STEADY-STATE CREEP DEFORMATION OF Cd SINGLE CRYSTALS

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ABSTRACT

The creep behaviour of Cd single crystals has been investigated in tension in the temperature range from 300 K to 450 K. The activation energies and the stress exponents of steady-state creep were calculated. The dependence of steady-state creep rate on the stress and temperature show a possible change in the rate-controlling mechanism for creep.

1. INTRODUCTION

The first theoretical predictions of creep behaviour in crystalline materials have been proposed by Bailey /1/, Orawan /2/, Cottrell and Jaswon /3/ and Friedel /4/. According to these theories, the motions of dislocations in crystals are hindered by impurity atom clouds around the dislocations. Consequently, these theories predict the linear dependence of steady-state creep on the stress and the magnitude of the yield stress.

The steady-state creep in Al of technical purity, which significantly influences the behaviour of solids during mechanical testing, has been examined in wide ranges of applied stresses and temperatures /5/. The stress sensitivity parameters of the steady-state creep rate (stress exponent n and activation energy Q) have been found to increase on increasing the applied stress and temperatures. Concurrently, creep studies on monocrystalline $NbCO_{0.89}$ have been conducted by Dement'yev /6/ between 2073 and 2973K using a stress level of 11.7 – 68.7 MPa. At temperatures < 2473 K, a stress exponent of 3.3 and an activation energy of 357 kJ/mol have been determined for the steady-state region; above 2473 K, the values were 4.8 and 502 kJ/mol. Based on this evidence, the Peierls stress was assumed to be the controlling dislocation glide at the lower temperatures while dislocation climb was the controlling process at high temperatures. These results have been confirmed by Chevacharoenkul and Davis /7/, using TEM studies. The functional dependence of steady-state creep rate on stress, temperature and the other parameters have been summarized in a number of reviews /8,9/.

Although the deformation mechanisms occurring in face-centred cubic (f.c.c.) metals at elevated temperatures are now reasonably well understood, the creep behaviour of hexagonal-close-packed (h.c.p.) metals has not been fully documented and is the subject of considerable speculation. Of the h.c.p. metals, magnesium has probably received by far the greatest attention in terms of creep studies and a summary of the data up to 1981 has been provided by Vaganali and Langdon /10/. The fundamental aspects of creep behaviour of these materials are, however, not well understood. The purpose of this study is to investigate the steady-state creep deformation behaviour of Cd single crystals by way of stress change tests.

2. EXPERIMENTAL METHOD

Single crystals were grown by a modified Bridgman method from 99.99% Cd. The crystal orientation was found by the Laue back reflection method. Crystals were 0.4 cm in diameter and 6 to 8 mm in length. The crystals were tested with the stress axis parallel to $<2\bar{1}\bar{1}3>$. In order to investigate the slip systems, the crystals were mechanically polished and then etched. The surfaces of etched crystals were observed by an optical microscope. To determine the stress and temperature dependence of steady-state creep in Cd single crystals, each of these variables was changed in turn while the other remained constant. The ranges used were 10 to 75 MPa at temperatures from 300 to 450K. These variables were maintained until a steady-state region was obtained. The degree of deformation was varied from 0 to 30%. The experimental set-up is described in more detail in reference /11/.

3. EXPERIMENTAL RESULTS

In order to obtain a rapid macroscopic deformation, a stress larger than the yield stress must be applied. In practice, however, plastic deformation also occurs when a load smaller than the yield stress is applied to the crystal for a prolonged time at not very low temperatures. At stresses below the yield stress, macroscopic deformations do not occur immediately, but the crystal defects in the substance may move at these stresses if the load is applied for a long time. This type of deformation is called creep /12/. Creep deformation is generally associated with a continuous increase in strain under either a constant stress or a periodically applied stress. When metals are stressed beyond their yield point, the plastic flow is large enough so that normal testing methods can be used to measure the amount of creep /13/.

