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HARDENING, RECOVERY, AND CREEP IN FCC MONO- AND POLYCRYSTALS[*]

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ABSTRACT

It is shown that the Bailey-Orowan approach to simultaneous strain hardening and recovery is in conflict with experimental results on the work-hardening behavior of many fcc mono- and polycrystals, and therefore should not be used in creep theories either. A more promising approach is the superposition of strain hardening and strain softening, a term used for mechanically rather than thermally activated recovery processes. The strain-rate dependence of the mechanical properties is then characterized by two exponents m and n, one for the isostructural flow stress and one for the strain-softening process. The latter dominates steady-state creep up to temperatures of about 0.6 of the melting point, and can, by extrapolation, even explain high-temperature creep.

THE RECOVERY GLIDE THEORY

The dependence of stress on strain at constant strain rate is usually described in two steps: the dependence of stress on strain rate and structure (such as dislocation density), and the evolution of the structure with strain. Cottrell and Aytekin [1] used the same approach to describe creep, in an expansion of the Bailey-Orowan law for steady-state creep: the strain rate is a function of stress at a given structure, and also enters through the relation that describes the change of structure with strain and time. Following Kocks [2], we shall describe the structure by the flow stress σ_o at some arbitrary reference strain rate $\dot{\epsilon}_o$

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and reference temperature, and the kinetic law connecting strain rate and stress at a given structure by

$$\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o} = \left(\frac{\sigma}{\sigma_o}\right)^m . \tag{1}$$

The power law is more convenient than the more proper Arrhenius law with stress-dependent activation energy; it provides an adequate description of material behavior, over a sufficient range of the variables, with an exponent m that is insensitive to stress and strain, but depends on temperature [3].

The change of structure with strain is described by the change of the reference flow stress σ_o. In the Bailey-Orowan model:

$$d\sigma_o = h\,d\varepsilon - r\,dt . \tag{2}$$

Here, h is the hardening coefficient which gives the increase in flow stress due to the strain increment $d\varepsilon$; r is the recovery rate which leads to a decrease of the flow stress in the time interval dt during which the strain increment $d\varepsilon$ is carried out. Dividing Eq. (2) by $d\varepsilon$ we obtain a net hardening coefficient

$$\theta_o \equiv \frac{d\sigma_o}{d\varepsilon} = h - \frac{r}{\dot{\varepsilon}} \tag{3}$$

which should describe work-hardening behavior. It is observed that stress-strain curves flatten out at high strains, i.e., $\theta \equiv d\sigma/d\varepsilon$ decreases continuously. If θ approaches zero, deformation takes place under constant stress and constant strain rate which is the steady-state creep condition. In this limit, Eq. (3) degenerates to $\dot{\varepsilon}_s = r/h$ (with $\dot{\varepsilon}_s$ = steady state creep rate). The experimentally observed steady-state creep rate depends on the stress by a power relation:

$$\dot{\varepsilon}_s = C'(T) \cdot \sigma^{n'} \tag{4}$$

where n' is the creep exponent. Combining this equation with the kinetic law (1) one obtains

$$\dot{\varepsilon}_s = \frac{r}{h} = C(T) \cdot \sigma_o^{\,n} \tag{5}$$

where

$$\frac{1}{n'} = \frac{1}{n} + \frac{1}{m} \tag{6}$$

The creep exponent n is usually much smaller than the isostructural exponent m so that in most cases $n' \simeq n$.

In Eq. (3), h is usually interpreted as being almost independent of temperature as well as of the degree of deformation, similar to the hardening coefficient of stage II in single crystals. Thus, the power dependence is due to that of the recovery rate r. Consequently Eq. (5) is equivalent to saying that, in the framework of the Bailey-Orowan approach, Eq. (3) has the form

$$\theta_\circ = h - \frac{r_\circ(T)\cdot\sigma_\circ^n}{\dot{\varepsilon}} \tag{7}$$

Equation (7) is certainly consistent with experimentally observed steady-state creep behavior. However, the question arises whether it describes also the strain-hardening behavior with acceptable accuracy.

EXPERIMENTAL OBSERVATIONS

The validity of Eq. (7) can best be tested with the help of experimentally observed relations between the slope of the stress-strain curve and the stress. These are shown in Fig. 1 for gold single crystals over a wide range of temperatures, for one strain rate [4]. (Here, the resolved shear stress τ was taken instead of σ, and θ is correspondingly defined as $\theta \equiv d\tau/d\gamma$ where γ is the shear strain.) Since the experiments were carried out in tension, steady state ($\theta = 0$) could not be reached exactly because of necking. It can be seen however, that the observed curves can easily be extrapolated to $\theta = 0$ and furthermore that $\theta = 0$ is approached by an almost linear θ-τ-dependence. This linear part covers a significant range of the high-stress end of each curve and therefore is related to the overwhelming strain range because θ is very small in this region. The linearity of the diagrams disproves the applicability of Eq. (7) which predicts a much stronger dependence of θ on τ (if one assumes h to be constant and $n \geq 3$).

