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COMMENT ON HARPER-DORN CREEP IN ALUMINUM

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ABSTRACT

Harper and Dorn (1957) obtained experimental evidence for a new mechanism of low-stress, high temperature creep in pure aluminum. Their results were recently questioned by Burton (1972) who argued from data on the creep of fine-grained aluminum foils. The present communication summarizes recent data confirming the existence of Harper-Dorn creep in aluminum and points out that the bulk of Burton's results are consistent with the expected transition from Harper-Dorn to Nabarro-Herring creep as sample grain size is made small.

1. INTRODUCTION

In studies on the steady-state creep of pure aluminum in the limit of low stress and high temperature Harper and Dorn (1957) found an anomalous creep behavior which shows two principal characteristics: (1) the steady-state strain rate increases linearly with applied stress at given temperature; (2) the steady-state strain rate at given temperature and applied stress is independent of grain size for samples of appreciable grain size. The second characteristic of the Harper-Dorn data indicated the existence of a new mechanism of steady state creep. Since the strain rate does not depend explicitly on grain size the classic Nabarro-Herring mechanism of diffusional creep cannot be used to explain the linear dependence between strain rate and applied stress.

In a recent paper Burton (1972) questioned the results of Harper and Dorn. He studied the low stress, high temperature creep of fine-grained thin foils of pure aluminum. He found steady state creep rates which did depend explicitly on grain size and were roughly in agreement with the prediction of the Nabarro-Herring model. On the basis of these data, he phrased the general conclusion that the low-stress, high temperature creep of pure aluminum follows the Nabarro-Herring model.

In this communication we make two points relevant to Burton's results: (1) the existence of Harper-Dorn creep in pure aluminum is well established experimentally; (2) the experiments conducted by Burton include only one which would be expected to show the influence of Harper-Dorn creep. The bulk of Burton's data, including all creep rates he was able to measure, are consistent with the expected transition from Harper-Dorn to Nabarro-Herring creep as the sample grain size is made small.

2. THE EXPERIMENTAL EVIDENCE FOR HARPER-DORN CREEP

Harper-Dorn creep was first observed in pure aluminum by Harper, Shepard, and Dorn (Harper and Dorn, (1957); Harper, Shepard, and Dorn, (1958)) who tested thin platelets of both single and polycrystalline alluminum in tension. The thickness (t) of their platelet specimens was approximately 2.5 mm. The mean grain diameter (d) of their polycrystalline specimens was approximately 3 mm. This creep behavior has more recently been studied by Muehleisen, Barrett, and Nix (Muehleisen (1969); Barrett, Muehleisen, and Nix (1972)), who tested bulk tensile specimens of both single and polycrystalline ($d \sim 10$mm) aluminum in tension, and by Mohamed, Murty and Morris (1972) who tested bulk double-shear specimens of both single and polycrystalline ($d \sim 9$mm) aluminum in pure shear.

The aggregate results of these three investigations are shown in figure 1, where we have plotted a non-dimensional shear strain rate ($\dot{\gamma}kT/DGb$) against a non-dimensional shear stress (τ/G). The symbols appearing in these parameters are: $\dot{\gamma}$, the shear strain-rate; k, Boltzman's constant; T, the absolute temperature; D, the self-diffusion coefficient; G, the shear modulus; b, the magnitude of the Burgers vector of a simple dislocation in the FCC aluminum lattice, and τ, the effective shear stress. To obtain this plot the tensile data of Muehleisen (1969) were transformed to shear data using the relations

$$\dot{\varepsilon} = \frac{2}{3}\dot{\gamma} \qquad\qquad [1]$$
$$\sigma = 2\,\tau,$$

where $\dot{\varepsilon}$ is the tensile strain rate and σ is the tensile stress. For simplicity in comparing the results to those of Burton the values of the self-diffusivity D are taken from the relation proposed by Burton (1972); different values of D are used in the original reports cited.

