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Elevated-temperature strengthening in carbide (Al_4C_3)-dispersed aluminium

M.V. GURJAR, G.S. MURTY, G.S. UPADHYAYA
Department of Metallurgical Engineering, Indian Institute of Technology, Kanpur 208016, India

The effect of strain rate on the compressive flow behaviour of DISPAL 2 is investigated in the temperature range 473–823 K. The stress exponent, *n*, was 28 in the temperature range 473–623 K, while it increased to 59 above 673 K. The activation volume and energy for deformation were 70 b^3 and 100–200 kJ mol^{-1}, respectively, in the temperature range 473–623 K. In the higher range, 673–823 K, the observed activation volume of 300–500 b^3 and the activation energy of $\sim$ 1086 kJ mol^{-1} cannot be reconciled with any of the deformation mechanisms. A new model-based creep equation for dispersion-strengthened materials proposed by Rosler and Arzt has been applied to the flow data from 673–823 K. Its predictions are in agreement with the experimental data in the temperature range 673–723 K. The predictions of the model, however, differ from the experimental data at 773 and 823 K.

1. Introduction

The carbide-dispersed aluminium, designated DISPAL, belongs to the class of dispersion-strengthened alloys developed specifically for high-temperature applications [1, 2]. The mechanism of strengthening in such alloys has been the subject of study for nearly 20 years. In the past, several models have been proposed to explain the elevated-temperature strengthening in dispersion-strengthened alloys [3–7]. The models, based on localized climb of dislocations, are more successful in explaining the deformation of dispersion-strengthened alloys at higher temperatures [5, 6].

Recent transmission electron microscopic (TEM) observations on dispersion-strengthened alloys deformed at elevated temperatures provided more detail on the exact mechanism of localized climb [8, 9]. It occurs under the influence of the attractive interaction between the dislocations and particles arising from the relaxation of dislocation energy at the interface. The resistance to the motion of dislocations is caused by the anchoring of the dislocations by particles at their departing end. Rosler and Arzt [10] developed a new exponential creep equation based on the theory of attractive interaction between the dislocations and particles. A preliminary analysis of this creep equation has indicated its suitability in describing the creep in some of the dispersion-strengthened systems.

The TEM studies on DISPAL have confirmed the existence of an attractive interaction between dislocations and carbide particles [11]. The available experimental data on DISPAL exhibit satisfactory correlation with Arzt's theory [10–12] at intermediate strain rates and temperatures above 673 K. The present investigation was aimed at exploring the applicability of Arzt's model to the elevated temperature deformation of DISPAL 2, which contains about 14 vol % dispersoids.

2. Experimental procedure

The material for the present investigation, DISPAL 2 was supplied by the manufacturer (Sinter-metall werk, Krebsoge, Germany). The nominal composition of this alloy was 2 wt % carbon (9 vol % Al_4C_3) and 2.5 wt % oxygen (5 vol % Al_2O_3). It was received in the form of bars of 25 mm diameter and 300 mm length, from which compression samples of 8 mm diameter and 12 mm length were machined.

The compression tests were performed on an MTS 810 servohydraulic universal testing machine. To study the effect of strain rate on flow behaviour, the tests were carried out with a step change in the strain rate at intervals of 1%–2% plastic strain. Initially the test was started on the sample at the slowest strain rate of 2×10^{-5} s^{-1}. The step changes in strain rate of one order of magnitude were subsequently employed up to a strain rate of 2×10^{-2} s^{-1}. This type of test was repeated at different temperatures between 473 and 823 K at steps of 50 K.

3. Results

The variation of the flow stress, σ, with strain rate, $\dot{\varepsilon}$, at different temperatures is shown in Fig. 1. The value of the stress exponent ($n = (\partial \log \sigma / \partial \log \dot{\varepsilon})_T$) obtained by regression analysis of the data between 473 and 623 K is 28, whereas in the higher temperature range it is 59.

Assuming the validity of a simple rate equation for the thermally activated plastic deformation [12], the activation parameters (activation volume and energy) were calculated. The activation volume, V^*, was evaluated from the equation

$$V^* = kT \left(\frac{\partial \ln \dot{\varepsilon}}{\partial \sigma} \right)_T \qquad (1)$$

