An Upper Bound on Strain Rate for Wedge Type Fracture in Nickel During Creep

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It is shown that measurements of the rate of grain boundary sliding using internal friction can be used for calculating an upper bound in strain-rate, above which wedge type of intergranular fracture will not occur. A transition in mode of fracture, from ductile-transgranular at high strain-rate to wedge-intergranular at a lower strain-rate, in Ni is adequately predicted by internal friction measurements. At a still lower strain-rate, a shift from wedge type to "r" type of intergranular fracture occurs. This transition apparently agrees well with the change in the overall creep mechanism from power-law creep to diffusional creep.

1. INTRODUCTION

THE distinction between "wedge" type and "r" type of intergranular fracture during creep has been well recognized in the literature. Grant[1] and coworkers studied wedge type fracture in considerable detail and have proposed a physical mechanism in which incompatability of sliding from adjacent grains at a triple junction node leads to the opening up of a wedge crack.[2] There have also been attempts to model wedge cracking on the basis of a sliding mechanism.[3,4]

Typically, wedge cracks appear at high strain-rates and intermediate temperatures. As the strain rate is lowered, or the temperature is raised, there is a transition to "r" type of cavitation failure. Sliding is unquestionably important in wedge cracking, (as seen in a classical picture from Ref. 5 which is reproduced in Fig. 1); therefore, in a uniaxial test, the wedge cracks usually form adjacent to boundaries that are aligned for maximum shear, since it is these boundaries that are likely to suffer the maximum amount of sliding. In "r" cavitation, cavities form exclusively at boundaries that are aligned normal to the tensile axis; in this instance there is little metallographic or theoretical[6] evidence that sliding is a vital part of the cavity nucleation and growth mechanism. The main distinguishing feature of a wedge crack, therefore, is the large sliding offset which provides the "crack opening displacement" for the propogation of the wedge crack, as illustrated schematically in Fig. 2. The actual mechanism of crack propagation is probably similar to the phenomenon of creep crack growth where it is believed that the crack is propelled forward by the nucleation and growth of cavities* ahead of the crack tip.[7,8]

*Most commonly, cavities form at second phase particles in the grain boundaries although cavitation in "clean" boundaries, at structural discontinuities such as ledges and dislocation-grain boundary interactions, cannot be ruled out.

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Although it is true that wedge cracking usually prevails at high strain-rates, we thought that there must come a strain rate, above which wedge cracking would cease because the sliding component of the total strain would decrease beyond a certain critical strain rate. This would occur because sliding is a time and temperature dependent phenomenon, whereas deformation of ductile crystals is always possible at all temperatures through a variety of dislocation mechanisms. Therefore, at intermediate strain-rates, when boundary sliding can keep up with the applied strain-rate, there will be considerable sliding; whereas at the very high strain-rates, the boundaries will remain essentially frozen. The transition from sliding to no-sliding behavior has been considered by Crossman and Ashby.[11] How broad the transition is depends to a large extent on the difference in the strain-rate sensitivity of pure sliding and pure crystal deformation. The greater this difference, the sharper the transition.

In this paper we show that the upper bound strain-rate, *i.e.*, the strain rate above which wedge cracking is not possible, can be estimated from measurements of grain boundary sliding by the internal friction technique. Strain-rate dependence of wedge fracture in nickel is shown to obey the upper bound strain-rate criterion calculated in this manner.

2. FORMULATION OF THE UPPER BOUND STRAIN RATE FOR WEDGE CRACKING

(a) Basic Equations

Consider a single grain boundary between a bicrystal (Fig. 3 is an example) across which a shear stress, σ_s, is applied. The boundary will slide, let us say at a rate $\dot{U}$, which in most experimental work[9,10] has been shown to be related linearly to σ_s. Therefore,

$$k_b \dot{U} = \sigma_s \quad [1]$$

where k_b is the sliding resistance.

k_b is expected to depend upon the microstructure of the grain boundary. It is usually difficult to estimate its value for engineering materials because information regarding diffusion coefficients and the second phase particles to which sliding is quite sensitive, is often not

