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Force-Distance Relations in Dislocation Forest Cutting Processes

R. E. MEDRANO
Instituto de Ciências, Departamento de Engenhuria de Materiais,
Universidade Federal de São Carlos, São Carlos SP*

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A brief descripiion of the mechanisms which take into account the thermal behavior of dislocations in f.c.c. single crystals and the techniques to obtain force-distance diagrams for dislocation-obstacle interactions are presented. It is shown that for Copper and other metals whose deformation behavior varies with temperature, so that more than one process occurs by which dislocations overcome obstacles, it is not generally possible to construct such a diagram from conventional test results. Finally, some common mistakes made in the construction of force-distance diagrams are described.

Apresenta-se uma breve descrição dos mecanismos que levam em conta o comportamento térmico das deslocações em cristais cúbicos de face centrada bem como das técnicas para se obter os diagramas de força-distância nas interações entre deslocações e obstáculos. Mostra-se que, para o cobre e outros metais cujo comportamento de deformação varia com a temperatura de forma a ocorrer mais do que um processo no qual deslocações ultrapassem obstáculos, não é possível geralmente construir tais diagramas a partir de resultados de testes convencionais. Finalmente, são descritos alguns erros frequentemente cometidos na construção desses diagramas.

The mechanism responsible for flow stress dependence upon temperature[1-4] may comprise three possible processes:

1. Intersection of edge dislocations with forest dislocations.
2. Intersection of screw dislocations with forest dislocations.
3. Generation of point defects by movement of jogs on screw dislocations.

If only one of these processes occurs, the strain rate will depend on temperature through an Arrhenius equation

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp(-\Delta G/kT) \tag{1}$$

where

$$\dot{\varepsilon}_0 = nAbv_d \, ; \tag{2}$$

*Postal address: 13560 - São Carlos SP.

n is the number of dislocation-obstacle intersections per unit volume;
A is the area swept out by the dislocation line in the cutting process;
b is the Burgers vector;
v, is the dislocation frequency (about two orders of magnitude smaller than the Debye frequency);
AG is the free energy barrier of the obstacle.

This free energy that must be supplied by thermal activation is the intrinsic energy of the barrier, ΔG_0, minus the work that the stress does during the process of surmounting the obstacle:

$$\text{AG} = \Delta G_0 - F.d. \tag{3}$$

Here d is the distance travelled during the cutting process; F is the force acting on the dislocation and is given by

$$\text{F} = (\tau - \text{z,})\ \text{Lb}, \tag{4}$$

where L is the average length of moving dislocation segments;
τ is the applied stress;
τ_μ is the internal stress at the point considered.

The negative sign is taken because dislocations are stopped at points where τ_μ is opposed to the applied stress. Thus:

$$\dot{\varepsilon} = \text{ri, } \exp\left[-\{\Delta G_0 - v(\tau - \tau_\mu)\}/kT\right], \tag{5}$$

where v = Lbd is called the activation volume. Hence, the dependence of τ on temperature is:

$$\tau = \begin{cases} \tau_\mu + (\Delta G_0/v) - (kT/v)\ln(\dot{\varepsilon}_0/\dot{\varepsilon}) & \text{for } T < T_0 \\ \tau_\mu, & \text{for } T > T_0 \end{cases} \tag{6}$$

where $T_0 = (\Delta G_0/k)\ln^{-1}(\dot{\varepsilon}_0/\dot{\varepsilon})$ is a critical temperature corresponding to a given strain rate. Below this critical temperature, the flow stress is the sum of two terms, the internal stress τ_μ, which is almost independent of temperature, and the thermal stress $(\Delta G_0/v) - (kT/v)\ln(\dot{\varepsilon}_0/\dot{\varepsilon})$. Above the critica1 temperature, thermal activation is unimportant and the flow stress is equal in magnitude to the internal stress.

From Eq. 5, it can be seen that the activation volume is given by

$$v = kT(\partial \ln \dot{\varepsilon}/\partial\tau)_T. \tag{7}$$

Thus activation volumes are usually determined through differential tests, by doing instantaneous changes of strain rate or stress, to obtain the derivative in Eq. 7 at constant structure, i.e., assuming no changes in internal stress τ_μ or the pre-exponential factor E,.

