state) creep strain rate $\dot{\varepsilon}_{\mathrm{m}}$ in a pure metal is a function of the temperature T and the applied stress σ and can be expressed as

$$\frac{\dot{\varepsilon}_{\mathrm{m}} b^2}{D} = A\left(\frac{\sigma}{G}\right)^n, \tag{1}$$

where D is the appropriate diffusion coefficient, b is the length of the Burgers vector, A is a dimensionless constant, G is the shear modulus, and n is the appropriate true stress exponent. The apparent stress exponent defined as

$$m_{\mathrm{c}} = \left(\frac{\partial \ln \dot{\varepsilon}_{\mathrm{m}}}{\partial \ln \sigma}\right)_{\mathrm{T}} \tag{2}$$

is equal to the true stress exponent n in the creep of pure metals.

[1] Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Žižkova 22, 616 62 Brno, Czech Republic
* corresponding author

2. The model

The minimum creep strain rate in a dispersion-strengthened metal exhibiting true threshold creep behaviour can be expressed as (e. g. Refs. [1, 2])

$$\frac{\dot{\varepsilon}_{\mathrm{m}}(DS)b^2}{D} = A(DS)\left(\frac{\sigma - \sigma_{\mathrm{TH}}(DS)}{G}\right)^n, \tag{3}$$

where DS means dispersion strengthening, $A(DS)$ is a dimensionless constant, $\sigma_{\mathrm{TH}}\,(DS)$ is the true threshold stress, which is independent of applied stress by definition and D and n are, as above, the appropriate diffusion coefficient and the true stress exponent, respectively. Thus in creep of DS metal (DS matrix) the apparent stress exponent is related to the true stress exponent as

$$m_{\mathrm{c}} = \frac{n\sigma}{\sigma - \sigma_{\mathrm{TH}}}. \tag{4}$$

This expression is obtained combining the definition Eq. (2) with the creep Eq. (3), in which the abbreviation DS is omitted. The exponent m_{c} is generally higher than the true stress exponent n. This is illustrated schematically in Fig. 1 – curves denoted "matrix" and "(DS) matrix". Note (Eq. (4) and Fig. 1) that m_{c} approaches n at applied stresses much higher than the true threshold stress.

Introducing a mechanically strong (rigid) discontinuous reinforcement into the (DS) matrix, the creep strength of the latter is further enhanced because the reinforcement impedes its plastic flow. The reinforcement strengthening can then

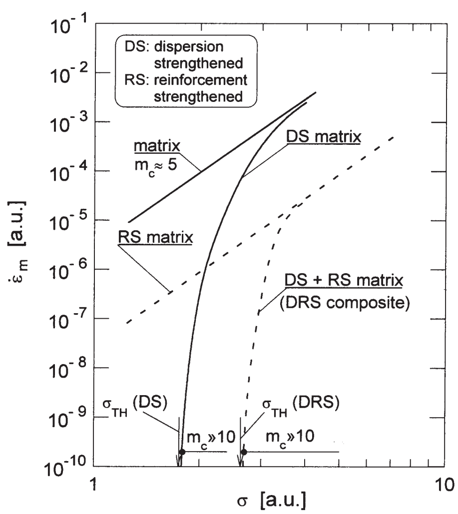

Fig. 1. Schematic representation of the relations between minimum creep strain rate and applied stress for a metal matrix, reinforced (RS) matrix, dispersion strengthened (DS) matrix, and DRS composite.