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available. In such cases internal friction is a viable method of obtaining k_b, and this is discussed in the following section. In simple model materials,[10,12] however, it is possible to obtain an estimate of k_b through the expression:

$$k_b = \frac{kT}{8\Omega}\frac{f_b p^2}{\delta D_b} \qquad [2]$$

where the rate of boundary sliding is assumed to be controlled by the presence of particles of diameter p, occupying an area fraction f_b in the boundary. Ω is the atomic volume of the metal atoms, and δD_b is the boundary width times the boundary self diffusivity. In Eq. [2] it has been assumed that boundary diffusion is more efficient than lattice diffusion in accommodating sliding around the particles;[10] this is usually true if the particles are smaller than about 5 μm and if the temperature is in the neighborhood or 0.4 to 0.7 T_m.

Returning to the calculation of the upper bound strain-rate for wedge cracking, the sliding rate, $\dot{U}$, given by Eq. [1] is the fastest possible rate of sliding for an applied shear stress σ_s. This rate will be achieved in a bicrystal, as shown in Fig. 3, in which there is no other constraint to sliding other than the sliding resistance of the boundary itself. It is easy to appreciate, that the same boundary will have a more complex sliding behavior when it is contained within a polycrystal; the main difference being the constraint experienced by a sliding length from the adjacent grains at the triple grain junctions. In a polycrystal containing a distribution of grain facet lengths and orientations, the extent of sliding would differ considerably from one boundary to another, but it is safe to assume that because of the constraint to sliding at triple junctions, in no instance will the sliding rate be greater than the sliding rate, $\dot{U}$, which is achieved in a bicrystal. Invoking the argument given in Section 1 that the sliding component of the total strain will become small if the polycrystal is deformed at a rate faster than the boundaries can slide, it can be asserted that if the applied shear strain rate $\dot{\epsilon}_s$ is greater than $\dot{U}/d$ where d is the grain size, then sliding would become unimportant. Therefore, $\dot{\epsilon}_s = \dot{U}/d$ is an "upper bound" strain rate for wedge cracking. Expressing the result in terms of the tensile stress, σ_1, and tensile strain-rate $\hat{\dot{\epsilon}}_1$, we obtain*

$$\hat{\dot{\epsilon}}_1 = \frac{\sigma_1}{3k_b d} \qquad [3]$$

where k_b is calculated through Eq. [2] or where it is measured using the internal friction technique (described below).

The upper bound notion of $\hat{\dot{\epsilon}}_1$ in Eq. [3] needs qualification. It contains the assumption that the transition from sliding to no-sliding behavior occurs abruptly; in fact, it will be gradual, spanning perhaps an order of magnitude in strain-rate. The chances are, however, that we are overestimating the magnitude of $\dot{\epsilon}_1$ because we have used the sliding rate in a bicrystal in its

*Here we have used $\sqrt{3}\sigma_s = \sigma_1$ and $\epsilon_s = \sqrt{3}\epsilon_1$, following the von Mises criterion for equivalent stress and strain.