Typical creep curves obtained from tests performed at different temperatures for a given constant stress as well as under different stresses at a constant temperature are shown in Fig. 1(a) and (b). In this study, the stresses applied, ranging from 10 to 75 MPa, were sufficient to provide steady-state creep rates. With the single crystal specimens, the high initial creep rates, observed immediately following the instantaneous strain on loading, decreased continuously until a steady-state was attained (Fig. 1(a)). Creep strain at a constant initial stress of 75 MPa increases with increasing temperature as expected in

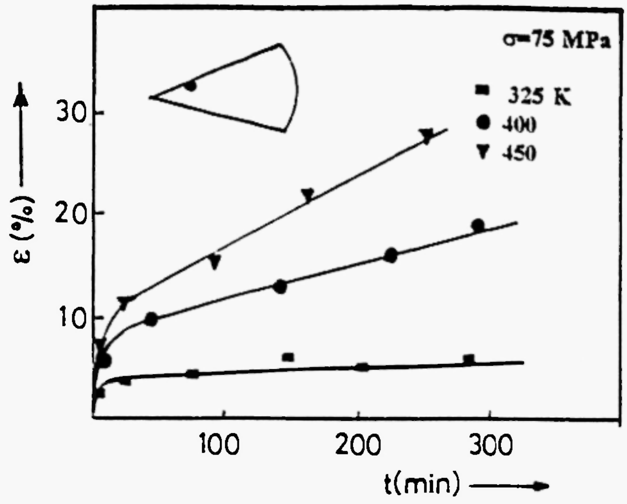

Fig. 1a: Typical creep curves of Cd tested at 75 MPa at different temperatures.

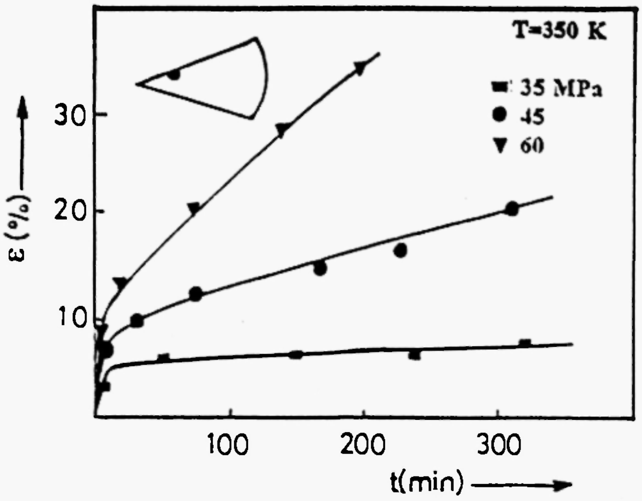

Fig. 1b: Typical creep curves of Cd tested at 350 K under different applied stress.

Fig. 1(b). As shown in Figs. 1(a) and (b), normal creep behaviour was obtained for Cd single crystals.

As a second demonstration, the creep curve for a Cd single crystal at 450 K under a constant stress of 75 MPa is shown in Fig. 2. Fig. 2 is a plot of the logarithm of creep rate versus strain. The creep curve resembles those observed for pure metals aand those non-metals which exhibit a normal primary creep period, during which the creep rate decreases with strain. After a steady-state period is reached, the creep rate remains essentially constant with strain. The steady-state creep rates were taken in this region.

