JOURNAL OF MATERIALS SCIENCE 21 (1986) 2664–2666

On the temperature dependence of the flow stress of metals and solid solutions

M. Z. BUTT
Department of Physics, Government College, Lahore, Pakistan
P. FELTHAM, I. M. GHAURI
Department of Physics, Brunel University, Uxbridge, Middlesex UB8 3PH, UK

The linear correlation between the logarithm of the CRSS, or of the yield stress in the case of polycrystals, and temperature, frequently encountered in representations of experimental data on metals and solid solutions, is shown to be consistent with the requirements of models in which kink-pair formation processes control the migration of dislocations.

1. Introduction

A linear temperature dependence of the logarithm of the CRSS of single crystals, as well as of that of the yield stress or flow stress of polycrystals, is frequently reported in the literature. Materials as diverse as tantalum crystals of high purity deformed between about 100 and 500 K [1], and 18 Cr–18 Mn polycrystalline stainless steels strained between 4 and 300 K [2], are specific cases; Figs 1 to 6 depict other examples. The main object of this paper is to show that this simple, "semi-empirical", representation is theoretically justifiable, and to discuss its scope and limitations.

2. Theory

A close analogy exists between the modes of "escape" of a dislocation segment from a Peierls barrier, i.e. by kink-pair formation, and the breakaway from a row of closely-spaced solute pinning points. This similarity has recently been discussed in some detail with reference to a model of solid solution hardening [12], initially developed for concentrated fcc solid solutions by Butt and Feltham [13, 14]; we shall use this model as our theoretical basis.

Its salient feature, of particular relevance here, is the activation energy, W, for the breakaway of a dislocation segment from a row of closely-spaced pinning points, i.e. in a concentrated solid solution. It is given by the relation [14]

$$W = W_0(x^{-1/2} - x^{1/2}) \quad (1)$$

with $W_0 = n(Uc^{1/2}G\boldsymbol{b}^3)^{1/2}$, and $x = \tau/\tau_0$, where τ/τ_0 represents the ratio of the CRSS at the temperature at which the experiment is carried out to that expected as $T \to 0$; n is the number of interatomic spacings by which the segment advances in one jump, c the solute concentration, and G and $\boldsymbol{b}$ have their usual meanings. For polycrystals τ/τ_0 is replaced by the corresponding ratio of tensile stresses, σ/σ_0.

If the unpinning takes place at an "observable" rate, then taking v to be of the order of 1 $\sec^{-1}$ as the criterion for the onset of deformation detectable by the usual means, the relation

$$v = v_0 \exp(-W/kT) \qquad v_0 \approx 10^{11}\,\sec^{-1} \quad (2)$$

together with Equation 1, embody the yield criterion

$$W = mkT \qquad m \approx 25. \quad (3)$$

With the transformation $x = \exp(-2\phi)$, one obtains from Equations 1 and 3: $W = 2W_0 \sinh \phi$, and for sufficiently low temperatures, as $x \to 1$, and thus $\phi \to 0$

$$W \approx 2W_0\phi = W_0 \ln(\tau_0/\tau) \quad (4)$$

With Equation 3, this yields $\ln(\tau_0/\tau) \approx mkT/W_0$ and, finally

$$\mathrm{d} \ln \tau/\mathrm{d}T \approx -mk/W_0 \quad (5)$$

Equation 5 is of the required form, i.e. the slope of the $\ln \tau$ against T curve is constant, equal to $-mk/W_0$. The numerical value of $\mathrm{d} \ln \tau/\mathrm{d}T$ facilitates the determination of W_0. The low temperature approximation, Equation 5, should, in general, prove adequate up to temperatures where, due to the occurrence of