The data divide into two regions of low stress creep behavior. Region I is Harper-Dorn creep. The data for this creep behavior are well represented by a linear relation

$$\dot{\gamma}kT/DGb = A\ (\tau/G) \qquad [2]$$

where A is a dimensionless constant equal to $2.9.10^{-11}$. The scatter about this curve is due principally to a small consistent deviation between the results of Muehleisen and those of the other two studies. The data also scatter somewhat near the knee of the curve where the mechanism of creep is changing. Region II of the curve represents creep behavior generally attributed to climb-dominated dislocation processes. The strain rate in this region is given by the power law

$$\dot{\gamma}kT/DGb = A'\ (\tau/G)^{4.5} \qquad [3]$$

found in several independent investigations (Bird, Mukherjee, and Dorn (1969)).

For comparison figure 1 also contains a plot of the creep rate predicted from the Nabarro-Herring model for the grain size (9mm) used in tests by Mohamed, Murty and Morris (1972). Nabarro-Herring creep obeys a linear relation of the form

$$\dot{\gamma}kT/DGb = B\ (b/d)^2\ (\tau/G), \qquad [4]$$

where B is a dimensionless constant expected to be about 21. As can be seen from the figure, the predicted rate of Nabarro-Herring creep is roughly three orders of magnitude below the measured values of the creep rate.

In light of the agreement between these three distinct investigations we conclude that the existence of Harper-Dorn creep in pure aluminum is well established experimentally. Recent results have shown, moreover, that creep of the Harper-Dorn type is not confined to pure aluminum. Murty, Mohamed, and Dorn (1972) found Harper-Dorn behavior in the low stress limit of creep in Al-3% Mg alloy. Mohamed, Murty and Morris (1972) have recently identified Harper-Dorn behavior in the low-stress limit of creep in lead and tin.

While the existence of Harper-Dorn creep is established the mechanism of this creep is uncertain. The problem is discussed in the original references cited above. A detailed review of the arguments is beyond the scope of this communication. In light of the comments of Burton (1972), however, we should note that the discussions concur that the "subgrain" type of diffusional creep suggested by Friedel (1964) is unlikely to be the governing mechanism of Harper-Dorn creep. The creep rates predicted from the Friedel model are low, the observed behavior of the subgrains seems inconsistent with the model, and there is specific evidence of dislocation activity during Harper-Dorn creep. Harper-Dorn creep appears to be governed by some dislocation mechanism whose details are not yet known.

3. DISCUSSION OF THE RESULTS OF BURTON (1972)

The relation governing Harper-Dorn creep (Equation [2]) predicts a creep rate independent of grain size, while the governing equation of Nabarro-Herring creep (Equation [4]) predicts a creep rate which increases as d^{-2} as the grain size is made smaller. Hence for given values of the coefficients A and B there exists a critical value of the grain size (d_c) such that for all samples of $d < d_c$ the Nabarro-Herring creep mechanism will dominate over the Harper-Dorn. If samples of $d < d_c$ are tested and if no third creep mechanism intervenes, one must expect to see creep rates which follow the Nabarro-Herring model and which are uniformly above the rates predicted by Harper-Dorn.

The creep rates which Burton was able to measure satisfy these criteria. In figure 2 we have replotted Burton's results on the creep of aluminum foil in vacuum. Equations [1] were used to transform Burton's data from the $\dot{\varepsilon}$-σ representation of this paper to the $\dot{\gamma}$-τ representation of the figure, using his reported values for the effective stress σ ($= \sigma_{applied} - \sigma_o$). The solid curve in figure 2 is the creep curve for bulk aluminum, taken from figure 1. The data reported by Burton fall uniformly above the Harper-Dorn (low stress) segment of this curve. These data may be fit to the governing equation (4) for Nabarro-Herring creep if d is replaced by the "effective grain size" of the foil of thickness t,

$$d' = (td)^{1/2}, \qquad [5]$$

and if B is taken to be approximately 130 (B = 43.3 if the $\dot{\varepsilon} - \sigma$ representation is used). This number is large compared to the expected value of 21 (7 in the $\dot{\varepsilon} - \sigma$ representation), but does not seem unreasonable given the uncertainty in the value of the self-diffusion coefficient D and the approximations inherent in the Nabarro-Herring model.