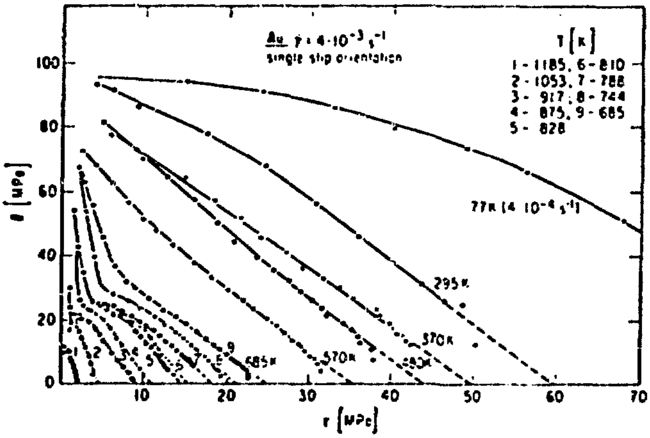

Fig. 1 Work-hardening rate versus flow stress [4].

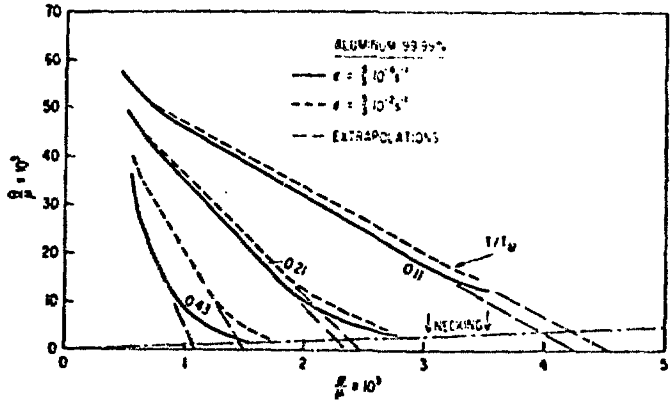

Fig. 2

Work-hardening rate versus flow stress for Al polycrystals [5]. μ=shear mod. T_m=melting temp.

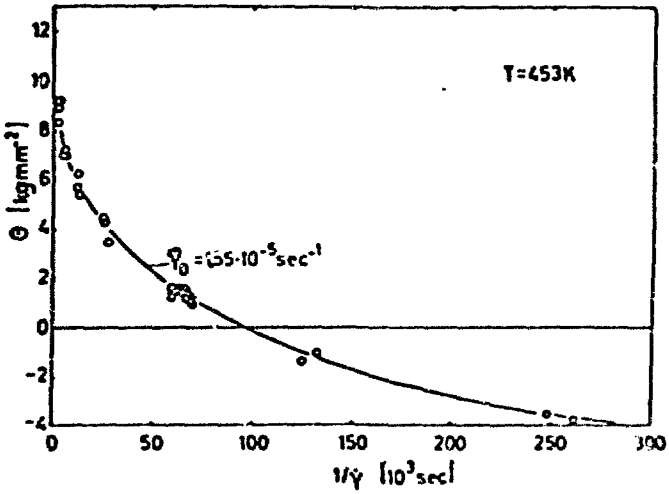

Fig. 3

Work-hardening rate versus strain rate at constant flow stress of 0.5 kg/mm^2 [6].

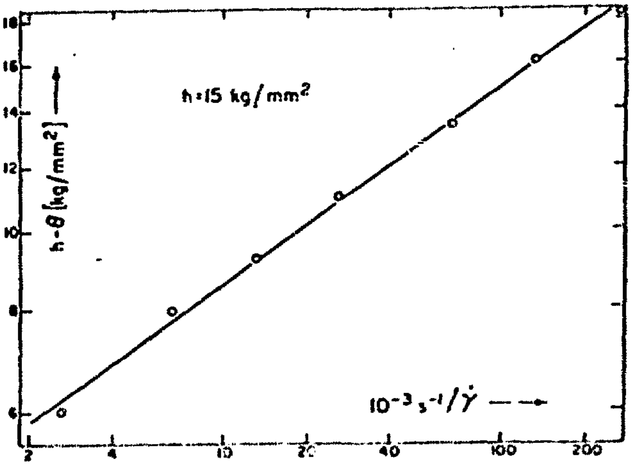

Fig. 4

Data of Fig. 3 replotted as log (h-θ) vs. log $(1/\dot{\gamma})$.

