Comments On The Work-Hardening Behaviour In Cd Single Crystal From Stress-Strain Curve Measurements

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ABSTRACT

The stage-I work-hardening behavior of Cd single crystals from stress-strain curve measurements has been investigated as a function of temperature and strain-rate. The results show that the temperature and the strain-rate introduce opposite effects on the work-hardening behavior. The stress was found to be approximately linear on the square root of strain for both low and high strain values at different temperatures. There is an inflexion point at intermediate strains. This inflexion point moves to higher strain values with increasing temperature.

1. INTRODUCTION

The explanation of work-hardening behaviour represents one of the most important contributions to the applications of dislocation theory. The idea of dislocations and the first detailed theory of work-hardening behaviour have been proposed by Taylor /1/ and Mott /2/. These older theories of Taylor and Mott were replaced by special theories of Hirsch and Lally /3/ and Argon /4/. One of the most important theories was developed by Seeger and co-workers /5~7/. Work-hardening theories developed in the framework of these models are extremely numerous and, in many cases, confusing and contradictory. Experimental investigations of the temperature dependence of the work-hardening of hexagonal close-packed (hcp) metals (Cd and Zn) until now were limited mainly to temperatures higher than 77 K /8~10/. In this temperature range, the experimental results seem to fit a model proposed by Seeger /5,7,8/ from which it follows that the work-hardening rate (hereafter referred to as WHR), or in other words, the derivative of the stress-strain curve, should be constant at low temperatures. In several papers, it is pointed out that the temperature dependence of work-hardening in Zn shows an anomaly around 77 K while in Cd it does not /8,11,12/. The strong temperature dependence has been interpreted in terms of the climb and disappearance of Orawan loops by a process of pipe diffusion during tensile deformation /13/. Also, Staton-Bevan /14/ showed that work-hardening behaviour, like critical resolved shear stress (CRSS), depends strongly on the crystal orientation. From this relationship, extensive studies have been started to understand the work-hardening mechanisms. Although the work-hardening behaviour of hcp metals has recently been studied intensively, it has proved difficult, however, to explain all observations by one unique model for deformation.

It is well known that the work hardening behaviour of metals is comprehensively represented by the stress-strain curves ($\sigma - \varepsilon$), which in the case of single crystals can be divided into three stages /15/. It is also important to do basic work-hardening investigations on Cd and Zn since these metals show basal glide because of the large c/a ratio. In this paper the stage-I work hardening behavior of Cd single crystals from stress-strain curve measurements were examined as a function of temperature and strain-rate.

2. EXPERIMENTAL PROCEDURE

Single crystals of 5 mm diameter were grown in a glass tube at the rate of 15 mm/h using a modified Bridgman method. The crystals are 80 to 100 mm in length and their orientations were determined by the Laue back reflection method. The orientation of all crystals was within $\pm 4^0$ of the required orientation. The crystal orientations are shown in the unit triangle in the figures. The crystals having the same growth direction and perfection were pulled along the growth directions with the use of an Instron-type machine at the different strain rates in the temperature range from room temperature to 500 K. It was found that slip occurred only on the basal plane. This assumption is consistent with the slip line observations obtained from surface photographs. Load and elongation curves were recorded during the tensile tests and stress-strain curves were calculated from these curves for all crystals at different temperatures and strain rates. Further experimental details are described in /16/.