Comparing equations [2] and [4] with B = 130 and A = $2.9 \cdot 10^{-11}$

we obtain d'_c = 640 μm; Nabarro-Herring creep should be anticipated for foils of lesser grain size. Of the foils tested by Burton only two had an effective grain size $d' > d'_c$. The remainder of his data fall in the Nabarro-Herring region and show agreement with the Nabarro-Herring creep model.

Of the two foils from Burton's set having $d' > d'_c$, the first (from the table on p. 649 of Burton (1972)) had a thickness of 2.5 x 10^3 μm and a mean grain size of $1.5.10^4$ μm, giving an effective grain size d' of approximately 6.10^3 μm. This sample was tested at an applied stress of 250 kN/m^2 corresponding (after subtracting Burton's value of σ_o) to an effective shear stress (τ/G) of $3.3.10^{-6}$. This value of the applied shear stress falls in the transition region at the knee of the creep curve of bulk aluminum; thick samples of coarse-grained aluminum show an apparent mixture of Harper-Dorn and climb-dominated creep at this stress level. However, Burton was unable to measure a creep rate for his specimen and reports creep rate zero.

The second coarse-gained specimen tested by Burton is described in Section 5 of his paper. The thickness of this foil is not given, but the grain size is reported to be $\sim 10^4$ μm. This sample was tested at an applied load of 304 kN/m^2, corresponding to an effective shear stress (τ/G) of $5.1.10^{-6}$. Reference to the creep curve of bulk aluminum shows that this value of the applied shear stress is well above the maximum value at which Harper-Dorn creep is observed. Thick samples of coarse-grained aluminum show an appreciable creep rate governed by the climb mechanism at this stress level. However, Burton failed to observed creep in his specimen and reports creep rate zero.

It is difficult to base any general conclusion on two data points in creep, particularly when the limit of resolution of the test apparatus and the reproducibility of the results are unknown. However there are only two possibilities: either the coarse-grained foils tested are thick enough to exhibit creep behavior typical of bulk aluminum or they are not.

If the foils are assumed thick their low creep rates may be attributable to experimental problems, but certainly cannot be used to question the existence of Harper-Dorn creep. As mentioned above, the latter foil was tested at a load well above the maximum at which Harper-Dorn creep is observed. At this load level ($\tau/G = 5.1.10^{-6}$) the climb mechanism acting alone would give a creep rate higher than four of the values measured by Burton in fine-grained specimens. The other coarse-grained foil was tested at an applied shear stress which falls in the knee of the creep curve. Again at this load level ($\tau/G = 3.3.10^{-6}$) an extrapolation of the curve representing climb dominated creep of aluminum shows that the climb mechanism acting alone would cause a creep rate above at least one of the values measured by Burton for thinner foils. Burton's results are markedly inconsistent with the measured creep behavior of bulk aluminum whether or not Harper-Dorn creep exists.

On the other hand thin foil effects may be responsible for the low creep rates of these samples. The annealing or pinning of dislocations at the free surfaces of a foil (which may be more significant in tests conducted in vacuum) should influence the rate of creep by dislocation-dominated processes, and may have the effect of suppressing the rate of creep due to either the climb or Harper-Dorn mechanism to values below those measurable by Burton's technique. In this context it is interesting that those of Burton's samples which appear to have undergone creep by the climb-dominated mechanism exhibit creep rates which are uniformly below the curve for bulk aluminum (region II in figure 2). While there is, unfortunately, only one relevant datum point, the deviation from bulk behavior is more pronounced for the thinner of the two fine-grained foils which appear to have crept by the climb mechanism.