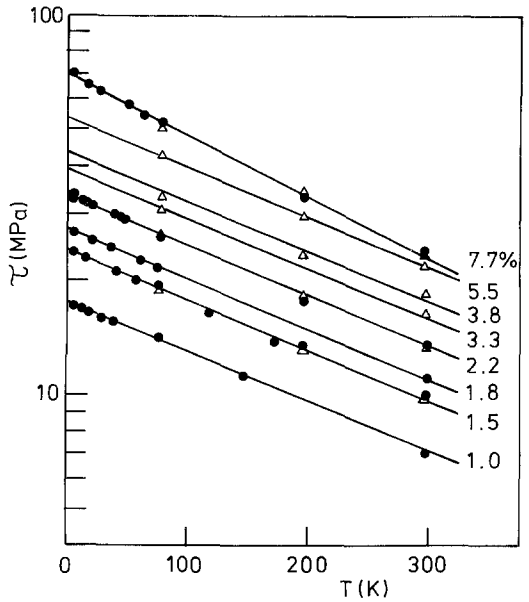

Figure 1 The temperature dependence of the CRSS of Cu–Mn crystals, with concentrations of manganese, in at %, as indicated. Data denoted by points are from [3], those denoted by triangles from [4].

0022–2461/86 $03.00 + .12

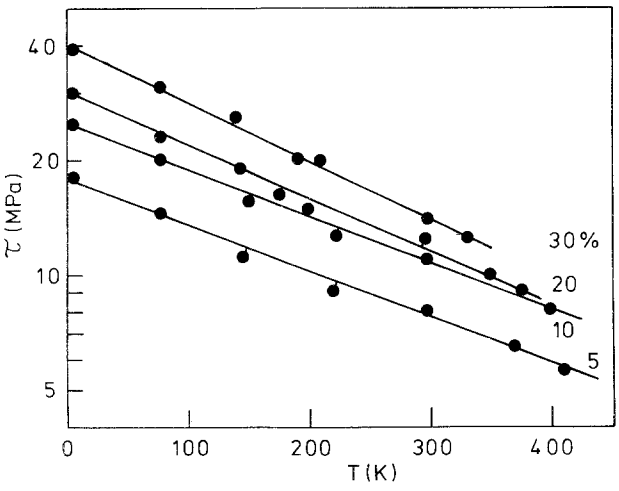

Figure 2 The temperature dependence of the CRSS of α-brass crystals, with the zinc contents as indicated (at %). Data points from [5].

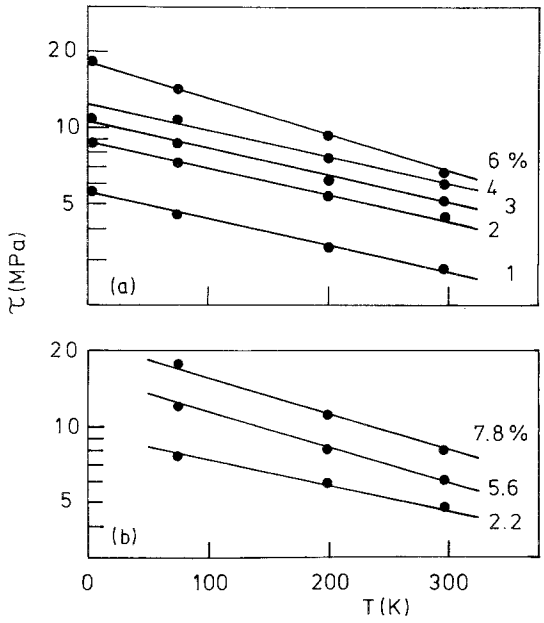

Figure 3 The temperature dependence of the CRSS of crystals of (a) Ag–Al and (b) Ag–Zn alloys. Solute contents are given in at %. Data points are from [6] and [7], respectively.

