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DETERMINATION OF THE STRENGTH OF »EFFECTIVE« OBSTACLES TO DISLOCATION MOTION IN Cu — Ge ALLOY SINGLE CRYSTALS

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The experimental observations of Traub et al[1] on the temperature dependence of the critical resolved shear stress (CRSS) of alloy single crystals of copper containing 0.5—7.3 at% Ge, in the range 77—400 K, are compared with that proposed by Kratochvil et al[2]. There is agreement between experimental and proposed shape of the CRSS-T curves at rather low temperatures for certain values of the strength of »effective« obstacles to dislocation motion, which are substantially higher than that for maximum interaction energy of a single solute atom with a dislocation.

1. Introduction

Recently, Traub et al[1] studied the temperature dependence of the critical resolved shear stress of Cu — Ge and Cu — Zn single crystals containing 0.5—7.3 at % Ge and 30 at % Zn, respectively, in the range 77—800 K. They viewed their own results in the light of current theories of solid — solution hardening, e. g. those of Riddhagni and Asimow[3], Labusch[4], Boser[5], and Feltham[6], pointing out the positive features as well as the limitations in each case. The main object of the present note is to extend their investigations in relation to comparison of experiment and theory, to Kratochvil's[2] model of solid — solution hardening, which we shall first briefly review.

2. *Review of Kratochvil's model*

Kratochvil et al[2] formulated an empirical relation for the temperature dependence of the CRSS of solid — solutions, assuming thermally — activated motion of dislocations over planes containing randomly distributed groups, rather than a more — or — less uniform distribution of isolated solute atoms as obstacles. The groups are categorised as monomers (i.e. isolated solute atoms), dimers, trimers or, generally, n-mers, depending on the number of solute atoms comprised in them, and their respective concentrations are determined by the methods of statistical thermodynamics. Single solute atoms would be the weakest obstacles, and could be overcome at the lowest temperatures, when groups comprising many solute atoms may not be »negotiable« by dislocations. Such groups would not therefore contribute to the thermally activated motion of dislocation segments held up at them, except at higher temperatures. By contrast, obstacles with »too few« atoms in the group may be »transparent« to the dislocations at the temperature. Hence a single type of solute atoms can form a spectrum of obstacles to dislocation motion and at any given temperature only certain groupings may be »effective«.

Kratochvil et al[2] express the activation energy U for the motion of the dislocations over the array of »effective« obstacles, in terms of the flow stress τ, by the empirical relation,

$$U = U_0 - \frac{U_0}{\ln 2} \ln\left(1 + \frac{\tau}{\tau_0}\right) \tag{1}$$

with the boundary conditions:

(i) $U = 0$ when $\tau = \tau_0$, i. e. at $T = 0$ K

(ii) $U = U_0$ when $\tau = 0$.

A different U_0 — value is attributed to each n-mer, i.e. U_0 depends on T. The activation volume, defined by $v = -\left(\frac{\partial U}{\partial \tau}\right) T$, obtained from Eq. (1) is

$$v = \frac{U_0}{\ln 2} \cdot \frac{1}{\tau + \tau_0} \tag{2}$$

and the CRSS due to alloying is given by

$$\tau = \tau_0 \left[2 \exp\left(-\frac{k\,T}{U_0} \ln 2 \cdot \ln \frac{\dot{a}_0}{\dot{a}}\right) - 1\right] \tag{3}$$

where $\dot{a}$ is the strain-rate and $\dot{a}_0$ the so-called structure — factor i.e. the maximum flow-rate attainable. It was shown to be appropriate to write $\ln(\dot{a}_0/\dot{a}) \approx 15$. The reduced flow stress $\tau' = \tau/\tau_0$ in Eq. (3) becomes negative for each specific type of obstacle, at a temperature $T > T_c$, where $T_c = \frac{U_0}{k \cdot \ln(\dot{a}_0/\dot{a})}$. Before this occurs,

i.e. at $T < T_c$., another type of obstacle determines τ', and T_c for the current »effective« obstacle then shifts to a higher value, for it depends on U_0. If there existed n-different types of effective obstacles, the resulting $\tau - T$ curve might be regarded as consisting of n parts, each corresponding to a given n-mer, being the rate determined over a certain temperature interval.

It may be noted that Kratochvil et al[2] consider the flow stress τ to have two additive components: $\tau = \tau_R + \tau_H$ where τ_R is the flow stress in the crystal in the absence of foreign atoms and τ_H is that corresponding to the presence of solute atoms in random distribution. However, they assume that τ_R is, in general, negligible as compared to τ_H so that one can take $\tau \approx \tau_H$. This approximation has been used in the present work while correlating the experimental data with the proposed $\tau - T$ dependence; the conclusions drawn are valid otherewise too.