The same follows from the strain-rate dependence. From Fig. 2, where θ is plotted for different strain rates at constant temperature for Al polycrystals [5], it can be seen immediately that the observed $\dot{\varepsilon}$-dependence is much weaker than expected from Eq. (7). From these results, one must conclude that Eq. (7) is in disagreement with the experimental observations. Rather, the experiments suggest that

$$\theta_o = h - \frac{C\,\sigma_o}{\dot{\varepsilon}^{1/n}} \tag{8}$$

is the appropriate form for the description of the superposition of hardening and recovery.

Equation (8) is additionally supported by experiments in which the change of the slope of the stress-strain curves after sudden strain-rate changes has been examined [6]. Fig. 3 shows the results in a plot of θ as function of $1/\dot{\gamma}$. As σ_o is constant, one would expect in this representation a straight line if Eq. (7) were valid. However the data follow a strongly curved course, which can be well described by Eq. (8) with an appropriate value of n. This can be seen from Fig. 4 where the data of Fig. 3 are plotted as $\log (h - \theta)$ versus $\log (1/\dot{\varepsilon})$ using $h = 15$ kg/mm^2, which value produced the best straight line in this kind of plot. It is very satisfactory that the best-fitting h value is very close to the stage II slope of the hardening curve for this orientation.

In summary, it follows that according to our experimental examination, the hardening behavior has to be described by Eq. (8) instead of Eq. (7). Both equations lead to the same steady-state creep law; they are, however, quite different with respect to the stress- and strain-rate-dependence of the hardening coefficient θ. The fundamental physical differences which distinguish these two equations will be discussed in the following.

MECHANICAL INTERPRETATION

If one insists on interpreting the experimentally confirmed Eq. (8) on the basis of the Bailey-Orowan law, Eq. (2), one has to introduce a strongly rate dependent recovery term:

$$r\,dt = C\,\sigma_o\,\dot{\varepsilon}^{(1-1/n)}\,dt \tag{9}$$

Since the recovery rate r is almost proportional to $\dot{\varepsilon}$, the amount of stress reduction, r dt, is almost proportional to the strain increment $d\varepsilon$. If this is true, Eq. (2) has lost its physical justification and it is more appropriate to introduce a term

$$s\,d\varepsilon = C\,\frac{\sigma_o}{\dot{\varepsilon}^{1/n}}\,d\varepsilon \tag{10}$$

We call it "strain softening" to distinguish it clearly from time-recovery: "dynamic recovery" is not stress-assisted time-recovery, but thermally-assisted strain-softening.

An analysis of the temperature dependence of the strain-hardening rate (8) in single crystals of Au (Fig. 1), Ag, Cu, and Al [4], and in polycrystals of Al and Cu [5] has led to the conclusion that it lies in the exponent n, not in the factor C as in Eq. (5):

$$n = \frac{A}{kT} \tag{11}$$

Here, A is a material constant which depends on shear modulus and stacking-fault energy. n varies from very high values at low temperature, to values of order 10 at half the melting temperature, and extrapolates to generally quoted values of the steady-state creep exponent in the range of 0.8 T_m. It thus appears possible that the low-temperature mechanism discussed here explains high-temperature behavior as well.

REFERENCES

[1] Cottrell, A. H., and Aytekin, V., The flow stress of zinc under constant stress, J. Inst. Met. 77, 389 (1950).

[2] Kocks, U. F., The recovery glide theory of creep in "Rate Processes in Plastic Deformation of Materials," J.C.M. Li and A. K. Mukherjee, eds., Am. Soc. Met. (1975), p. 356.

[3] Kocks, U. F., Argon, A. S., and Ashby, M. F., "Thermodynamics and Kinetics of Slip," Prog. Mater. Sci. 19, B. Chalmers, J. W. Christian and T. B. Massalski, eds., Pergamon (1975) p. 1.

[4] Mecking, H., Description of hardening curves of FCC single- and polycrystals," Conference report of 1975 ASM/AIME Fall Meeting, AIME in press.

[5] Kocks, U. F., Laws of work-hardening and low-temperature creep, J. Eng. Mater. Techn. (Trans. ASME series H) 98, 76 (1976).

[6] Fischer, H., Doctoral Thesis, Techn. Hochschule, Aachen (1976).