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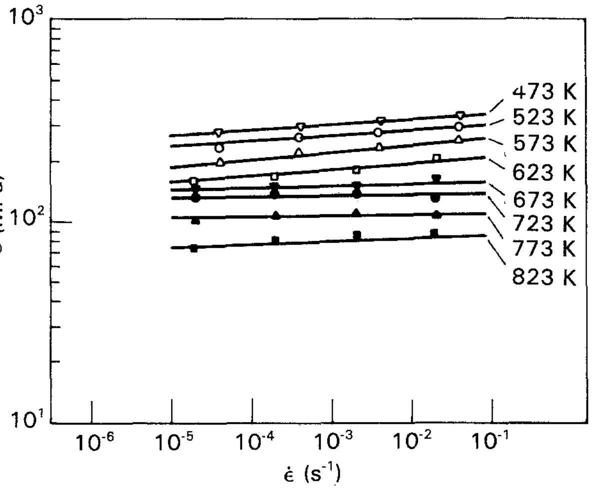

Figure 1 Plot of flow stress, σ, against strain rate, $\dot{\varepsilon}$, at different temperatures.

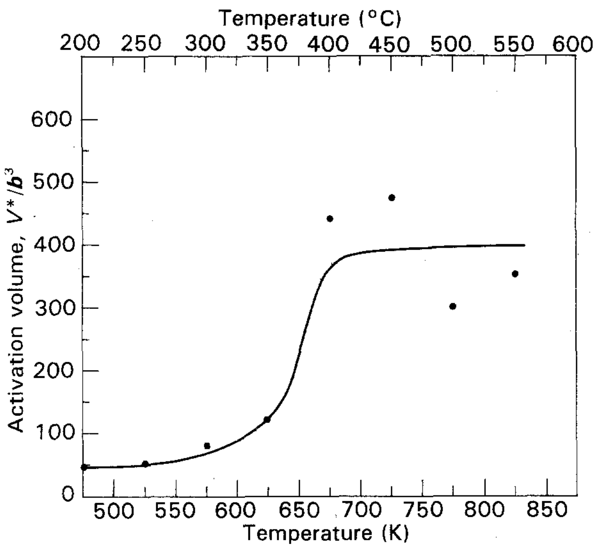

Figure 2 Activation volume for flow as a function of temperature.

where k is the Boltzmann constant, T the temperature, $\dot{\varepsilon}$ the strain rate, and σ the flow stress. The increment in the flow stress, $\Delta\sigma$, arising from the strain rate change from $2 \times 10^{-5}\ s^{-1}$ to $2 \times 10^{-4}\ s^{-1}$ was measured. The activation volume data thus obtained over the temperature range 473–823 K are shown in Fig. 2. The activation energy, Q, was evaluated using the equation

$$Q = -TV^* \left(\frac{\partial\sigma}{\partial T}\right)_{\dot{\varepsilon}} \qquad (2)$$

The temperature variation of activation energy between 473 and 823 K is similar to that of activation volume. In the lower range of 473–623 K, the activation energy is between 100 and 200 kJ mol^{-1}, whereas above 673 K it is between 900 and 1000 kJ mol^{-1}.

An alternate approach was used for evaluating the activation energy on the basis of the steady state power law creep equation. In this approach, the activation energy is given by

$$Q = nR \left[\frac{\partial \ln \sigma}{\partial (1/T)}\right]_{\dot{\varepsilon}} \qquad (3)$$

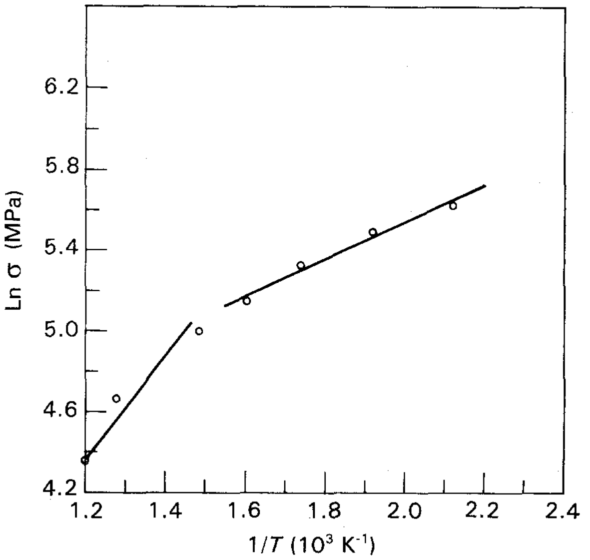

Figure 3 Arrhenius plot of ln σ versus $1/T$ at a strain rate of $10^{-4}\ s^{-1}$.

