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A COOPERATIVE GLIDE THEORY OF YIELDING AND SLIP BAND FORMATION

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In an annealed crystal few dislocation segements will lie exactly on a plane of maximum atomic population. The concentration of jogs or steps where a line passes from one high density layer to the next should vary for different segments. At high temperature the dislocation network has approached a configuration of metastable equilibrium by both conservative and nonconservative motions. Assuming that the energy associated with a jog is small, elastic strain energy, is minimized when dislocation segments approach linearity and nodes become symmetrical. Therefore in metals of medium to high stacking fault energy few segments will lie exactly on low index glide planes. Recent direct observations of dislocations in annealed copper crystals by Merlini et al. support this picture.[1] Differences in jog concentration from one segment to another are also suggested by the results of etch pit experiments on copper:[2] Dislocations begin to move at widely different resolved shear stresses; some having moved at $4 g/mm^2$ while others have not moved at $30\ g/mm^2$. Recent experimental results,[3] to be reported elsewhere, show that heavily jogged dislocations in pure copper do not move at an appreciable rate at a stress of $50 g/mm^2$.

When a small stress is applied to an annealed crystal the first segments to glide will be those having the lowest jog density on the slip system

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sustaining the highest resolved shear stress. If the stress is less than $\frac{\mu b}{\ell}$, where ℓ is the average length of dislocation segments in the three dimensional network, μ is the elastic shear modulus and b is the Burgers vector, then the distance moved will generally be small. Motion will terminate when the bowing dislocation reaches the equilibrium radius of curvature corresponding to the applied stress. If the bowing segment was initially longer than the average for the network then it will usually come up against other dislocation segments that pierce its glide plane before it reaches equilibrium curvature. By forming new attractive junctions with some of these intersecting dislocations its length will be reduced to something close to the average length for the network. The theory of yielding proposed here is based on the idea that bowing of a highly mobile segment on the primary glide system will sometimes promote cooperative glide of connecting forest segments that will in turn allow the bowing segment to continue to expand even though the applied stress is considerably less than $\frac{\mu b}{\ell}$.

When a dislocation loop, expanding on the primary glide plane, is held up by strong elastic interactions with intersecting dislocations the potential energy of the system may often be decreased if local displacement of some of the intersecting dislocations takes place, on their own glide surfaces, allowing a further advance of the primary dislocation. The direction in which a pinning point due to an intersecting dislocation can move, without involving any nonconservative motions of the dislocations involved, depends on the Burgers vector of the intersecting dislocation. For the FCC structure, if the Burgers vector of the forest dislocation is one of the three that lie in the primary glide plane, then the trace on that plane of all its possible glide surfaces is a straight line parallel to the Burgers vector and passing through its initial position. If the interesting dislocation has a Burgers vector that does not lie in the primary glide plane then the trace of its glide surface on the primary plane can follow any path.

If forest dislocations glide the distance between pinning points for some segments of the bowing primary dislocation would increase as illustrated by Fig. 1. If the longest bowing segments can grow slowly by this process to the length $\mu b/\tau$ where τ is the resolved shear stress in the primary system then the dislocation will continue to move forward continuously pushing aside the most easily displaced intersecting dislocations. The moving dislocation loop would follow a tortuous path partially clearing away the forest of intersecting dislocations in the neighborhood of its glide plane as shown in Fig. 2a. Some intersecting dislocations should be more easily displaced than others depending on (1) their jog densities, (2) whether the applied stress aids or opposes their motion, (3) what happens at the terminal nodes of the forest segment; cooperative glide may occur at these nodes also extending the local rearrangement of the network somewhat above and below the active plane.

Extensive cooperative glide of forest dislocations seems unlikely unless the applied stress level is high enough to cause glide of heavily jogged segments as well as those that lie on {111} close-packed planes. It has been shown experimentally[4] that for dislocation velocities that are small compared to the rate of propagation of elastic shear waves the stress dependence of velocity can be expressed as:

$$v = v_0\left(\frac{\tau}{\tau_0}\right)^m$$

Etch pit experiments suggest that τ_0 is a function of jog concentration.[3] Because m is large for copper and other pure metals, the dislocation velocity will decrease rapidly as τ becomes appreciably less than τ_0. The rate at which cooperative rearrangements of the network take place should be controlled by the rate of motion of the least mobile segments.

If nucleation of a slip band involves cooperative bowing of a part of the network having dimensions larger than ℓ then the critical stress for slip band formation and yielding might be:

$$\tau_y = \tau_{0_{max}} + \frac{\mu b}{\alpha \ell}$$

where $\tau_{0_{max}}$ is a frictional stress equal to the critical stress for motion of the most heavily jogged segments of the network and α is a constant greater than unity such that $\alpha\ell$ represents the effective cooperative bowing length.

