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CREEP OF POLYCRYSTALLINE ALUMINIUM AT 333 K

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Creep of 99.999% pure aluminium polycrystal was studied at 333 K for compressive stresses of 20, 22, 24, 26 and 28 MPa. The observed stress dependence of the slope $s = \mathrm{d}\varepsilon/\mathrm{dln}\,(1 + t/t_0)$ of the creep strain-time curves in semi-logarithmic representation was examined in terms of a stochastic model of logarithmic creep. The intrinsic height of the rate-controlling energy-barrier, 0.95 eV, derived from the model was compatible with the activation energy for cross-slip (1.05 eV). The inference that-cross-slip facilitated recovery was consistent with the concurrent examination of slip-lines on the surfaces of crept crystals.

1. Introduction

In their paper on logarithmic creep of polycrystalline OFHC (oxygen-free high-conductivity) copper and aluminium of 99.95% purity at room temperature, Buckle and Feltham[1] outlined a stochastic model of creep, which is based on the concept of a spectrum of energy barriers to dislocation motion and takes into account the tendency of dislocation assemblies to assume minium energy configurations. The modul, which is a simple variant of a more detailed one encompassing also high-temperature creep[2-4], was considered to be adequate in connection with the relatively restricted modes of dynamic recovery operative in the absence of diffusion. They found that the parameter, s, in the creep equation

$\varepsilon = s \ln (1 + t/t_0)$, where ε is the creep strain at time t, and t_0 a fixed, usually small, time-increment necessary to linearise the creep curves in the usual semilogarithmic representation, was given by the relation:

$$s = k T\sigma/(U_0 - m k T) X. \tag{1}$$

Here U_0 refers to the intrinsic height of the dominant energy-barrier, i. e. not reduced by stress, X is the coefficient of work-hardening at the stress level σ and m a constant close to 25.

Buckle and Feltham[1] discussed the significance of the parameters s and t_0, which were found to be structure-sensitive, and attempted to relate measured s-values with those derivable from equation (1). They obtained good agreement in the case of copper while the observed dependence of s on σ for aluminium could not be reconciled with the proposed functional form satisfactorily. Buckle and Feltham[1] attributed this discrepancy to the ease of dynamic recovery through cross-slip in aluminium at room temperature as well to the impurity effects. It was, therefore, considered more appropriate to study the applicability of their stochastic formulation of the creep process to 99.999% pure aluminium polycrystal, i. e. in the absence of the possible role of impurity effects.

2. *Experimental*

Cylindrical rods of polycrystalline aluminium of 99.999% purity, 20 cm long and of 0.6 cm diameter, were supplied by Johnson and Mathey, London. The main metallic impurities (in ppm) were Mg $\approx$ 10, Si $\approx$ 7, Fe $\approx$ 5, Cu $\approx$ 3, Ca $\approx$ 1 and Na $<$ 1. Specimens, 1 cm long, were cut from the *as-received* rods by means of a fine saw. They were then annealed for 45 minutes in 12 kPa of argon of spectroscopic purity at 723 K. Average grain diameter obtained by the line-intercept method was about 420 μm. All specimens were chemically polished acquiring a smooth, bright, surface suitable for studying slip-lines developing during creep by the use of optical microscopy.

The creep tests were carried out at 333 K for compressive stresses of 20, 22, 24, 26 and 28 MPa in a continuously evacuated glass chamber, the specimen being sandwiched between two ground alumina rods. The *working* pressure was approximately 7×10^{-3}Pa. To inhibit barrelling effects, arising due to friction between the contact surfaces of the rods and the crystal, the end faces of specimens were lubricated with molybdenum disulphide powder. Barrelling was in any case expected to be negligible, because the highest compressive strain did not exceed 2%.

