Takamura, J.: In pure crystals, the decrement is believed to be independent on the strain amplitude, as far as the small strain amplitude is concerned. If the relationship is valid also in impure crystals, the curve c of Fig. 3 rather than the curve b may be the case. However, I do not know whether such amplitude dependence has been experimentally established in solid solution alloys.

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Interaction between Prismatic and Glissile Dislocations

G. SAADA*
Inorganic Materials Research Division, Lawrence Radiation Laboratory
University of California, Berkeley, California, U.S.A.

AND J. WASHBURN
Department of Mineral Technology and Inorganic Materials Research Division
Lawrence Radiation Laboratory, University of California
Berkeley, California, U.S.A.

A theoretical study is made of the interaction between moving dislocations and large point defect clusters in the form of Frank sessile loops and perfect prismatic loops. Long range interactions are shown to be negligible. The contact interaction depends on the type and orientation of the loops relative to the glide plane and Burgers vector of the gliding dislocation:

a) Perfect prismatic loops can interact with moving dislocations in four different ways. These cases are analyzed in detail.
b) The interaction with a Frank sessile loop depends on its size. However, even loops possibly too small to be visible by transmission electron microscopy can form strong locking points on a moving dislocation.

1. Introduction

The clustering of excess vacancies due to rapid quenching of f.c.c. metals from high temperature leads to the formation of prismatic dislocation loops (both perfect and imperfect), stacking fault tetrahedra, and helical dislocations[1)-4)]. In pure aluminum only perfect loops with Burgers vector $a/2\ \langle 110\rangle$ and stacking fault loops with Burgers vector $a/3\ \langle 111\rangle$ are observed. Fig. 1 shows a typical quenched and aged substructure in pure aluminum.

The presence of these loops causes an increase in the yield strength and a low initial rate of work hardening[5)]. It has also been observed that small amounts of plastic deformation destroy the loop substructure and it has been suggested that this accounts for the low initial hardening rate[6)].

It is the purpose of this paper to explain the increase in the yield strength and the sweeping away of the loop substructure on the basis of a detailed analysis of the interactions between moving dislocations and prismatic loops in the f.c.c. structure. Possible effects due to isolated vacancies or very small clusters will not be considered.

2. Long Range Interaction

When the distance between a moving dislocation and a prismatic loop that cuts its glide plane is large compared to the radius R_L of the loop, there is little interaction. The stress field due to the loop falls off as $1/d^2$ where d is the distance to the loop. If d is smaller than R_L then the loop will be equivalent to two "trees" of opposite Burgers vector[7)] as defined in the forest theory of flow stress[8)-13)].

* On leave from October 1961 to September 1962 from IRSID, Saint Germain en Laye SO, France.