3. *Comparison with experimental data and conclusion*

Some of the experimental data of Traub et al[1] appertaining to Cu — Ge alloy single crystals ($T = 77$—400 K) have been reproduced in terms of »reduced flow stress« τ' (denoted by points) in Fig. 1. The values of τ_0, given in Table 1, were obtained by extrapolating the experimental $\tau - T$ curves to the stress axis. With certain values of U_0 (Table 1), the temperature dependence of τ, implied by Eg. (3) and represented by full curves in Fig 1, agrees with the observations at

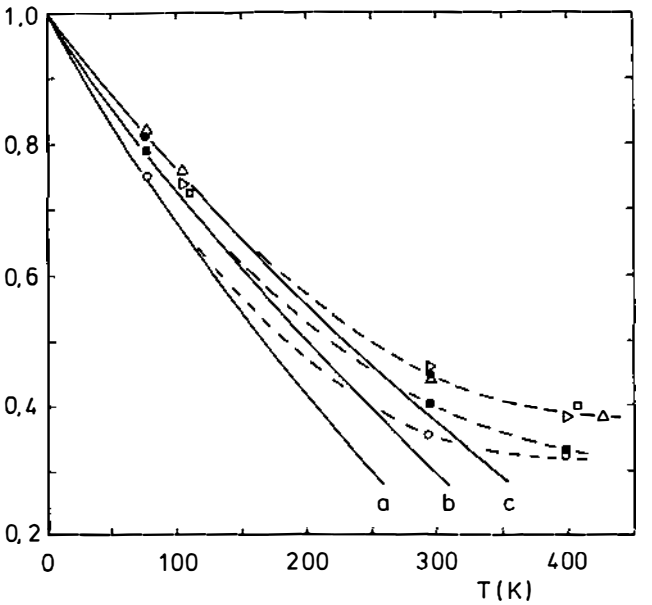

Fig. 1. The temperature dependence of the yied-stress of Cu-Ge single crystals containing (○) 0.5, (■) 1.0, (●) 2.0, (▷) 3.8, (△) 5.6 and (□) 7.3 at % germanium. The points represent the results of Traub et al[1] and the full curves were obtained by means of Eq. (3) with parameters given in Table 1.

rather low temperatures. The U_0 — values determined in this manner are a measure of the strength of the »effective« obstacles to dislocation motion in this temperature interval; these are substantially higher than the maximum elastic interaction energy between a single substitutional solute atom of germanium in copper lattice and a dislocation[7,8] (Table 2).

TABLE 1

Curve	Solute content c (at %)	τ_0 (10^6 N/m^2)	U_0 (eV)
a	0.5	5.88	0.52
b	1.0	9.32	0.62
c	2.0	16.2	0.71
	3.8	23.5	0.71
	5.6	30.9	0.71
	7.3	39.2	0.71

Parameters used in deriving the »theoretical« curves, a—c, in Fig. 1 by means of Eq. (3). The values of τ_0 were obtained by extrapolating the experimental $\tau - T$ curves to the stress axis.

TABLE 2

Type of interaction	Max. interaction energy (eV)
Edge/modulus	0.057
Edge/size	0.26*
Edge/electrostatic	0.06
Screw/modulus	0.045
Screw/size	0.079*

Maximum interaction energies of germanium solute atoms in copper lattice with edge and screw dislocations (after Saxl[7]).

Thus the foregoing evidence shows that at low temperatures, the »effective« obstacles to dislocation motion in Cu — Ge solid — solutions are groups of solute atoms, the number of solute atoms comprising such an »effective« cluster--obstacle seems to be an increasing function of alloy concentration in »Friedel — domain« i.e. when $c < 2$ at %, and is, probably, little dependent on that in rather concentrated solutions. At higher temperatures i.e. for $\tau' < 0.6$, specific assumptions about the form of U_0 (T) would have to be made in order to enable one to assess the applicability of Eg. (3) to the observed CRSS — T dependence.

* Haasen[8] suggests that these values are too large by about 50 per cent as a result of Saxl's error in calculations.

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ODREĐIVANJE JAKOSTI »EFEKTIVNIH« PREPREKA GIBANJA DISLOKACIJA U MONOKRISTALIMA SLITINE Cu-Ge

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Eksperimentalna opažanja Trauba i suradnika[1)] temperaturne ovisnosti kritične komponente naprezanja smicanja (CRSS) monokristala slitina bakra sa 0.5—7.3% germanija, u intervalu od 77 do 400 K interpretirana su modelom Kratochvila i suradnika[2)]. Pri niskim temperaturama bilo je moguće odrediti vrijednost jakosti »efektivnih« prepreka gibanja dislokacija za različite koncentracije slitine. Te jakosti su bitno veće od maksimalne energije interakcije između pojedinog otopljenog atoma i dislokacije.