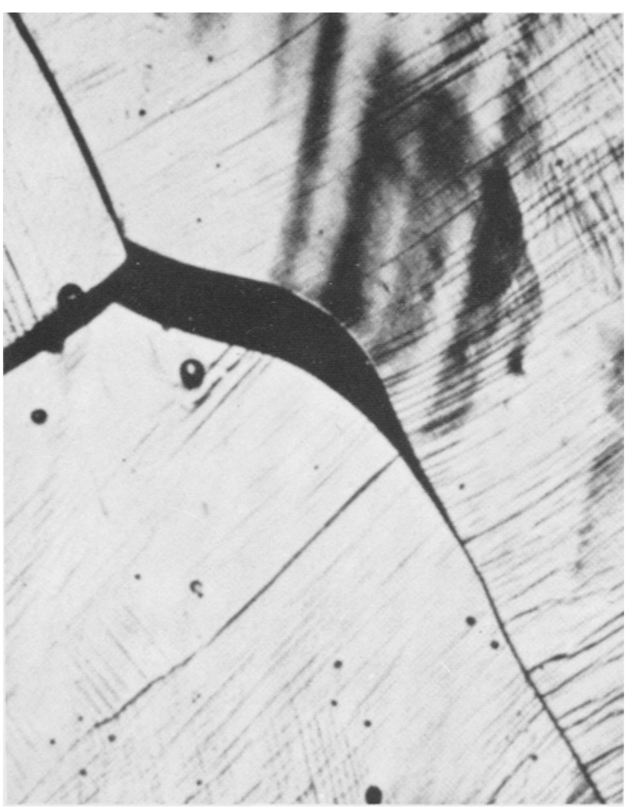

Fig. 1—A wedge crack instigated and propagated by grain boundary sliding reproduced from Ref. 5. Permission to publish granted by ASM. (Magnification for the micrograph not available).

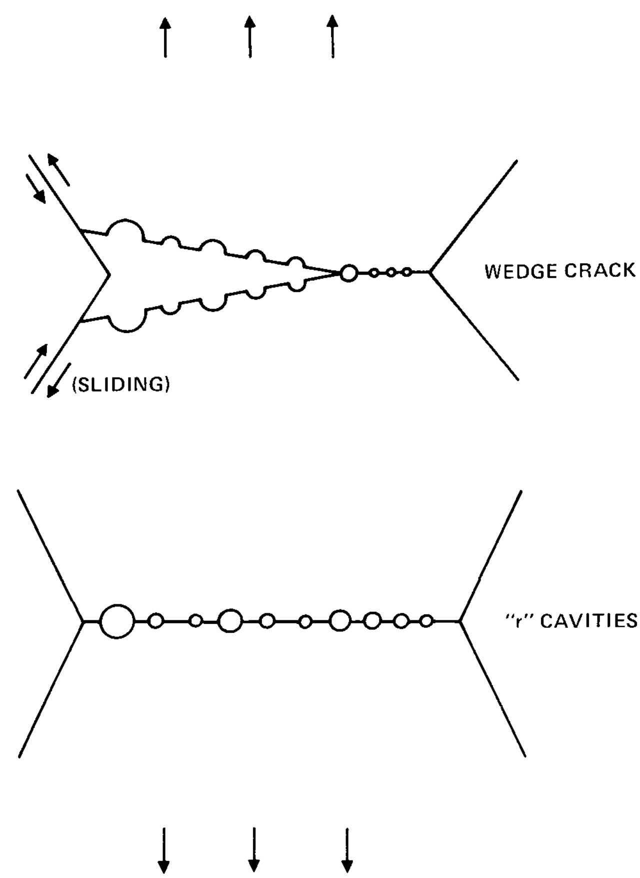

Fig. 2.—A schematic for the appearance of a wedge crack and 'r' type cavities.

derivation rather than the sliding rate in a polycrystal, which is likely to be lower.[13] This overestimate should serve to compensate for the error arising from the assumption of abrupt transition from sliding to no-sliding behavior. It should also be pointed out that we have chosen to use von Mises equivalent stress rather than maximum shear stress because it is the form commonly used to describe plastic flow in multiaxial stress states. The difference between the two is minor in comparison with the other assumptions in the model.

The right hand side in Eq. [3] contains material parameters k_b and d, and a loading parameter σ_1. Although in any given experiment σ_1 is well defined, it would be useful for the purpose of engineering calculation if it could be assigned a fixed value. A clue to its approximate magnitude can be obtained from inspection of fracture maps[14] which delineate the stress and temperature regime in which wedge cracks have been observed. In nickel and its alloys, wedge cracks are seen in a narrow range of stress, spanning a factor of less than two. The mean value of the stress for wedge cracking increases from about $\sigma_1 = 6 \times 10^{-4}E$ for commercially pure nickel[14] to about $\sigma_1 = 3 \times 10^{-3}E$ for Nimonic 80A.[14] A substitution of the appropriate mean stress for σ_1 in Eq. [3] will, therefore, simplify the calculation of $\hat{\dot{\epsilon}}_1$ considerably without sacrificing its accuracy by more than a factor 2. Of course, if the constitutive equation for flow in the material is well known, it can be substituted to convert σ_1 into $\dot{\epsilon}_1$. For the sake of simplicity, though, we shall resort to fracture maps to ascertain the approximate value for σ_1.

