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On the power law description of low-stress uni-axial steady-state high-homologous-temperature deformation

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ABSTRACT

The “power law” is often used to describe steady state/minimum creep rate as well as steady state superplastic deformation, both of which are observed under low-stress, high-homologous temperature conditions. In these cases, the activation energy, the proportionality constant in the strain rate equation and the stress exponent, n , change with the physical mechanism. Here a simpler alternative procedure for introducing a dimensionless stress term in the rate equation compared with the one used by materials scientists is advocated. The microstructure/crystal structure dependence of strain rate is introduced using the Buckingham Pi theorem. For the case where the contribution from the structure/microstructure terms to the isothermal deformation rate is constant, Laurent’s theorem helps generate a set of admissible values for n . The simplest solution of n being independent of stress, but a linear function of temperature, describes low stress, steady state creep rather well. (The case where n is independent of both stress and temperature follows as a special case of this solution.) The next simplest solution of n being a linear function of both temperature and stress corresponds to steady state superplasticity. Using the equations derived, the stress exponent, real and apparent activation energies for the rate controlling flow and strain rate values at different stresses and temperatures can be estimated. The equations are validated using experimental results pertaining to many systems. The implications of the findings are discussed.

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1. Introduction

Creep failure often determines the life of high-temperature components. Frequently costly components are allowed to continue in service beyond their design lives. Steady state creep strain rate or minimum creep rate in industrial alloys is used as a criterion for designing components. For ensuring safe operation and

predicting the residual life of a component in service, the constitutive (rate) equation of flow should be accurate.

Superplastic forming, in contrast, is an important (near-) net-shape forming process which finds application in several areas, e.g. aerospace, surface transport, architecture, entertainment and sports goods industry etc. As optimal superplasticity is observed only within a narrow strain rate-temperature window, an accurate constitutive equation for the rate of flow is desirable for efficient forming. Both creep and superplasticity are low stress, high homologous temperature deformation processes.

The total strain suffered by a specimen during high homologous temperature deformation is the sum of

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instantaneous elastic and plastic strains and time-dependent strain (Rabotnov, 1969; Odquist, 1953; Hoff, 1956). As the first two strain contributions are small compared with the third, they are often ignored. Many studies (Padmanabhan and Davies, 1980; Kaibyshev, 1992; Nieh et al., 1997; Padmanabhan et al., 2001; Garofalo, 1965; Hart, 1967; Mukherjee et al., 1969; Gittus, 1975; Dieter, 1988; Mukherjee, 2002) have established the relationship $\dot{\epsilon} \propto \exp(-\frac{Q}{kT})$, where $\dot{\epsilon}$ is the strain rate, Q the activation energy for the rate controlling process, k the Boltzmann constant and T is the absolute temperature of deformation. When the contribution from the structure terms, S , is constant, materials scientists often describe uniaxial, low stress, steady state, high homologous temperature deformation in terms of the equation

$$\dot{\epsilon} = A_1' \left(\frac{\sigma}{G}\right)^n \exp\left(-\frac{Q}{kT}\right) \quad (1)$$

where A_1' and n are temperature-, material- and grain-size-dependent constants. The structure term is introduced using the average grain size, L , viz., as

$$\dot{\epsilon} = A_1'' \left(\frac{L}{b}\right)^p \left(\frac{\sigma}{G}\right)^n \exp\left(-\frac{Q}{kT}\right), \quad (1a)$$

where b is Burgers vector and A_1'' is another constant.

$$\dot{\epsilon} = A_2' \left(\frac{G}{T}\right) \left(\frac{\sigma}{G}\right)^n \exp\left(-\frac{Q}{kT}\right), \quad (2)$$

with A_2' yet another constant, is also used (Mukherjee et al., 1969; Mukherjee, 2002; Raj and Langdon, 1989; Brown and Ashby, 1980). Eqs. (1)/(2) has been used extensively to interpret creep/superplasticity data assuming this equation to be universal and relevant for all the physical mechanisms associated with high temperature deformation, not only in metals, but also in industrial alloys. Even in the latter, where a number of physical processes could co-exist, often the assumption is that there is one rate controlling process among the many processes present. Therefore, an experiment was conducted in our laboratory in Muenster to check if a correlation between high temperature creep and volume diffusion of carefully chosen species exists in equiatomic NiTi alloy (Taillebot et al., 2008). The results were inconclusive. This finding compelled us to take a re-look at Eqs. (1) and (2).