Heating of the specimen was initiated when the pressure in the chamber had dropped below 10^{-2} Pa. On attaining the desired temperature i. e. 333 K, the specimen was held at that temperature, generally for about four hours, by which time the system, including the specimen, had attained thermal equilibrium, i. e. thermal expansion or contraction effects in the system had ceased. The change in length of the specimen during creep was measured with an inductive displacement transducer actuated by a stabilised power-supply. The calibration of the

transducer was checked, and was found to be linear. The transducer-output was recorded as function of time, on a chart-recorder of high-impedance.

In view of its possible utility in the analysis of the creep data, stress-strain curve was also obtained at 333 K by deforming the specimen in compression in a »hard« floor-model TT-C Instron machine at a strain-rate of about 0.07% per second.

3. *Results and discussion*

Creeps curves obtained with polycrystalline aluminium of 99.999% purity at 333 K for compressive stresses between 20 and 28 MPa are given in Fig. 1. Reference to Fig. 2 shows the stress dependence of the slope $s = \mathrm{d}\varepsilon/\mathrm{dln}\,(1 + t/t_0)$ of the linearised creep strain-time curves in semilogarithmic representation. The points denote measured values and the curve drawn through those was derived by means of equation (1) on using $(\sigma - \sigma_y)$ rather than σ in the numerator, i. e.

$$s = k\,T\,(\sigma - \sigma_y)/(U_0 - m\,k\,T)\,X, \tag{2}$$

with $U_0 = 0.95$ eV and $\sigma_y = 16$ MPa, the latter being seemingly the elastic limit of the material (Fig. 3). Values of X used in equation (2), measured from the slopes of the stress-strain curve (Fig. 3) at stress levels 20, 22, 24, 26 and 28 MPa, were 0.98, 0.83, 0.80, 0.73, and 0.69 $\times$ 10^3 MPa, respectively. Agreement between theoretical formulation and experiment can be seen to be very satisfactory.

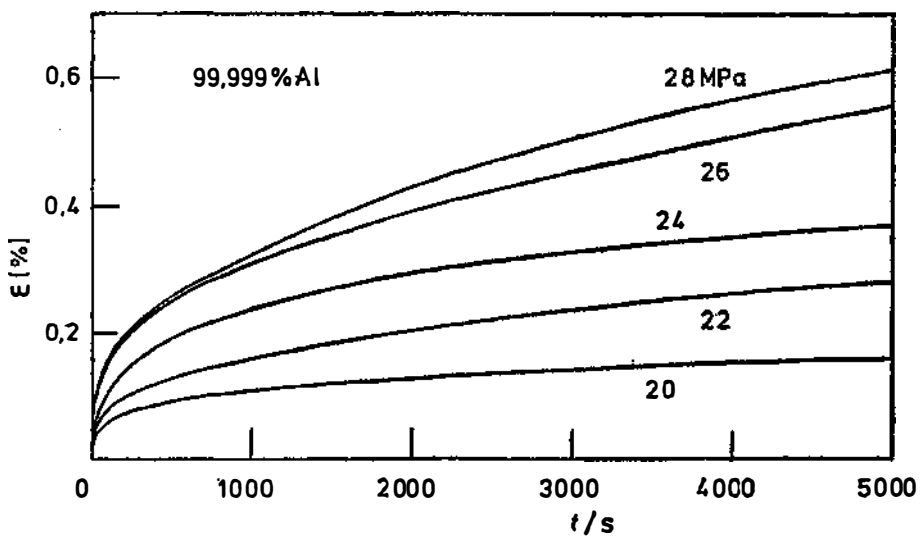

Fig. 1 Creep curves of polycrystalline aluminium at 333 K for a series of stress levels.