(b) Measurement of k_b by Internal Friction

A single dashpot would be an adequate representation of the sliding response in a bicrystal. In a polycrystal a sliding boundary will experience an elastic back stress from the adjacent grains, which obstructs its motion at the triple points. In this instance, a spring-dashpot combination, as shown in Fig. 4, will be a more appropriate representation of the time dependent strain response of the polycrystal. The constitutive equation of the dashpot will still be the same *i.e.* given by Eq. [1].

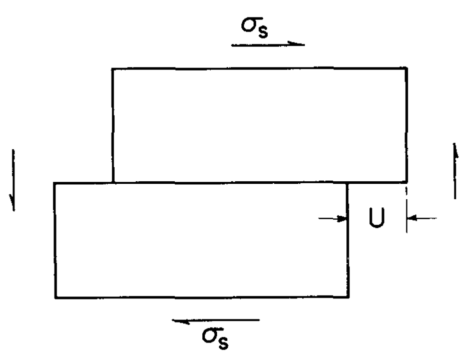

Fig. 3—The sliding resistance of a grain boundary is most easily defined by considering sliding at a single boundary in a bicrystal.

The strength of the spring is expressed by the equation

$$\sigma_s = \beta U \quad [4]$$

where β has been calculated to be[13,15]

$$\beta = \frac{E}{1.14(1 - \nu^2)} \frac{1}{d} \quad [5]$$

where E, ν are the elastic constants for the crystal.

The spring dashpot pair in Fig. 4 is equivalent to an anelastic system having a time constant τ_s, which will be given by[12]

$$\tau_s = \frac{k_b}{\beta}$$

which leads to:

$$k_b = \frac{E}{1.14(1 - \nu^2)} \cdot \frac{\tau_s}{d} \quad [6]$$

The time constant, τ_s, can be measured by the internal friction technique, as has been demonstrated by Kê[9] and by Mosher and Raj.[12]

The internal friction procedure is to measure the temperature at which the damping peak is observed when the specimen is vibrated at a given frequence, ω. At the peak temperature, the condition that $\omega\tau_s = 1$ is obeyed, which leads to the measurement of τ_s. The temperature dependence of τ_s is determined by measuring the shift in the temperature peak with a change in ω. Typically, vibration frequency in the range of 1 to 10 Hz yields good results for this type of damping peak.

Measurement of τ_s and its substitution in Eq. [6] for k_b and substitution of k_b into Eq. [3] yields the value for $\hat{\dot{\epsilon}}_1$.

$$\hat{\dot{\epsilon}}_1 = \frac{0.38\sigma_1(1-\nu^2)}{E\tau_s} \quad [7]$$

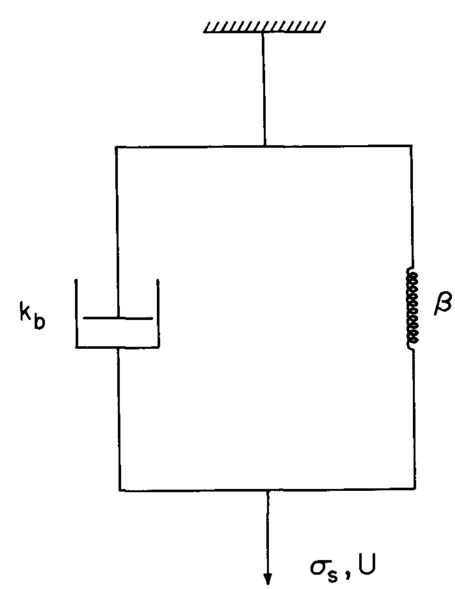

Fig. 4—Spring dashpot analog of sliding in a polycrystal.