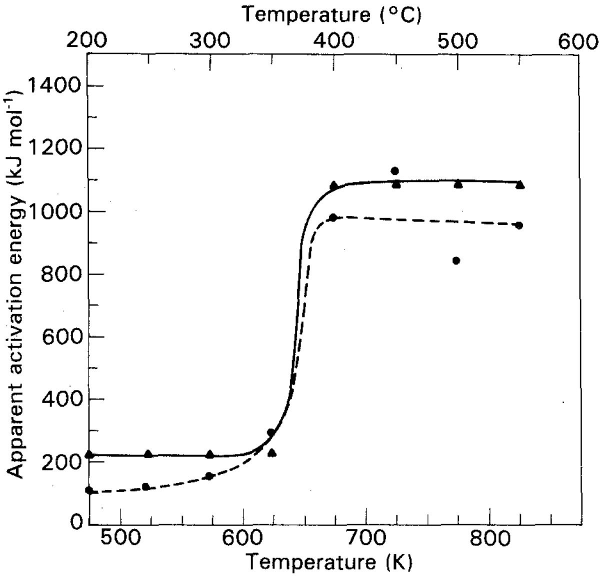

Figure 4 Apparent activation energy for flow as a function of temperature. (▲) Based on Equation 3, (●) based on Equation 2.

where n is the stress exponent and R the gas constant. The Arrhenius plot of ln σ against T^{-1} at a strain rate of $10^{-4}\ s^{-1}$ is shown in Fig. 3. As in the results shown in Figs 1 and 2, the activation energy is different in the two temperature ranges of below 623 K and above 673 K. The mean value of the stress exponent was used for calculating the activation energy in each region. The activation energy data evaluated by the two methods are compared in Fig. 4 over the entire temperature range of this investigation.

4. Discussion

Based on the results presented in Figs 1, 2 and 4, the temperature range from 473–823 K can be divided into two regions: 473–623 K and 673–823 K. The observations of each region are discussed separately.

4.1. Temperature range 473–623 K

The activation volume and energy evaluated in this range are $\sim 70\ \boldsymbol{b}^3$ and 100–200 kJ mol^{-1}, respectively. Among the deformation mechanisms normally associated with activation volume in the range 10–100 $\boldsymbol{b}^3$ [12], cross-slip of screw dislocations over particles is probable in this temperature range. The stress required for cross-slip is comparable with that for Orowan bowing of dislocations [3]. Moreover, the activation energy for cross-slip in pure aluminium (117.5 kJ mol^{-1}) [13] is within the observed range.

4.2. Temperature range 673–823 K

Both the activation energy and volume are higher in this temperature range. The activation energy is seven to eight times that for self diffusion of aluminium ($\sim$142 kJ mol^{-1}) and the activation volume is 300–500 $\boldsymbol{b}^3$. While the activation volume between 100 and 10 000 $\boldsymbol{b}^3$ may be associated with mechanisms such as the intersection of dislocations and non-conservative motion of jogs [12], anomalously high activation energy cannot be reconciled with any of the deformation mechanisms. The previous studies [8, 9] on dispersion-strengthened alloys suggest localized climb of dislocations over the particles as the mechanism of deformation at high temperatures. The activation volume and energy associated with this process are 1 $\boldsymbol{b}^3$ and 142 kJ mol^{-1} [12], respectively.

Rosler and Arzt [10] proposed an exponential law for creep based on the theory of attractive interaction between dislocations and particles. The creep equation is of the Arrhenius form

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left(-\frac{E_d}{RT}\right) \qquad (4)$$

where $\dot{\varepsilon}_0$ and E_d are frequency factor and apparent activation energy for deformation, respectively. These can be expressed as

$$\dot{\varepsilon}_0 = \frac{6\lambda\rho D_v}{\boldsymbol{b}} \qquad (5)$$

and

$$E_d = G\boldsymbol{b}^2 r(1-K)^{3/2}\left(1-\frac{\sigma}{\sigma_d}\right)^{3/2} \qquad (6)$$

where G is the shear modulus, $\boldsymbol{b}$ the Burgers vector, D_v the diffusion coefficient, ρ the dislocation density, 2λ the inter-particle spacing, $2r$ the particle size, K the relaxation parameter, σ_d the athermal detachment stress, and σ the applied stress.

The athermal detachment stress, σ_d, is defined as

$$\sigma_d = \sigma_{or}(1-K^2)^{1/2} \qquad (7)$$

where σ_{or} is the Orowan stress. The relaxation parameter defined as the ratio of dislocation energy at the particle/matrix interface and away from the particle, is a material parameter. Rosler and Arzt [10] calculated the k value to be $\sim$0.74 for DISPAL. This reported value is used in the present analysis.

The estimation of the Orowan stress involves the measurement of particle size and inter-particle spacing. As these microstructural parameters were not measured in the present study, the Orowan stress is taken as the room temperature yield stress (340 MPa) of the alloy. The athermal detachment stress was evaluated from Equation 7 using the corrected modulus at the respective temperatures.