If the activation volume is independent of stress, a curve of flow stress versus temperature should be obtained as shown by the solid line in Fig. 1. Actually, the activation volume will usually depend upon stress, as demonstrated by Friedel[3] and Basinski[S], so that most real curves will be as shown in Fig. 1 by the broken line.

The flow stress versus temperature curve for Aluminum[5,6] is similar to the broken line in Fig. 1 and, therefore, it is possible to assume that only one of the three possible processes is operative. If two or more processes

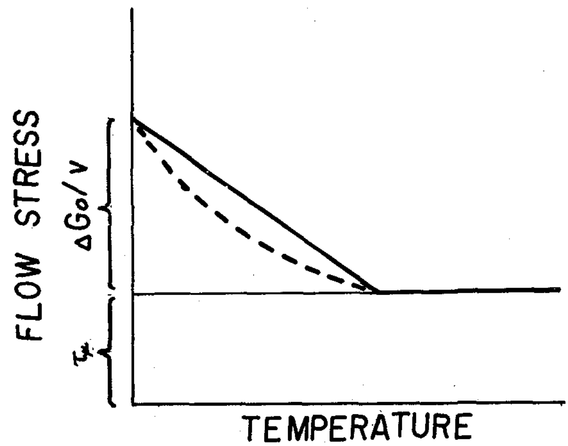

Fig. 1 - Schematic representation of the temperature dependence of the flow stress according to Eq. *(6)*.

are operative, the behavior will depend on whether these processes are dependent as, for example, cooperative intersection of screw dislocations coupled with point defect generation. If the processes are dependent, the flow stress will be governed by the more difficult process. That is, the stress will correspond to the hard process. If the processes are independent, however, the flow stress will correspond to the easier, or soft, process.

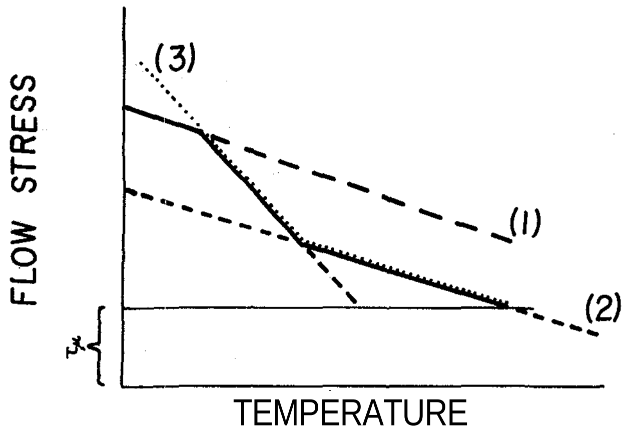

Fig. 2 - Temperature dependence of the flow stress of Copper.

Seeger[7] has considered the behavior of screw and edge dislocations in Copper. In Fig. 2, curve 1 indicates the behavior of edge dislocations in a forest-cutting process, curve 2 that of screw dislocations in the same process and curve 3 corresponds to generation of point defects by movement of jogs on screw dislocations. As the processes 2 and 3 are dependent of each other but independent of process 1, the expected overall behavior is indicated by the solid line.

When one process prevails over a wide enough temperature, a force-distance diagram can be constructed from activation volume values. Such a diagram, as was suggested by Basinski[5] and Mitra *et al.*[6], is indicated in Fig. 3.

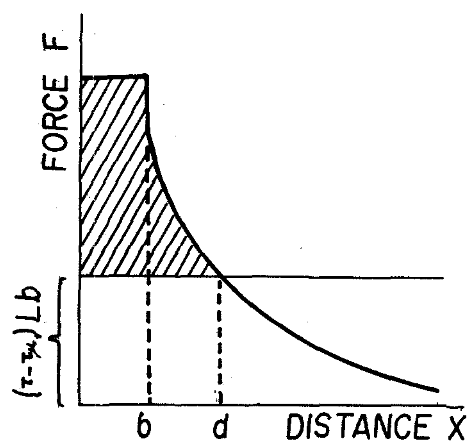

Fig. 3 - Schematic representation of force-distance diagram.