3. EXPERIMENTS WITH Ni

(a) Creep Fracture

In this section we will describe the results of creep fracture experiments with Ni of commercial purity,* in which the strain rate was varied from $10^{-2}\ s^{-1}$ to $10^{-9}\ s^{-1}$ and in which a transition from ductile fracture to wedge type intergranular fracture was seen at about $10^{-3}\ s^{-1}$, with a second transition from wedge type to "r" type of intergranular fracture observed at about $10^{-9}\ s^{-1}$. The grain size of the polycrystals was about 100 μm, and all tests were done at 973 °C in vacuum under constant load. The stress-strain rate and stress-time to fracture plots of the data for the intergranular mode of failure are shown in Fig. 5.

*Kindly supplied by Henry Higgins Co., England. Nominal composition in wt pct: C(0.15), Mn(0.35), Fe(0.4), S(0.01), Si(0.35), Cu(0.25), Ni(balance).

(b) Internal Friction

The internal friction tests were carried out on an inverted torsional pendulum similar to the one described earlier.[12,16] The maximum amplitude of the free oscillations in our specimens corresponded to a shear strain of 0.0003. The procedure for measuring the damping coefficient, Q^{-1}, has also been described earlier.[12] A typical damping curve is shown in Fig. 6. The damping curves, after subtracting the background, are shown in Fig. 7 for a frequency of 0.56 Hz, 1.38 Hz and 3.50 Hz.

An activation energy plot of τ_s, determined from the equality $\omega\tau_s = 1$ at the peak temperature, is shown in Fig. 8. An activation energy of 110 kJ mol^{-1} was measured; this is in good agreement with the best estimate[17,18] of the activation energy for grain boundary self diffusion (114 kJ mol^{-1}). This result is in line with the belief that boundaries in which sliding is controlled by accommodation around fine structural features such as grain boundary ledges and particles (smaller than about 1 μm) the kinetics of sliding should depend upon grain boundary diffusivity.[9,10,12]

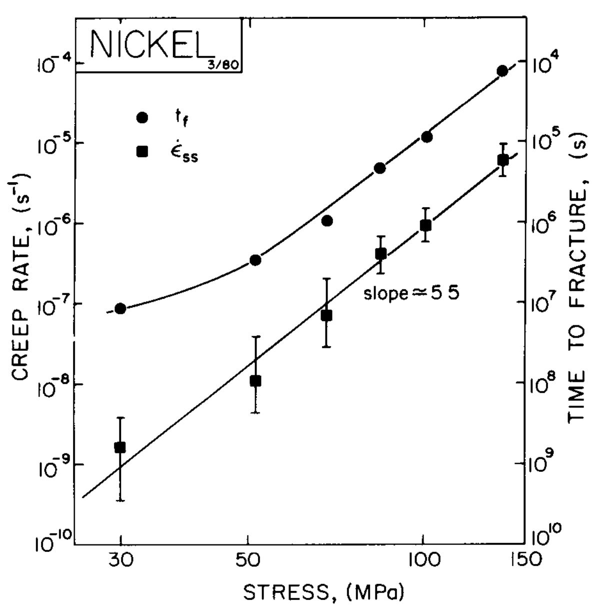

Fig. 5—Measurement of steady state creep rate and t_f as a function of stress for Ni at 973 K.

4. A COMPARISON OF THE TRANSITIONS IN THE MODE OF FRACTURE WITH PREDICTED UPPER BOUND STRAIN RATE FOR WEDGE CRACKING

(a) Calculation of the Upper Bound $\hat{\dot{\epsilon}}_l$

The graph in Fig. 8 yields the following equation for τ_s:

$$\tau_s = 3.20 \times 10^{-8} e^{\frac{110\ \mathrm{kJ\ mol^{-1}}}{RT}}\ s \quad [8]$$

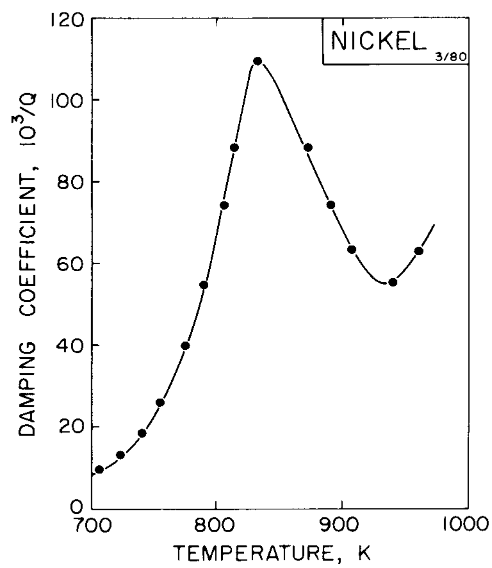

Fig. 6—An internal friction damping curve for polycrystalline Ni at 0.56 Hz.