be accounted for by a modified creep equation

$$\frac{\dot{\varepsilon}_{\mathrm{m}}(DRS)b^2}{D} = A(DS)\left(\frac{\sigma/\Lambda - \sigma_{\mathrm{TH}}(DS)}{G}\right)^n, \qquad (5)$$

where $(DRS) = (DS + RS)$ means combined effects of the dispersion and reinforcement strengthening and Λ is the factor, by which the flow stress of the matrix is reduced due to load transfer and build-up of hydrostatic stresses (see later). Eq. (5) can be rewritten as

$$\frac{\dot{\varepsilon}_{\mathrm{m}}(DRS)b^2}{D} = A(DRS)\left(\frac{\sigma - \sigma_{\mathrm{TH}}(DRS)}{G}\right)^n, \qquad (6)$$

where $A\,(DRS) = A\,(DS)\,/\Lambda^n$ and

$$\sigma_{\mathrm{TH}}(DRS) = \Lambda\sigma_{\mathrm{TH}}(DS). \qquad (7)$$

Thus, the true threshold stress $\sigma_{\mathrm{TH}}\,(DRS)$ of dispersion- and reinforcement-strengthened matrix, i.e., discontinuously reinforced (DS) matrix is equal to the product $\Lambda\sigma_{\mathrm{TH}}\,(DS)$.

The factor Λ can be expressed as [3]

$$\Lambda = 1 + 2(2 + l_{\mathrm{R}}/d_{\mathrm{R}})f_{\mathrm{R}}^{3/2}, \qquad (8)$$

where $l_{\mathrm{R}}/d_{\mathrm{R}}$ is the aspect ratio of the reinforcing short fibres, (l_{R} is the length and d_{R} is the diameter of a fibre) and f_{R} is the volume fraction of reinforcement. It should be pointed out that Eq. (8) holds strictly for a stress exponent of minimum creep strain rate approaching infinity and short fibres aligned to the tensile stress direction [3]. As schematically illustrated in Fig. 1, the apparent stress exponent m_{c} of the minimum creep strain rate of DRS composite is much higher than that of the matrix. Hence, the first of the above validity conditions of Eq. (8) seems to be fulfilled for such a composite. Also, it is important to note that the factor Λ as given by Eq. (8) does not depend either on applied stress or on temperature.

3. Comparison with experiment

To illustrate the above analysis, two examples of comparison of Λ estimated from the experimental creep data using Eq. (7) with the prediction of Eq. (8) will be given.

1. The Al-8.5Fe-1.3V-1.7Si (8009Al type) alloy processed by rapid solidification and powder metallurgy, dispersion-strengthened with fine particles of $Al_{12}(Fe,V)_3Si$

phase exhibits the true threshold creep behaviour at least at temperatures ranging from 623 to 723 K. When further reinforced with 15 vol.% SiC particulates of the mean diameter of $\sim$ 4.5 μm, its creep strength increases noticeably, which is manifested with higher threshold stress of the Al-8.5Fe-1.3V-1.7Si-15SiC$_p$ composite [4] as compared to the unreinforced alloy [5] (Fig. 2). Setting $l_R/d_R = 1$ for approximately spherical reinforcement – SiC particulates – in a dispersion strengthened composite, from Eq. (8) $\Lambda = 1.35$ is calculated, while from the creep data $\Lambda = \sigma_{TH}$ (composite)/σ_{TH} (alloy) = 1.48 at 673 K (cf. Fig. 2). The agreement between the calculated and the experimentally determined values of Λ is very good. However, it should be pointed out that at $l_R/d_R \cong 1$ the effect of reinforcement may disappear due to diffusional relaxation of load transfer, especially at higher temperatures and small particulate diameters [3].