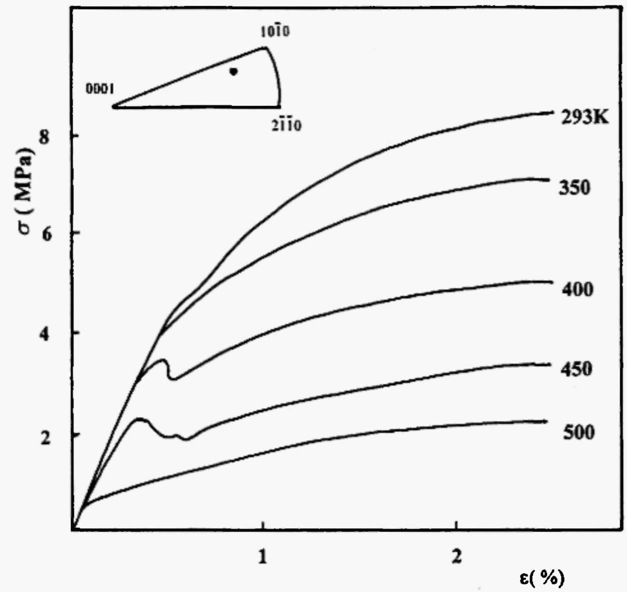

Fig. 1: Stress-strain curves of Cd single crystals of basal slip (0001)[$2\bar{1}\bar{1}0$] at a strain rate of $1.6x10^{-5}$ s^{-1} and the different temperatures.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The work-hardening of hcp crystals is in its whole behaviour frequently similar to that of face centred cubic (fcc) crystals. Some researchers have pointed out that stage II and III do not occur when slip takes place mainly only in the basal plane in hcp crystals /15/. For this reason the work-hardening of hcp metals and stage-I of work-hardening of fcc crystals can theoretically be investigated together only for glide in the basal plane. It is likely that a considerable part of work-hardening of hcp crystals is produced by dislocation loops formed on the basal planes by the aggregation of vacancies generated by dislocations /8/.

In this study, the stress-strain curves of Cd single crystals were measured. The results are provided in Figs. 1 and 2 with respect to a basal slip (0001)[$2\bar{1}\bar{1}0$] at the different temperatures and strain-rates, respectively. It can be seen from these figures there is only stage-I on these curves in the indicated strain range. In this stage, stress-strain curves are

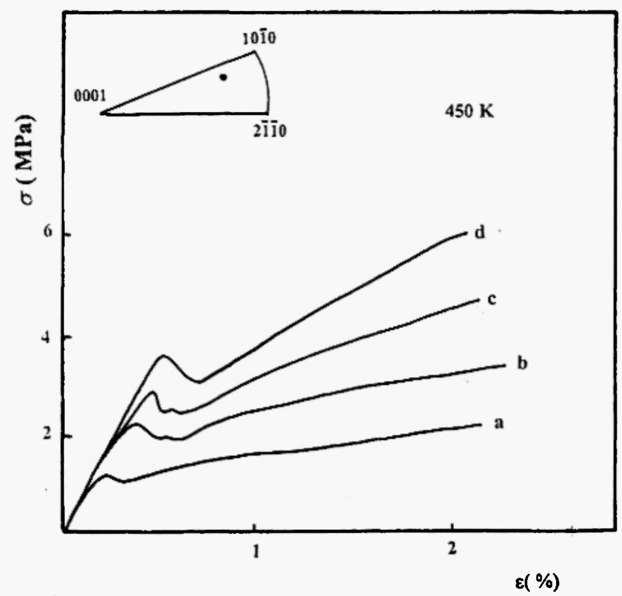

Fig. 2: The effect of the strain rate on the stress-strain curves; (a) $1.1x10^{-6}$, (b) $1.6x10^{-5}$, (c) $1.0x10^{-4}$, (d) $4.2x10^{-3}s^{-1}$.

approximately linear at high temperatures, while they are concave at low temperatures. This concavity increases with decreasing temperature. As seen in Fig. 1, stress increases with increasing strain continuously for all temperature values. The WHR is positive and there is a high initial WHR especially at low temperatures. This high WHR leading to strengthening is essentially due to the Kear-Wilsdorf (hereafter referred to as K-W) mechanism. It is well known that a specimen which has been deformed at low temperatures contains many so-called Kear-Wilsdorf locks /17/. These K-W locks which behave as a barrier would result in a relatively high WHR. The WHR continuously decreases with increasing temperature (Fig. 1). This result could be explained by a decreasing resistance to dislocation motion on the slip plane and by the break-down of K-W locks as dislocations become mobile on the slip plane. The following dislocations are then able to keep moving, giving rise to a lower WHR. This suggestion is supported by evidence from the Transmission Electron Microscopy (TEM) studies /14/ and is consistent with a proposal by Oblak and Rand /18/ that there is a decrease in the plane lattice friction force with increasing temperature. Meanwhile, the reduction in the WHR with increasing temperature has been explained by Hazzledine and Hirsch /19/ by shrinkage and disappearance of Orawan loops and formation of prismatic loops with climb.