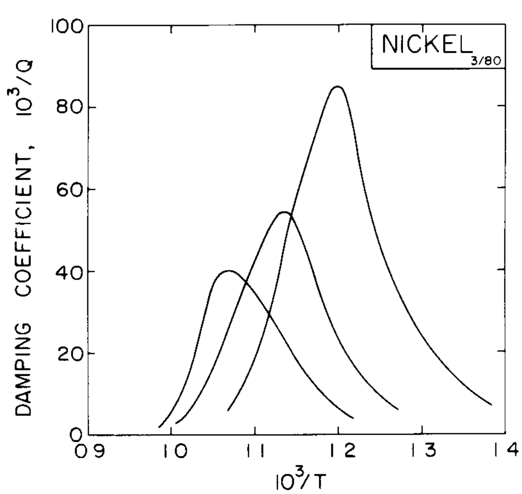

Fig. 7— Debye peaks in Ni at 0.56 Hz, 1.38 Hz and 3.50 Hz.

By substituting $E = 15.4 \times 10^{10}$ Pa (at 973 K)* and

* Actually the temperature dependent value of E is given by $2.1 \times 10^{11}(1 - (T - 300) \times 3.7 \times 10^{-4})$ Pa. Since E changes much less rapidly with temperature than τ_s, we simply assume it to remain constant.

$\nu = 0.33$ into Eq. [7], we obtain

$$\hat{\dot{\epsilon}}_l = 1.3 \times 10^4\, e^{\frac{-110\ \text{kJ mol}^{-1}}{RT}}\ s^{-1} \quad [9]$$

where we have chosen that $\sigma_l = 1.2 \times 10^{-3}E$ which lies toward the high side of the stress spanned by the wedge cracking regime in the fracture map for nickel.[14] It is also the highest stress which was used in the fracture experiments.

(b) Comparison with Data

A plot of $\hat{\dot{\epsilon}}_l$ *vs* T in the regime of interest is shown in Fig. 9. The upper bound strain rate for wedge cracking is indeed observed for our measurement[19] and also for other data in the literature.[20–23]

At the lower strain-rates, the mode of fracture changes from wedge type to "r" type intergranular, we do not have a good explanation for this at present. It probably relates to the relaxation of stress-concentrations at the triple junctions which are produced by sliding. Two competitive rate processes will be involved, one seeking to increase the stress-concentration and the other trying to relax it. If the latter is faster, then wedge cracking should not occur. As a practical matter, if the polycrystal is deforming overall by the diffusional mechanism, either Nabarro-Herring or Coble, then the stresses at triple junction should be relaxed[24] The strain rate at which one would expect a transition from power-law creep to diffusional creep behavior, also drawn on Fig. 9, does seem to be in about the right place for the shift in the mode of fracture from wedge type to "r" type. The data for the transition from power law creep to diffusional creep was obtained from Ref. 25.

ENGINEERING SIGNIFICANCE OF $\hat{\dot{\epsilon}}_l$

Min and Raj[26,27] have postulated that wedge cracking may be an important mechanism of failure when fracture occurs intergranularly under creep-fatigue conditions, especially when an unbalanced strain-rate cycle—the so called slow/fast cycle—is imposed.[28] The idea is that wedge damage can accumulate with every cycle by a ratcheting mechanism, if the strain rate during the tension half of the cycle is more favorable to sliding than in the compression half. This condition would be achieved if a slow/fast cycle were imposed and, under such condition, drastic reductions in life are indeed observed. If this is the correct mechanism, then the concept of $\hat{\dot{\epsilon}}_l$ and the procedure for its measurement, as we have shown here, are of engineering significance since they can be used to define bounds in strain rate in which creep-fatigue interaction effects can be reduced to minimum. Wedge cracking is also of concern in hot working of metals, and the concept of an upper bound strain rate may be useful in defining the "safe" operating regime of strain-rate and temperature.