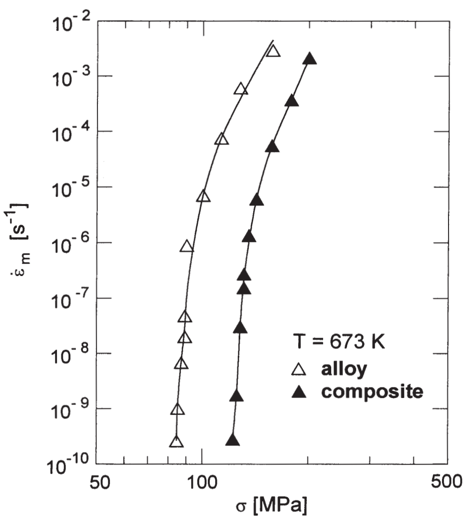

Fig. 2. Relation between minimum creep strain rate $\dot{\varepsilon}_m$ and applied stress σ for an Al-8.5Fe-1.3V-1.7Si-15SiC$_p$ composite [4] and an Al-8.5Fe-1.3V-1.7Si alloy [5] at a temperature of 673 K. For the composite, the true threshold stress $\sigma_{TH} = 118.2$ MPa, for the alloy, $\sigma_{TH} = 79.7$ MPa.

2. From the creep data presented by Peng et al. [6] for an Al-8.5Fe-1.3V-1.7Si-15SiC$_w$ composite (the subscript w stands for whiskers) and the Al-8.5Fe-1.3V-1.7Si alloy the factor $\Lambda \cong 1.3$, while from Eq. (8) $\Lambda = 2.4$ follows for $f_R = 0.15$ and $l_R/d_R = 10$, i.e., reinforcement parameters reported and/or assumed by the authors [6]. This result cannot be accounted for easily. The whisker diameter d_R ranged from 0.1 to 0.5 μm and the assumption on the aspect ratio l_R/d_R may not seem reliable enough. The whiskers were not aligned to the applied stress direction [6]. Besides, the values of σ_{TH} as obtained by the authors using the linear extrapolation technique assuming the true stress exponent $n = 5$ and listed in their Table 1 may be affected by the interval of the measured creep strain rates approximately covering three orders of magnitude only, which may not be sufficient to determine σ_{TH} reliably (cf. Ref. [7]). In fact, the creep strain rate vs. applied stress relations presented by the authors can be well approximated by straight lines in this narrow creep strain rates interval: the exponent m_c (Eq. (2)) increasing with decreasing applied stress was not detected. Nevertheless, the author's finding that the true threshold stress for the composite is higher than that of the matrix alloy is significant.

However, it should be pointed out that the load transfer may be partly or fully relaxed by diffusion-assisted flow [8], i.e., by diffusion via reinforcement/matrix interfaces. Such a relaxation is the more likely the smaller the aspect ratio of the reinforcing short fibres is, though the dimensions of these fibres play a significant role, too. This may explain some observations (e.g. ref. [9]) on the absence of load transfer in alloys, reinforced with mechanically strong particulates, for which the aspect ratio is effectively close to 1. The disagreement between the factor Λ predicted by Eq. (8) and the value of this factor following from the creep data presented by Peng et al. [6] may by partly caused also by relaxation of load transfer by diffusion-assisted flow [8].

By preliminary results of a comprehensive investigation of creep in copper dispersion strengthened with fine alumina particles and reinforced with alumina short fibres [10], the concept of load transfer effect in the true threshold creep behaviour is apparently strongly supported.

4. Concluding remark

The above simple modelling illustrated in Fig. 1 is in a way similar to the modelling performed recently by Rösler and Bäker [3] and illustrated in their Fig. 5. These authors accepted the creep model developed by Rösler and Arzt [11], i.e., the model based on thermally activated detachment of dislocations from interacting particles as the creep strain rate controlling process. They do not admit the existence of the true threshold stress arguing that the energy necessary for thermally activated detachment of a dislocation from an interacting particle is low and thus always available in the detachment event.

However, the true threshold creep behaviour of dispersion-strengthened and discontinuously reinforced aluminium alloys obviously represents a reality, at least if the apparent stress exponent m_c, Eq. (2), increasing with decreasing applied stress is taken as the relevant criterion of such a behaviour (e.g. Refs. [12–14]). According to the above analysis, the true threshold creep behaviour of the discontinuous composites with dispersion strengthened matrix should be expected once the matrix exhibits the behaviour in question [4, 5, 12–14].

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