The U_0-value, referred to above, is in good agreement with the value of activation energy for cross-slip (1.05 eV) derived theoretically by Schoeck and Seeger[5]. It is also close to the value of the intrinsic energy-barrier (1.1 eV) asso-

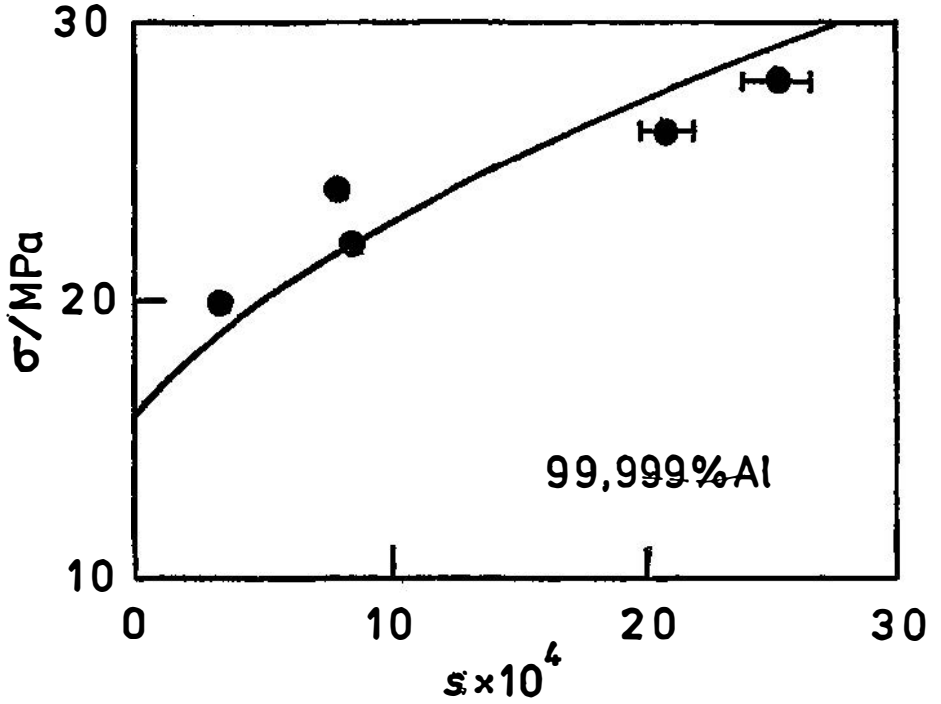

Fig. 2. Relation between s and σ for polycrystalline aluminium at 333 K. The curve drawn through data points was obtained from equation (2) with the values of the parameters given in the text.

ciated with the recovery process, as deduced by Butt and Feltham[6] from the creep data of 99.999% pure aluminium single crystals at low temperatures. Evidence of cross-slip was obtained in the present work during the examination of the surfaces of crept crystals made by optical microscopy.

The relation between σ and t_0 has been illustrated in Fig. 4; the parameter t_0 increases linearly with σ and the $\sigma - t_0$ line on extrapolation to $t_0 = 0$ cuts the stress-axis at about 18 MPa, which is close to the elastic limit of the aluminium polycrystal (Fig. 3). Now, the »retardation time« t_0, as defined in the stochastic model of creep developed by Feltham[2], is given by $t_0 = D^{-1} \exp(U^*/kT)$. Here $D = \nu \delta U/kT$, U^* is the most probable barrier height in the distribution $U_1 \leq U^* \leq U_2$ subdivided into levels of equal width δU, and ν is a Debye frequency of the order of $10^{11}\ s^{-1}$. The observed increase of t_0 with stress σ (Fig. 4), suggests that an increase in stress facilitates »additional« deformation which favours work-hardening rather than recovery. Dislocations are »blocked« more strongly as further effective barriers to their motion are introduced; U^* is thus displaced to higher values and t_0 increases.