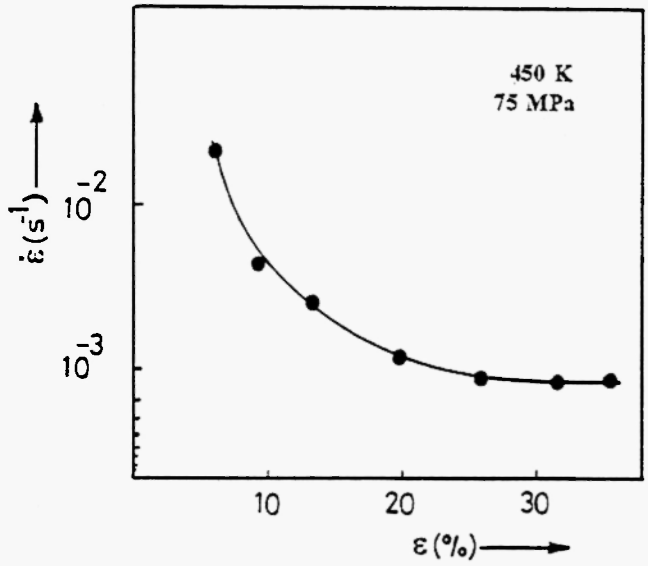

Fig. 2: The creep rate versus strain for Cd single crystals.

Examples of the relationship between the steady-state creep rate and the applied stress are shown in Fig. 3. The results are plotted on a logarithmic scale. The slope of these curves according to equation $\dot{\varepsilon} = A\sigma^n$ is the stress exponent /14,15/. As can be seen from Fig. 3, the stress exponent is equal to 4.2 and decreases with increasing temperature. Our value for the stress exponent is in fairly good agreement with other experimentally determined values for magnesium at temperatures less than about 350 K, where deformation is predominantly basal slip and stress exponents of about 5 have been found /10,16/.

There are several theoretically derived creep laws which can be used to explain high temperature creep at high and low stresses /17,18/. One of these, to explain the creep behaviour of many single crystalline metals at intermediate stress levels, has been given by an expression of the form /19,20/

$$\dot{\varepsilon} = S\left(\frac{\sigma}{E}\right)^n \exp\left(-\frac{Q}{RT}\right)$$

where $\dot{\varepsilon}$ is the steady-state creep rate, S is a material constant, Q is the activation energy, n is the stress exponent, E is the elastic modulus, R is the gas constant, T is the absolute test temperature. The activation energy for creep was determined from the temperature dependence of the steady-state creep rate. From the above equation, the activation energies were obtained from the logarithm steady-state creep rate versus the inverse of the absolute temperature at constant stress. The slope of these lines gives the activation energy of the steady-state creep rate (Fig. 4). As seen in Fig. 4, it decreased linearly with

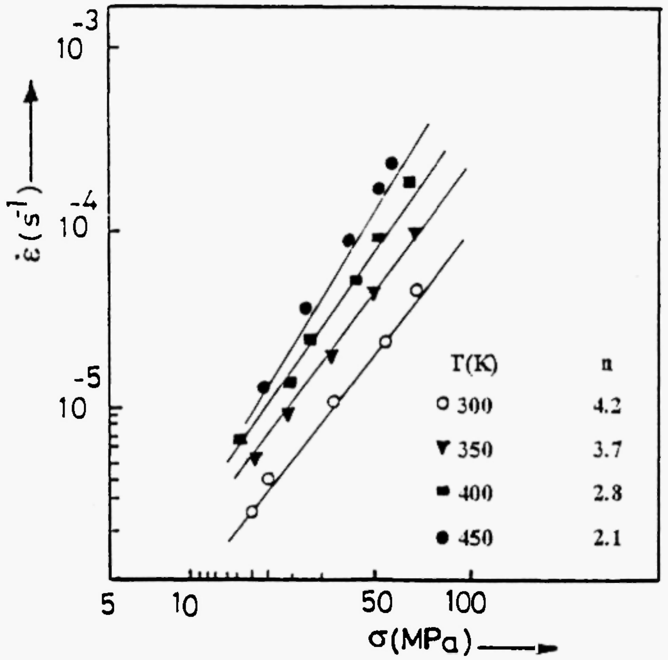

Fig. 3: The applied stress dependence of steady-state creep rate for Cd single crystals. n is the stress exponent.