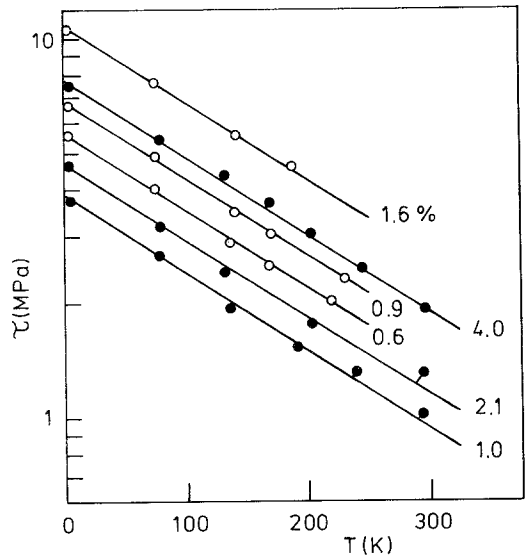

Figure 4 The temperature dependence of the CRSS of magnesium crystals containing either aluminium or indium in solid solution (at %). The data points were taken from [8]. (○) Mg–Al, (●) Mg–In.

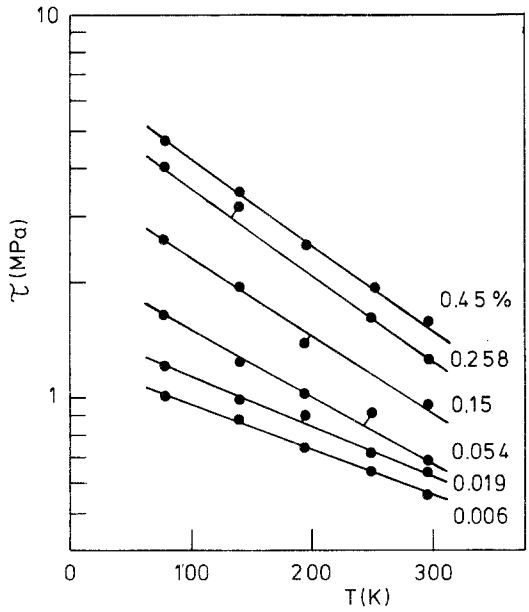

Figure 5 As Fig. 4, but with zinc as solute. Data points are from [9].

diffusional recovery processes in the crystal the model used would cease to be applicable.

3. Discussion and conclusions

As the functional form of the stress dependence of the energy barrier, W, as given by Equation 1, holds for concentrated [13] and dilute [14–16] close-packed solid solutions, as well as for bcc metals and their concentrated solid solutions [12, 17], Equation 5 would be expected to be applicable in these cases. Figs 1 to 6

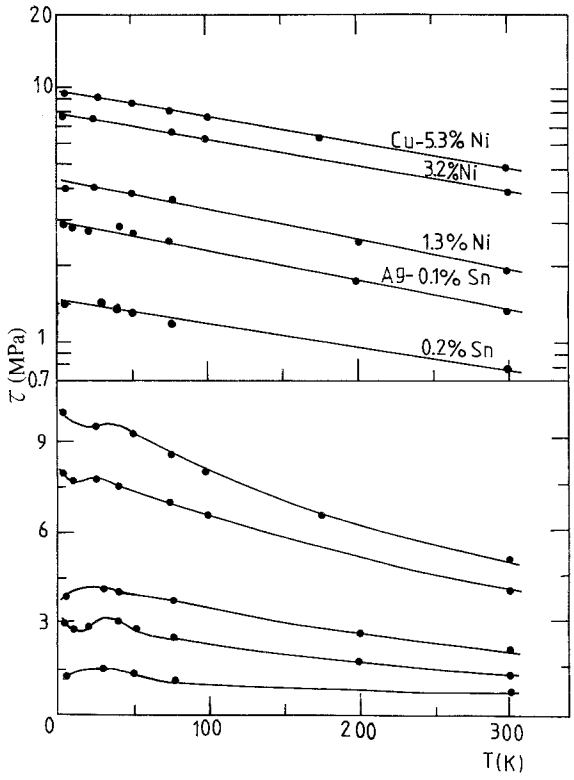

Figure 6 The temperature dependence of the CRSS of copper-based solid solutions containing either nickel or tin (at %). The data points were taken from [9] and [10], respectively. Deviations from linearity are apparent in the linear (lower diagram) representation, but could remain unresolved with the upper, semi-log, co-ordinates. (For silver-based alloys see [11]).

illustrate the linearity, implied by Equation 5, in a few cases.