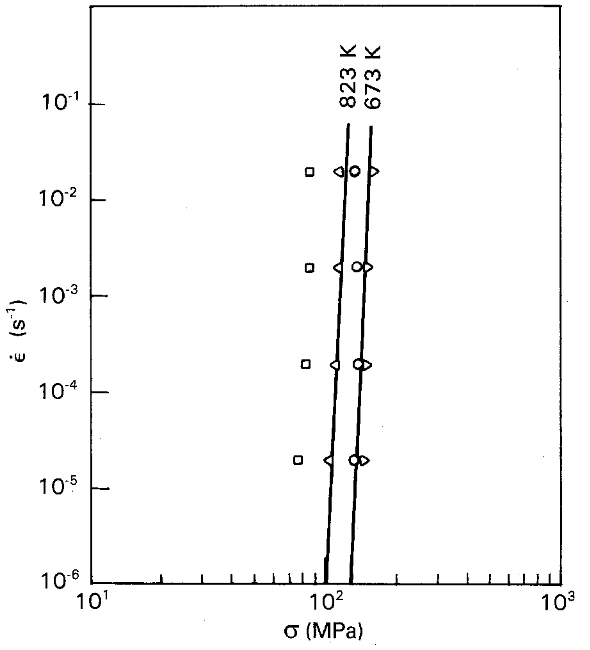

Figure 5 Comparison of the experimental data of strain rate, $\dot{\varepsilon}$, versus flow stress, σ, with (—) the predictions of Arzt's model. $K = 0.74$, $\sigma_{or} = 340$ MPa, (▷) 673 K, (○) 723 K, (◁) 773 K, (□) 823 K.

The particle size, $2r$, and inter-particle spacing, 2λ corresponding to a particle volume fraction, f, of 0.14 and Orowan sress of 340 MPa were calculated from the geometrical relation [14]

$$(2\lambda) = \frac{2}{3}(2r)\left(\frac{1-f}{f}\right) \qquad (8)$$

and the expression for Orowan stress

$$\sigma_{or} = \frac{0.84\ G\boldsymbol{b}}{2(\lambda - r)} \qquad (9)$$

The particle size of 12 mm and an inter-particle spacing of 49.4 mm were thus obtained. Using a dislocation density of 10^{13} m^{-2} for DISPAL 2 (AIC2) [10] and substituting for different parameters in the creep equation (Equation 4), the flow stress variation with strain rate was calculated for the strain-rate range of this study. The predictions made by the Arzt model are compared with the experimental data in Fig. 5 in the temperature range 673–823 K.

It is seen from Fig. 5 that the agreement between the experimental data and the prediction of the Arzt model is satisfactory at 673 K, whereas it is not so at 823 K. The observed flow stress variation with temperature is wider than the predictions of the model. The Arzt model predicts a stress-strain-rate relation that is less sensitive to the temperature compared to the experimental data. Rosler and Arzt [10] attributed this difference to the grain-boundary sliding which is considered to yield an offset in the data without altering the stress exponent significantly. The same argument may be extended to the temperature variation of the flow data in the present investigation. While the temperature sensitivity of the flow stress is well predicted by the Arzt model from 673–723 K, an offset is present at temperatures 773 and 823 K. The fall in strength from 723 K is also accompanied by a lowering of stress exponent. The results of Arzt and Rosler [11] concerning the influence of grain-boundary sliding on stress exponent in AlCO (DISPAL 0) are in agreement with the present observation. Thus, by considering that the grain-boundary sliding is dominant in the higher temperature range 773–823 K, the Arzt equation satisfactorily predicts the stress exponent and the temperature sensitivity of the stress–strain rate data. As suggested by Rosler and Arzt [10], the predictions of the model thus agree with the experimental data in the absence of any grain-boundary effects.

5. Conclusions

1. The deformation behaviour of DISPAL 2 at elevated temperatures can be divided into two ranges: 473–623 K and 673–823 K.

2. Between 473 and 623 K, the flow parameters of the alloy are (i) a stress exponent of 28, (ii) an activation volume of 70 $\boldsymbol{b}^3$, and (iii) an apparent activation energy of 100–200 kJ mol^{-1}.

3. In the higher temperature range above 673 K, the stress exponent is 59. The activation volume is 300–500 $\boldsymbol{b}^3$ and the apparent activation energy for flow is anomalously high (~ 1086 kJ mol^{-1}).

4. While the Arzt's exponential creep equation is in agreement with the present flow data at intermediate strain-rate ranges in the temperature interval 673–723 K, there is an offset between the predictions of the model and the data at 773 and 823 K.

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