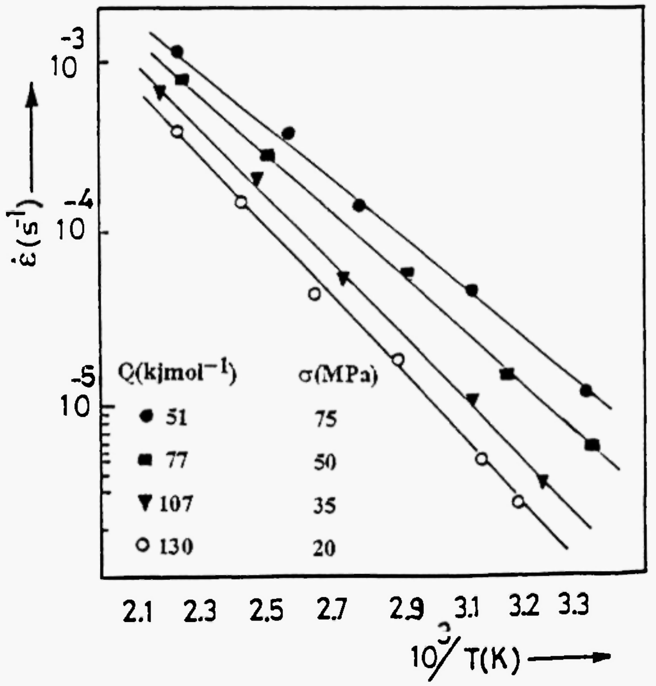

Fig. 4: The temperature dependence of steady-state creep rate for Cd single crystals. Q is the activation energy.

increasing stress from 130 kJ/mol at $\sigma = 20$ MPa to 51 kJ/mol at $\sigma = 75$ MPa. These values are in close agreement with the activation energy for steady-state creep determined from isothermal tests /21/.

4. RESULTS AND DISCUSSION

As indicated in refs. /22,23/, the steady-state creep rate changes with temperature and stress. This change has been explained by sub-grain boundaries and the presence of impurities which changes the level of internal stresses on the moving dislocations. Although there is a reasonable amount of data in the literature on the stress exponents of the steady-state creep for h.c.p. metals, there is a paucity of data on internal stresses for h.c.p. metals /16/. In this study, slip in crystals deformed in tensile stress at room temperature occurred along the $[11\bar{2}0]$ direction on the basal plane only where the stress exponent equals 4.2. The results for polycrystalline Cd at room temperature for stresses $\sigma > 20$ MPa where $n = 6.12$ are reasonably consistent with previously reported data /24/. Accordingly, we observed by means of slip traces on the crystal surfaces that there was an increasing tendency for slip to occur predominantly on $\{10\bar{1}0\}$ and $\{11\bar{2}2\}$ planes with increasing temperature and decreasing stress exponent. As seen from Fig. 3, the stress exponent decreases with increasing temperature. A similar decrease of the stress exponent has been reported by Roberts /25/. This case is attributed to the fact that slip occurred on a system other than basal. Nortwood and Smith /16/ showed that non-basal slip gives rise to a stress exponent smaller than that for basal slip. The same results have been obtained for Mg /8/ and Zn /26/. At the same time, we also showed that there exists a cross-slip by means of the work-hardening rate in Cd single crystals from (0001) to $(01\bar{1}1)$ planes at around 0.7 T_m (T_m is the melting point). This result shows that cross-slip is the rate-controlling recovery process for steady-state creep deformation at high temperatures. Meanwhile, there was also a corresponding decrease in activation energy (Fig. 4). This case supports a possible change in the rate-controlling mechanism for creep.

In conclusion, the stress exponent and activation energy obtained in the present study for Cd single crystals are in good agreement with results for h.c.p. crystals, especially magnesium. Stress exponent and activation energy depend on both temperature and stress. There is a thermally activated cross-slip at around 0.7 T_m. This case indicates a possible change in rate controlling for creep at this temperature.

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