Slip bands will be formed, according to this theory, as soon as a stress is reached at which some bowing segments start to clear parts of the forest. The partially cleared trails that would be created should often turn back on themselves as in Fig. 2b. Whenever this happens a dipole would be formed because the sum of the components of the Burgers vectors of the intersecting dislocations in the encircled part of the forest will not generally be zero. Eventually the cleared area for some expanding loops will reach the back side of the original starting point as in Fig. 2c or will turn back on itself as in Fig. 2b at a point where the expanding loop has been annihilated by recombination with a forest dislocation of antiparallel Burgers vector.[5] When this happens a slip band source will have been nucleated. The dislocation can then repeatedly follow an already cleared path. Each successive trip of the dislocation around the circuit will generally be on a glide layer displaced above or below that of the immediately preceding trip for the same reason as that explained above for the formation of dipoles. The pile-ups of dislocations of the primary system that will be formed against the boundaries of the cleared areas will usually consist of dislocations of like sign on a set of equally spaced levels. In the case of edge dislocations they would form a short dislocation wall rather than a planar pile-up. For screw dislocations cross slip would be promoted at the edge of the cleared area due to the mutual repulsion of the dislocations in the direction normal to the primary glide plane. The intersection cross-slip mechanism[6] should make this possible even in metals of low stacking fault energy. The dislocation density would be increased above and below the active glide zone.

The essential idea of this theory is that extensive cooperative motion of dislocations may be associated with the nucleation of slip bands in a crystal containing a three dimensional network of mobile dislocations. If this is so then the velocity of heavily jogged dislocations may be a more important parameter in determining the flow stress of a crystal than is the velocity of jog free dislocations. The former might determine the number of slip bands nucleated during a given interval of time while the latter would determine their rate of growth. The time required for nucleation may be large compared to the time during which the slip band grows.

This picture of yielding also leads naturally during stage I of the stress strain curve to the formation of regions of high dislocation density surrounding relatively clear areas.

Further experimental work on the stress dependence of dislocation velocity for jogged dislocations would be of particular interest.

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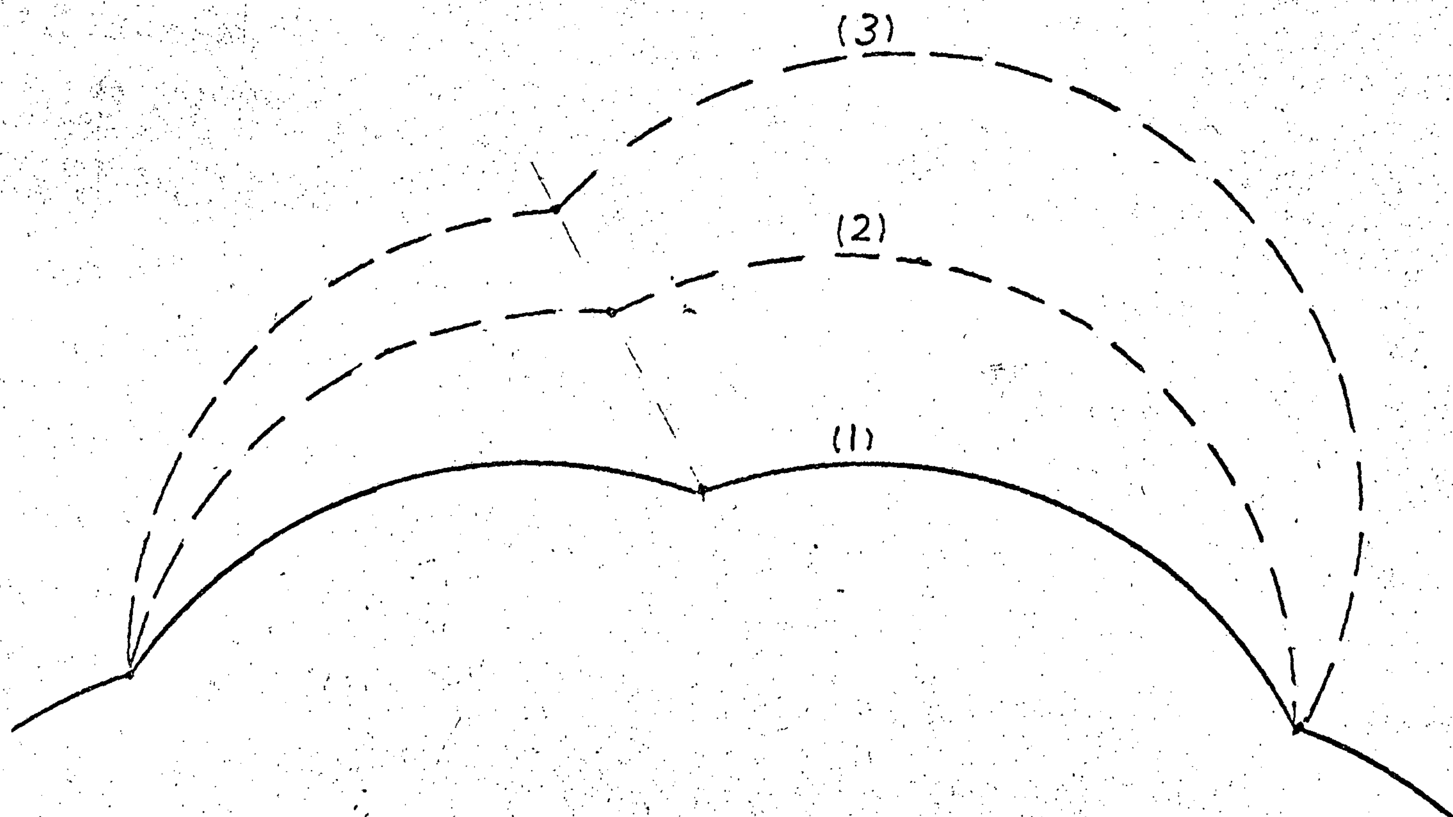