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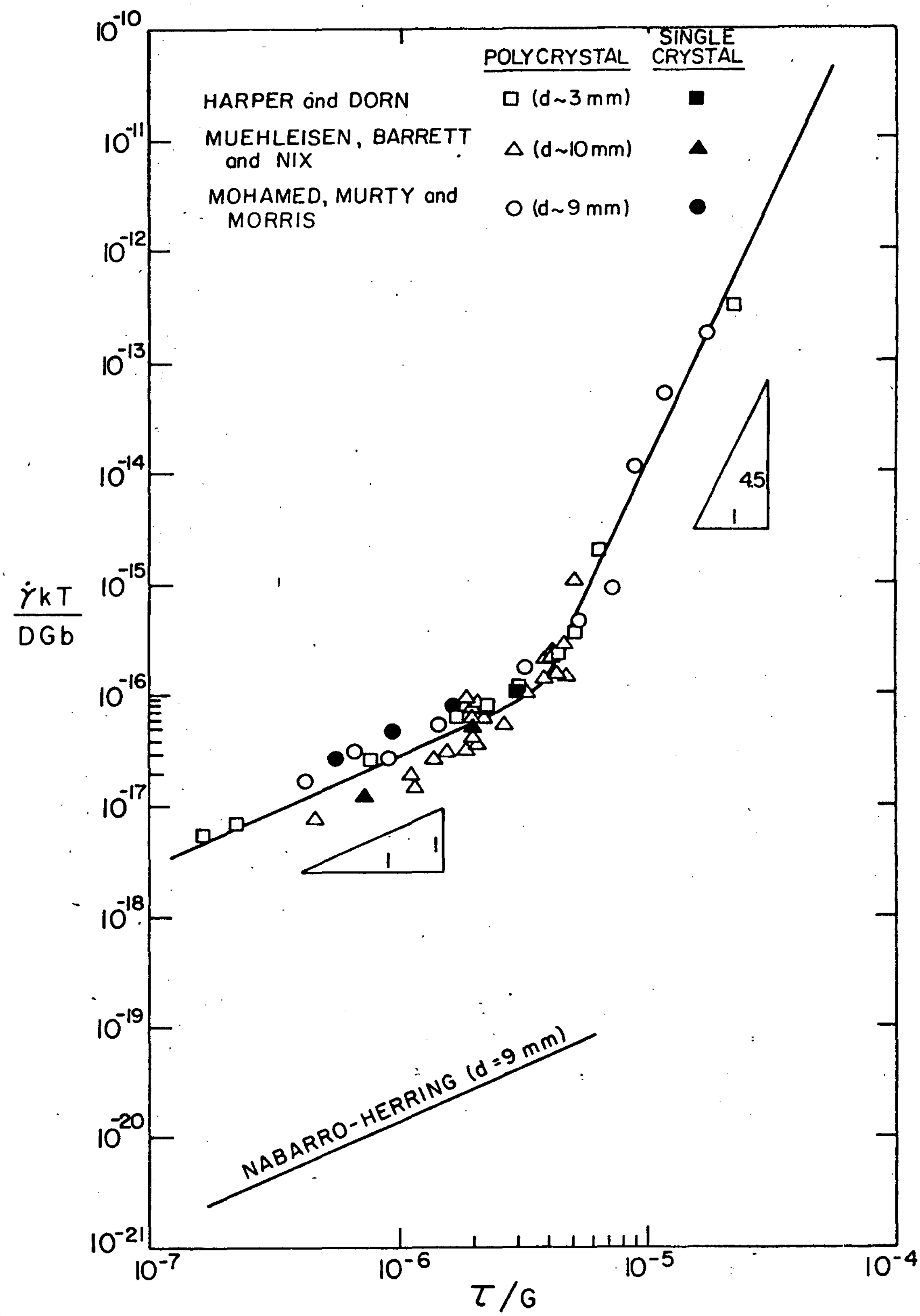

Fig. 1 Data of three investigations of the low-stress, high temperature creep of coarse-grained aluminum.