As seen in Fig. 3, the WHR increases with increasing strain-rate. This behaviour can be explained by decreasing amount of K-W locks. When the strain-rate increases, the mobile dislocation density must increase in order to compensate for the increase in strain-rate. The same results have been reported in ref. /20,21/. Therefore, the opposite effect is likely to be induced by temperature and strain-rate on the work-hardening behavior of Cd single crystals.

Important characteristics of stress-strain curves can be recognised if the stress is plotted against the square root of strain. Figure 4 shows the obtained stress-strain curves by subtracting the elastic region of the stress-strain curves given in Fig. 1. From this figure, both at small strain values and high strain values, the stress depends in an approximately linear manner on the square root of strain for all temperature values. Also, it

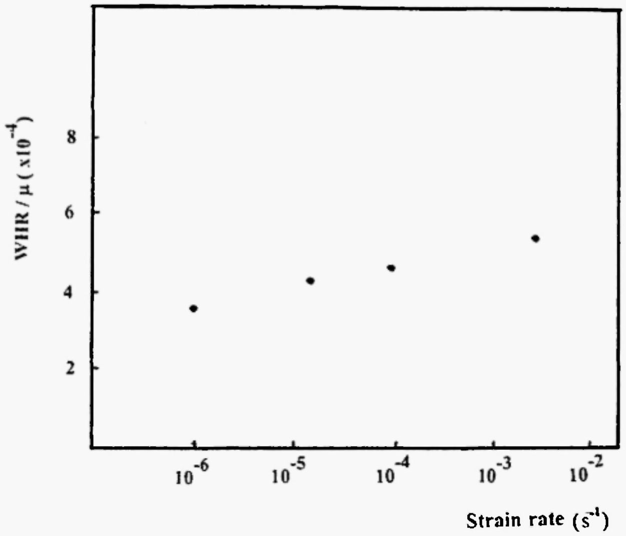

Fig. 3: The strain-rate dependence of WHR of Cd single crystals.

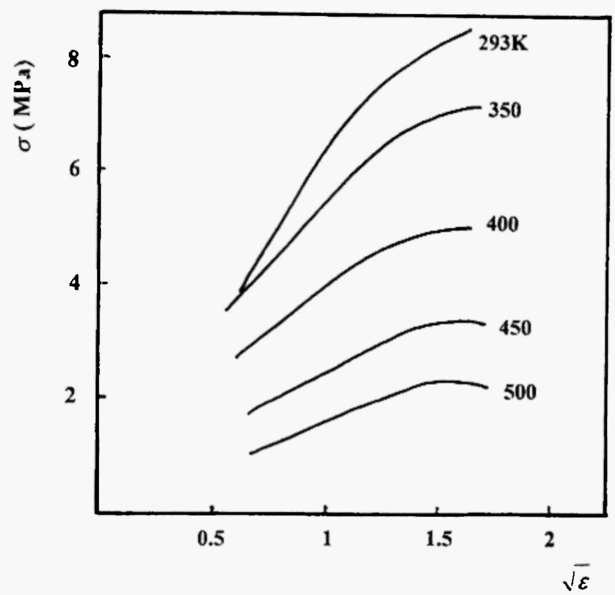

Fig. 4: The obtained $\sigma = \sqrt{\varepsilon}$ curves by subtracting the elastic region of the stress-strain curves of Cd single crystal in given Fig.1.

can be seen from this figure that all curves exhibit two-stage work-hardening behavior and there is an inflexion point at intermediate strains. This inflexion point moves to higher strain values with increasing temperature. Above 450K, the WHR changed from a positive to negative temperature dependence after the inflexion point. This suggests that some factors begin to contribute K-W mechanism at 450 K, but details are not known. On the other hand, to express the ($\sigma - \varepsilon$) relation as a simple power function, a similar inflexion point has been indicated by Doherty /22/. So, we can say that the coordinates of this inflexion point as a function of temperature are the most important parameter of the stress-strain curves for macroscopic hardening of crystals.

In conclusion, the K-W mechanism is considered to play an important role in the work-hardening behaviour of Cd single crystals. It can be said that work-hardening behavior is strongly dependent on the test temperature and strain-rate. Some discussion of work-hardening of Cd and Zn is give in ref. /23,24/. The present results are in good agreement with those previously published. On the basis of these results, the present authors maintain the view that the work-hardening behavior is essentially controlled by the K-W mechanism.

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