Fig. 1

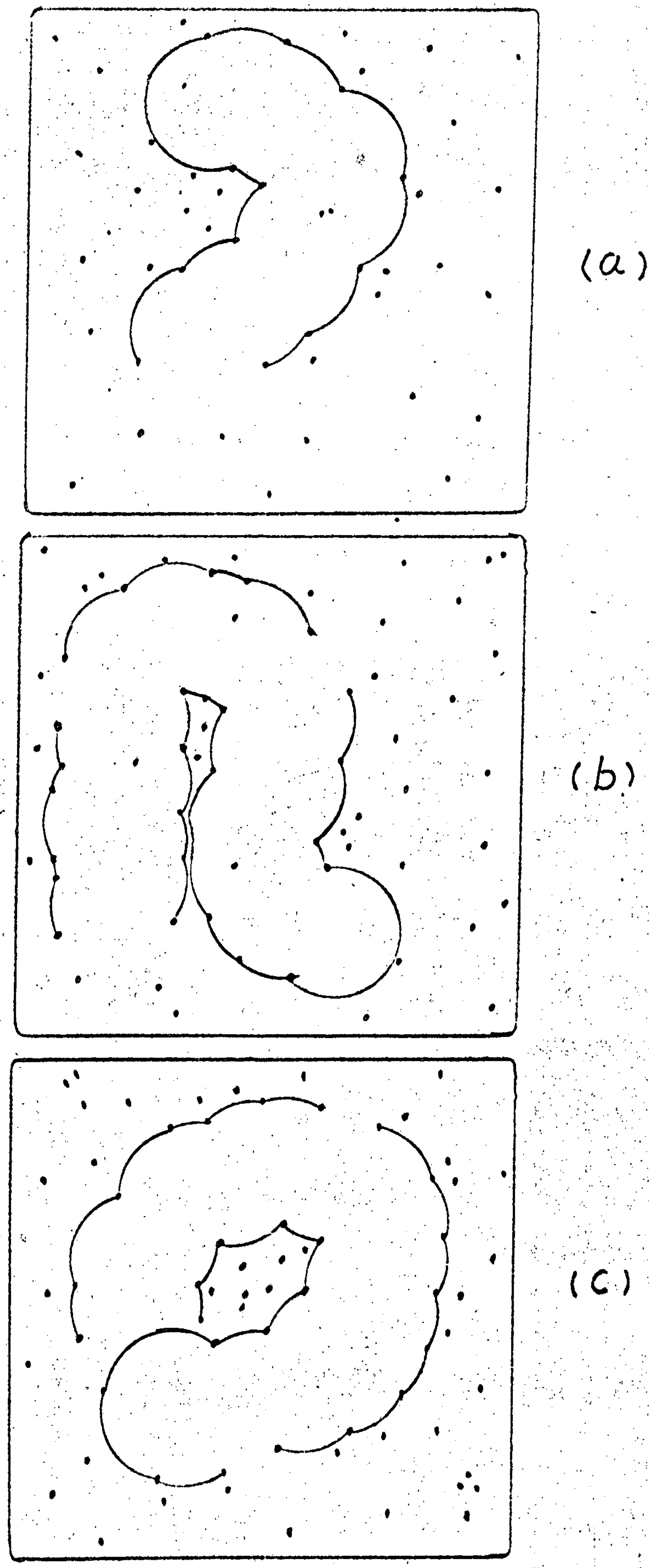

Fig 2