Finally, Fig. 5 refers to the variation of the slope s with the retardation time t_0. The observed linear dependence of s on t_0 can be inferred from the logarithmic creep equation i. e. if $\ln \varepsilon = s \ln (1 + t/t_0)$ one takes $t/t_0 \ll 1$ i. e. for »short« times, then

$$\varepsilon \approx st/t_0 \quad \text{or} \quad d\varepsilon/dt \approx s/t_0. \tag{3}$$

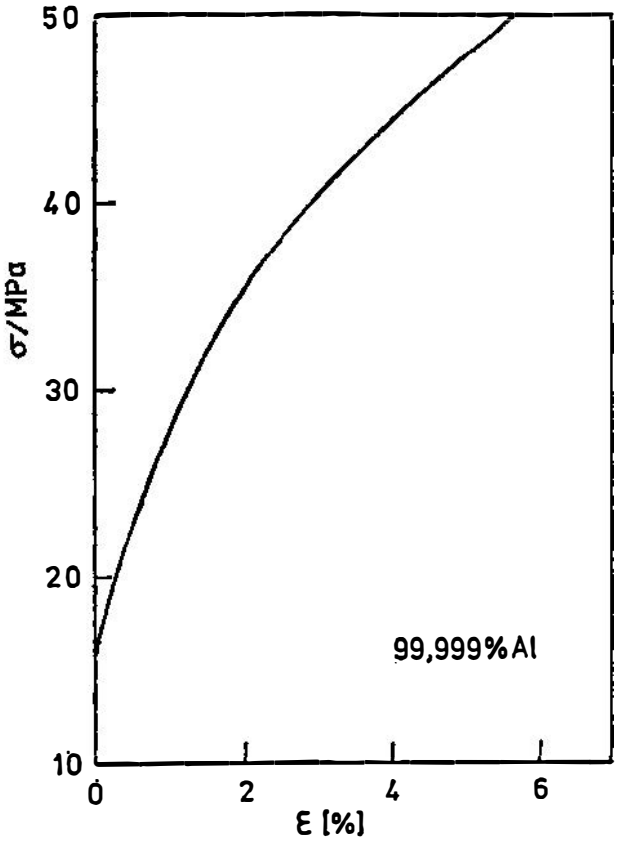

Fig. 3. Stress-strain curve of aluminium polycrystal at 333 K.

This relation can be checked from the data given in Figs. 1 and 5. It is readily found by redrawing the linear initial parts of otherwise logarithmic creep curves, as examplified by Buckle and Feltham[1], that $d\varepsilon/dt$ is of the order of 10^{-6} while s/t_0 is equal to about 2.5×10^{-6} (Fig. 5). Both values are thus in reasonable agreement.

4. *Conclusions*

It is apparent, from the foregoing, that the principal features of the creep of 99.999% pure polycrystalline aluminium at 333 K, i. e. below the temperatures where vacancies are known to become rather mobile, can be interpreted satisfactorily within the framework of the stochastic model proposed by Buckle and Feltham[1]. The intrinsic height of the energy-barrier (0.95 eV) associated with the recovery process, as here deduced from the data appertaining to aluminium polycrystal by using $(\sigma - \sigma_i)$ rather than σ in their theoretical s—σ relation, is of the right order for cross-slip. The inference that mainly cross-slip facilitates recovery is corroborated by the surface study of crept crystals.