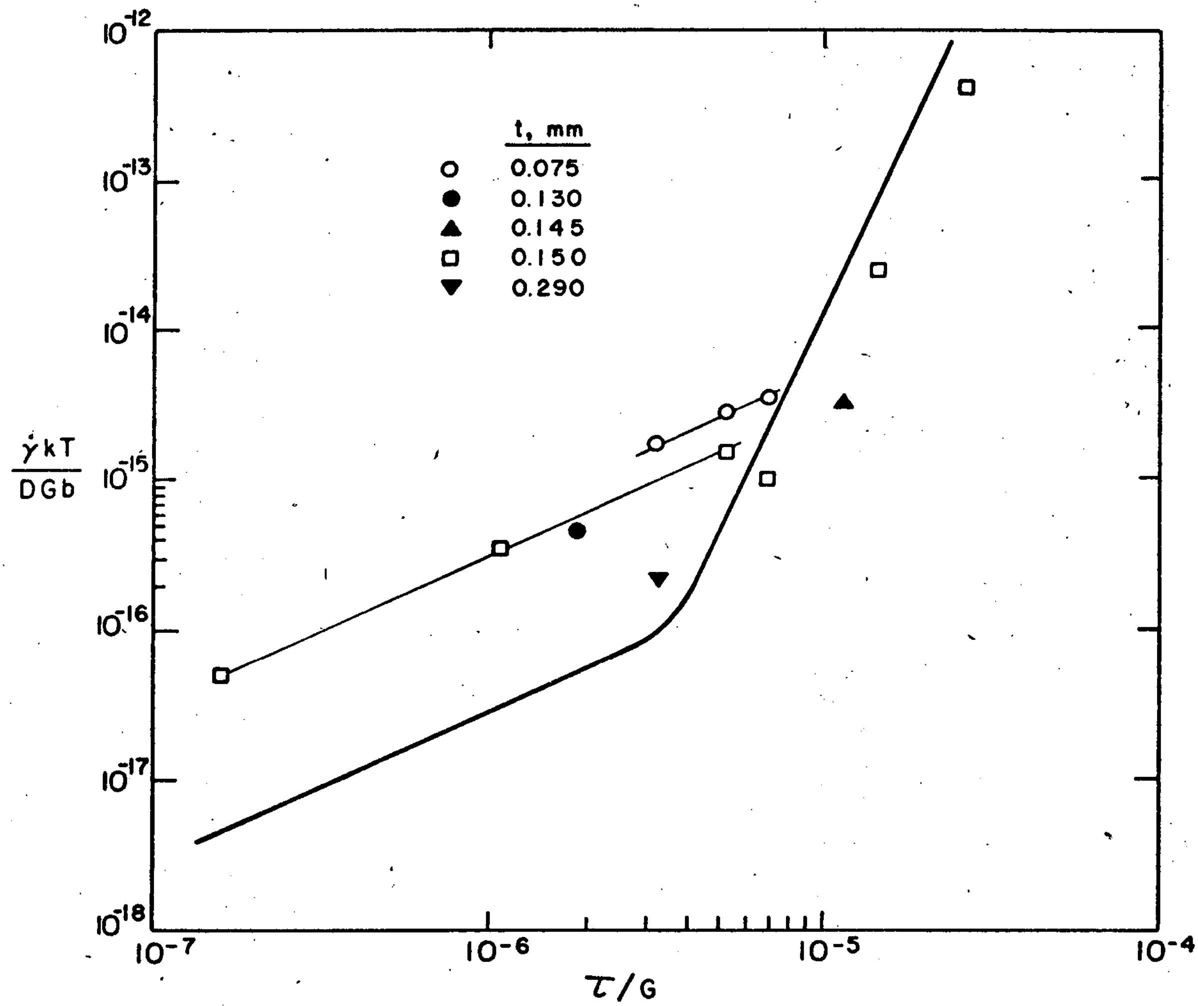

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Fig. 2 The data of Burton (1972) on the creep of fine-grained foils of aluminum in vacuum (data points) compared to creep behavior of aluminum in bulk samples (solid line).