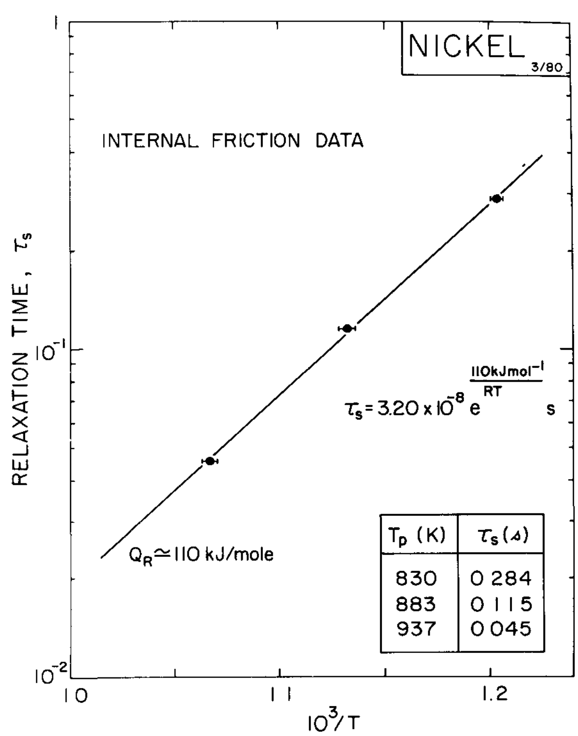

Fig. 8—An activation energy plot for the relaxation time as measured from internal friction.

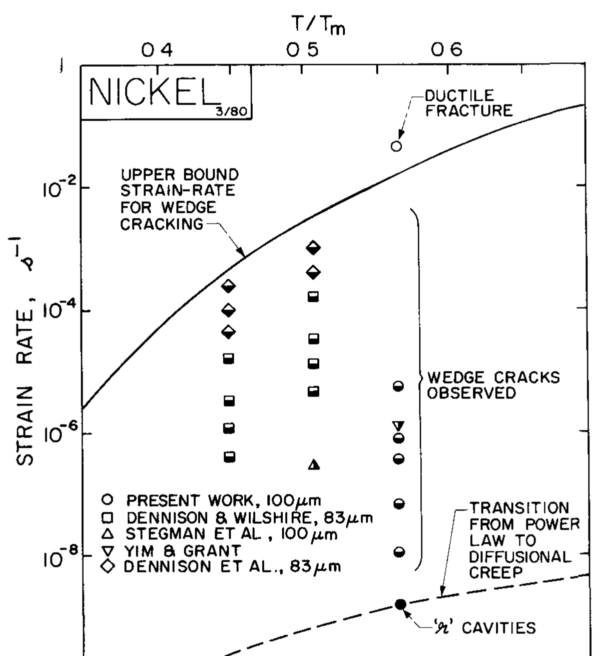

Fig. 9—Transition from ductile, to wedge cracking, to "r" cavitation failure with decreasing strain rates. The upper bound strain-rate for wedge cracking was computed with the use of sliding rate measurements from internal friction. The transition from wedge to "r" type fracture appears to coincide with the change in the overall creep mechanism from power-law creep to diffusional creep. The numbers in μm stand for the grain size.

CONCLUSIONS

i) An upper bound strain rate, $\hat{\epsilon}_1$, can be defined, above which wedge type of intergranular fracture should not be possible.

ii) $\hat{\epsilon}_1$ can be estimated by measuring the relaxation time for the grain boundary damping peak in internal friction experiments.

iii) Creep fracture experiments in Ni, which show a transition in the fracture mode from ductile transgranular to wedge type intergranular, as the strain rate is decreased, are consistent with the upper bound criterion based on the estimate of $\hat{\epsilon}_1$ from internal friction measurements.

iv) The $\hat{\epsilon}_1$ for wedge cracking may well have significance during intergranular failure in creep-fatigue, and in hot working of metals.

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