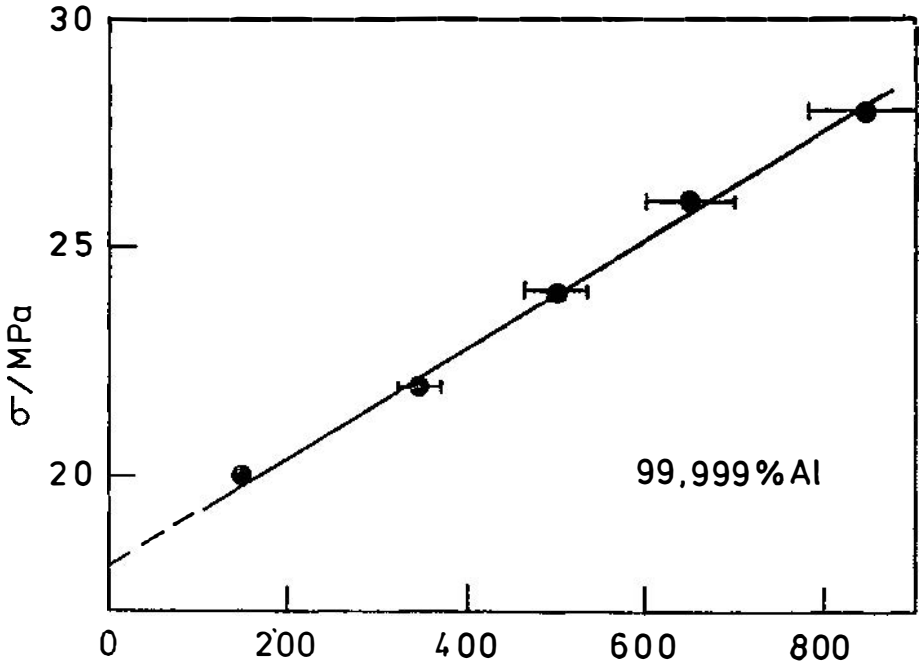

Fig. 4. Variation of t_0 with σ in polycrystalline aluminium at 333 K.

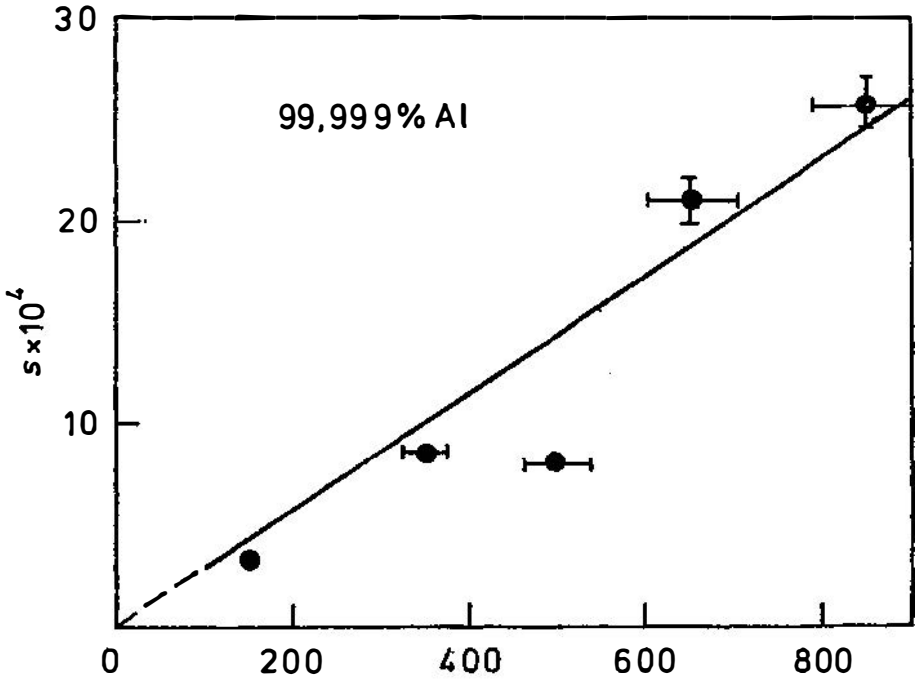

Fig. 5. Relation between s and t_0 for aluminium polycrystal at 333 K.

Acknowledgment

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PUZANJE POLIKRISTALIČNOG ALUMINIJA PRI 333 K

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Proučavano je puzanje polikristaličnog aluminija, čistoće 99,999 % pri 333 K, za kompresivna naprezanja od 20, 22, 24, 26 i 28 MPa. Zapažena ovisnost naprezanja o nagibu krivulja deformacije puzanja — vrijeme, ispitivana je u uvjetima stohastičkog modela logaritmičkog puzanja. Intrinsična visina energijske barijere od 0,95 eV, koja je dobivena tim modelom, u skladu je s aktivacijskom energijom poprečnog klizanja (1,05 eV). Zaključeno je da poprečno klizanje olakšava oporavak kristala, što je potkrijepljeno ispitivanjem površine kristala podvrgnutih puzanju.