With alloys substantially work hardened Equation 5 may not, however, provide a good basis for correlating flow stress and temperature. Thus, for instance, in concentrated polycrystalline α-brasses [18] work hardening, i.e. dislocation interaction, is the dominant source of strength for tensile deformations exceeding about 4%; only for significantly lower strains does the resistance to dislocation movement derive mainly from solid-solution effects.

Further, anomalies in the temperature dependence of the yield stress are generally observed in metals and alloys at comparatively low temperatures; they do not seem to be confined to specific crystal structures [19, 20]. In the log τ against T representation their occurrence could be obscured, for a relatively poor resolution of the data is obtained in semi-log co-ordinates for low T values, e.g. with certain stainless steels [2], and with the alloy crystals referred to in Fig. 6. Finally, failure of the anomalies to manifest themselves may lie in an artifact, i.e. lack of data in the temperature region extending from 77 to 4 K (e.g. Figs 2 to 4), in which the anomalies frequently occur.

One may conclude that, on making appropriate allowance for possible deviations from linearity of the $(\log \tau)/T$ relation, due to the effects referred to, it provides an appropriate functional form for the representation of the temperature dependence of the CRSS and yield stress for a wide range of crystalline materials.

References

1. P. FELTHAM, *Brit. J. Appl. Phys.* (*J. Phys. D*) **2** (1969) 377.
2. R. P. REED and J. M. ARVIDSON, *Adv. Cryost. Eng. Mater.* **30** (1984) 263.
3. T. WILLE, B. WILKE and C. SCHWINK, *Scripta Metall.* **16** (1982) 561.
4. C. SCHWINK and T. WILLE, *ibid.* **14** (1980) 1093.
5. T. E. MITCHELL and P. R. THORNTON, *Phil. Mag.* **8** (1963) 1127.
6. G. E. TARDIFF and A. A. HENDRICKSON, *Trans. AIME* **230** (1964) 586.
7. A. A. HENDRICKSON and M. E. FINE, *ibid.* **221** (1961) 967.
8. A. AKHTAR and E. TEGHTSOONIAN, *Phil. Mag.* **25** (1972) 897.
9. *Idem, Acta. Metall.* **17** (1969) 1339.
10. K. KAMADA and I. YOSHIZAWA, *J. Phys. Soc. Jpn.* **31** (1971) 1056.
11. H. SUGA, Y. SUEKI, M. HIGUCHI and T. IMURA, *Jpn. J. Appl. Phys.* **14** (1976) 379.
12. M. Z. BUTT, K. M. CHAUDHARI and P. FELTHAM, *J. Mater. Sci.* **18** (1983) 840.
13. M. Z. BUTT and P. FELTHAM, *Acta Metall.* **26** (1978) 167.
14. *Idem, Rev. Deform. Beh. Mater.* **3** (1978) 99.
15. M. Z. BUTT, I. M. GHAURI, R. QAMAR, K. M. HASHMI and P. FELTHAM, *Acta. Metall.* **29** (1981) 829.
16. M. Z. BUTT, K. M. HASHMI and P. FELTHAM, *J. Phys. F.* (*Metal Phys.*) **11** (1981) L275.
17. M. Z. BUTT, K. M. CHAUDHARI and P. FELTHAM, *J. Mater. Sci. Lett.* **2** (1983) 713.
18. M. Z. BUTT and P. FELTHAM, *Met. Sci.* **18** (1984) 123.
19. P. FELTHAM, *Scripta Metall.* **17** (1983) 1337.
20. P. FELTHAM and M. Z. BUTT, *Cryst. Res. Technol.* **19** (1984) 325.

Received 6 August
and accepted 18 September 1985