Theoretical justification for generic equations like Eqs. (1) and (2) lies in dimensional analysis. Experience of a century in the field of plasticity suggests that for making stress dimensionless, a carefully selected reference stress could definitely be an easier to determine normalization basis compared with the shear modulus, e.g. Tresca yield criterion. This alternative stress normalization procedure is advocated here. It emerges that in some cases this method helps reduce the number of physical mechanisms needed to interpret a given set of experimental data compared with the method in which the normalization basis is G .

2. Definition of the problem

Eq. (1) was examined in Brown and Ashby (1980), Stocker and Ashby (1973), Derby and Ashby (1984), Pharr (1985). The following conclusions were drawn. (a) In different systems, n varies from 3 to 12, A_1' from 1 to 10^{17} . Therefore, A_1' is not a constant, as is assumed. (b) On an empirical basis, a linear relation exists between A_1' and n for many classes of materials. Therefore, a value of A_1' , independent of n , as assumed (Zhu and Langdon, 2005), cannot be justified. (c) Experimentally, the majority of creep data lies in a very narrow range $10^{-4} < (\sigma/G) < 10^{-3}$ (due to G being far greater than σ), which makes accurate inferences difficult. (d) On an empirical basis the constant (the analog of A_1') obtained after normalizing σ by the tensile yield stress, σ_y , to a good approximation, is a constant for a given structural class of solids (Brown and Ashby, 1980).

The present authors encountered a few additional difficulties. (e) The shear modulus, G , is calculated, ab initio, using quantum mechanical considerations (Cottrell, 1988). Flow stress, in contrast, belongs to the realm of classical mechanics. One may, nevertheless, simplify the temperature dependence of G to a linear form, as done by Frost and Ashby (Frost and Ashby, 1982). But, the latter authors advocate the use of the same temperature dependence expression for all alloys of a given major component, e.g., Al-alloys, steels etc. This approximation makes its usefulness limited when comparing alloys of the same base element, e.g., comparing different Ni-alloys, steels or Al-alloys. Moreover, the temperature dependence of flow stress, σ , is exponential. Therefore (σ/G) is not temperature independent. In view of this, we prefer to introduce a carefully chosen reference stress as the normalizing basis, which will make the normalized term dimensionless under all experimental conditions. (f) In many experiments, e.g., (Loveday and Dyson, 1979), where $n = 9$, an experimental inaccuracy in the value of n of, say, 5% (a common experimental error), will change the strain rate by an order of magnitude when the normalization is with respect to G , i.e., the accuracy of calculations is adversely affected. Also, in many cases even in a narrow temperature range in which a change in the rate controlling mechanism is not expected, the value of n changes with T . Therefore, ignoring the 10–20% variation seen experimentally in the value of n (Raj and Langdon, 1989) and/or assigning a mean n value for the temperature range of interest is not wise. (g) In many cases (e.g. Raj and Langdon, 1989), the true activation energy determined using Eq. (1)/Eq. (2) decreases with increasing magnitude of the constant (σ/G) ratio at which Q is determined and the authors assume a further dependence of the 'true' activation energy on the magnitude of the applied stress, which has no justification.

In the present analysis, the room temperature tensile yield stress of the material is proposed as the normalization basis for stress, σ_c , in the creep equation. The normalization basis in case of superplastic flow is the stress at which n is unity in the strain rate – dimensionless stress space, which can be calculated (see below). The possibility that n could be a function of T or T and σ is not ruled out. The problem

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