When a force $F = (\tau - \tau_\mu)Lb$ is applied to the dislocation, it begins to approach the obstacle. When its position is d, the forest and gliding dislocations are joined and begin to constrict, thus increasing F. When the separation x decreases to the value b, there is complete constriction and a jog is formed. If the thermal energy available is equal to the shaded area in Fig. 3, i.e., the intrinsic energy AG, *minus* the work done by the stress $(\tau - \tau_\mu)Lbd$ (*Eq. 3*), the dislocation will pass through the obstacle.

At low temperatures, the thermal energy available is small and the activation volume is approximately b^2L, since most of the work is done over the distance b. At high temperatures ($T > T_0$) no thermal energy is required for plastic flow, only $\tau > \tau_\mu$. Therefore, in theory, the parameters L and τ_μ could be determined by measuring the activation volume at one low temperature and the flow stress at one high temperature. Then, from another activation volume and flow stress measurements at an intermediate temperature, it is possible to obtain a point on the diagram $F = (\tau - \tau_\mu)Lb$ versus $d = v/Lb$. However, the parameters L and τ_μ change with deformation and at present there is no acceptable way to compare values corresponding to different deformations in f.c.c.. Thus, if one process prevails over a sufficiently wide temperature range, the force-distance diagram can be inferred from a series of three corresponding measurements (approximately at the same deformation) at low, intermediate and high temperatures.

Friedel[3] points out that the value of L must be corrected for temperature because this model does not take into account that at the same forest dislocation density, at low temperature when the higher stress bends the dislocation, it intersects more dislocations than at the level corresponding to the intermediate temperature. By using his formula, the value of L at intermediate temperature is,

$$L_T = [(\tau_{LT} - \tau_\mu)/(\tau_T - \tau_\mu)]^{1/3} L_{LT}, \tag{8}$$

where subscripts LT and T respectively denote low and intermediate temperatures.

In many materials, however, over the range of temperature necessary to obtain L and τ_μ, the flow stress-temperature curves indicate that more than one dislocation process occurs. In 99.99 % Copper, Diehl and Berner[8], and Schule *et al.*[9] have observed deformation behaviors corresponding to the solid line Fig. 2. In 99.999 % Copper and 99.999 % Silver, Basinski[5] observed only behavior corresponding to curves 2 and *3* which is indicated in this figure by a dotted line. In these cases, the value of L, obtained at low temperature, and the value of τ_u, obtained at high temperature, correspond to different processes; but a force-distance diagram cannot be constructed unless the values of L and τ_μ are the same for both processes. In general, this is not the case in f.c.c. single crystals since the value of L is different for the three possible cutting processes. For process *3*, it is the distance between neighboring jogs. For processes 1 and 2, L is the distance between pinning points, which are the attractive intersections between gliding and forest dislocations[10]. In the case of gliding screw dislocations there are six possible intersection reactions while in the case of edge dislocations there are four. Thus, the ratio expected between the spacing of pinning points on edge dislocations *L,,* and on screw dislocations *L,,* for the same forest density, is

$$L_e/L_s = \sqrt{3/2}. \tag{9}$$

Also, different values of interna1 stresses τ_μ have been found'' for the two types of dislocations.

Examples which illustrate the violation of the foregoing principles can be found in the literature.

In Aluminum, Guyot[12] constructed a diagram with values at three temperatures: 77°, 173° and *223" K*. In his flow stress versus temperature curves, the last two temperatures are greater than T_0, so his values only correspond to d r b and $\tau \cong \tau_\mu$.

Osborne[13] in OFHC copper has constructed a diagram, without any check on how many processes occur. Work by Diehl and Berner[8] with Copper of similar purity indicates that the three temperatures used by Osborne correspond to three different processes.

Basinski[5], in Copper and Silver, obtained a diagram by usins values which, according with his flow stress versus temperature curves, correspond to two different processes.

In summary, unless only one process prevails over the temperature range between T_0, and a low temperature where the assumption L r v/b^2 is valid, it is impossible to construct a dislocation-obstacle force-distance diagram from measurements of activation volumes at different temperatures.

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