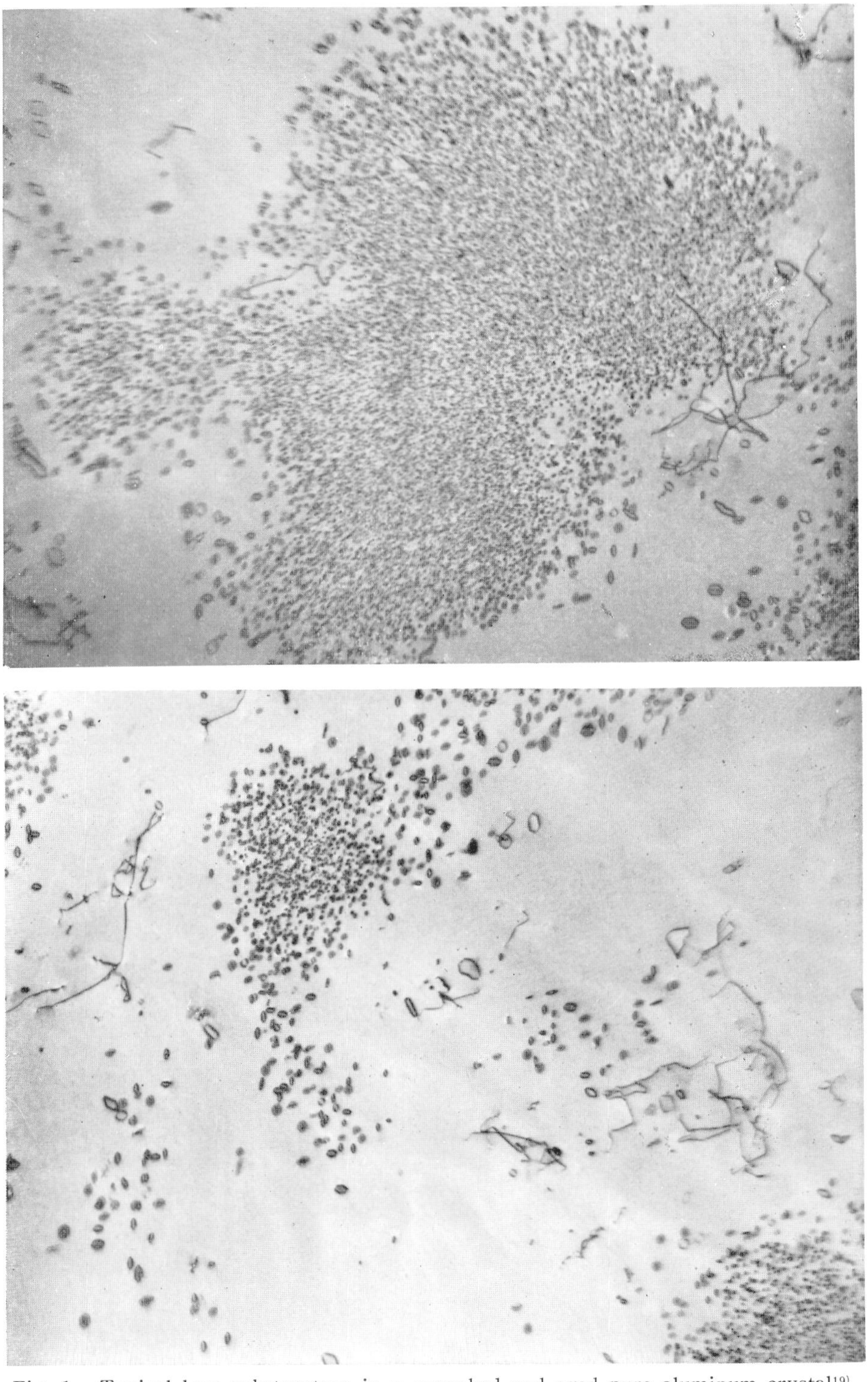

Fig. 1. Typical loop substructure in a quenched and aged pure aluminum crystal[19].

If a loop does not cut the glide plane of the moving dislocation but lies within the volume $\pm R_L$ to either side, and if R_L is less than a few hundred angstroms there are three processes, one of which will probably bring the two into contact:

a) cross slip of a segment of the moving dislocation

b) conservative climb of the loop (as observed by Kroupa and Price)[14]

c) motion of a perfect loop along its glide cylinder.

3. Contact Interactions

Dislocation reactions that may occur when a moving dislocation intersects a prismatic loop will be described with the aid of Thompson's[15] notation (Fig. 2). The moving dislocation will always be assumed to have Burgers vector BC and glide plane *a*. (The plane, *a*, is shown shaded in Fig. 2).

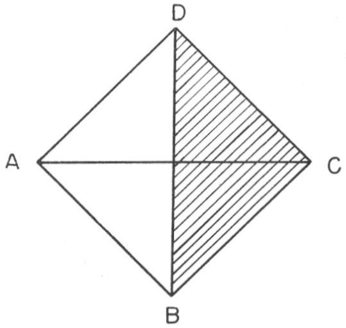

Fig. 2. Thompson tetrahedron.[15]

3.1 *Interactions with Perfect Loops*

Perfect prismatic loops formed by condensation of excess vacancies can have any of the six Burgers vectors, AB, BC, CD, AD, AC, BD. The energy of a perfect loop probably varies only slightly for small rotations on its glide cylinder away from the plane of minimum dislocation length, {110}, which lies at right angles to its Burgers vector. For example, a loop with Burgers vector $\overrightarrow{AD}$ can probably lie on the {111} planes *a* or *d* or on any intermediate plane. Therefore, interaction with a moving dislocation may often result in rotation of a prismatic loop.

Four different cases can be distinguished on the basis of the angular relationships between the Burgers vector of the loop, the direction BC, and plane *a*:

a) Consider first the interaction of a moving dislocation with a prismatic dislocation that has $\overrightarrow{AD}$ (or $\overrightarrow{DA}$) as its Burgers vector. In this case the Burgers vectors of the loop and the moving dislocation are at right angles. Only long range interactions occur.

b) If the dislocation loop has $\overrightarrow{BC}$ or $\overrightarrow{CB}$ as its Burgers vector, the result of the intersection will be as depicted in Fig. 3. After the cutting, the loop is smaller and the moving dislocation has acquired a loop *MM′* that does not lie in the original glide plane. If the moving dislocation is not pure screw, these segments will probably be able to slide along the dislocation in the direction of the Burgers vector and follow it. Therefore, this interaction will cause a progressive destruction of the substructure. If the jogs do not glide, the arms *ML* and *M′L′* of the moving dislocation will have to develop in spiral, meet and annihilate without destroying the loop.

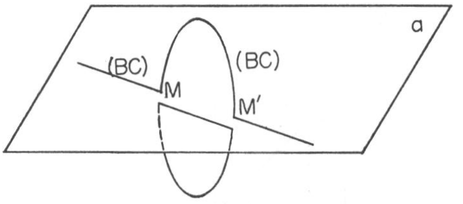

Fig. 3. Intersection of a prismatic dislocation with a moving dislocation of the same or of opposite Burgers vector.

Provided there are equal numbers of loops for each of the possible $a/2\langle 110\rangle$ Burgers vectors, a given dislocation will interact in this way with one loop out of six. Therefore, the number of these events associated with an increment of strain is:

$$dn = \frac{NR}{3b} de \qquad (3)$$

where

de is the amount of strain

N is the number of loops per unit volume

R is the average radius of the loops

If it is assumed that the moving dislocations are not nearly screw, *i.e.*, each time a loop is cut the jogged segment *MM′* is always able to glide away conservatively in the direction of its Burgers vector, then a uniformly distributed shear of 10% will make one loop out of six smaller than $10b$ in diameter. If shear takes place simultaneously in all of the six glide systems, then all the loops will be swept away. The experimentally observed disappearance of prismatic loops in quenched aluminum deformed by rolling[6] probably occurs by this mechanism.

c) Suppose now that the prismatic dislocation has $\overrightarrow{BD}$ or $\overrightarrow{DC}$ (or their opposites) as Burgers vector and lies in a plane cutting the plane *a*.

In Fig. 4 the glide cylinder of the loop, P, is cut by the glide plane a of the dislocation, BC, along two straight lines (shown as dashed lines). Let M be the point of intersection where the configuration of the dislocation lines and their Burgers vectors is such that $\vec{b}_1 \cdot \vec{b}_2 < 0$ at the quadruple node. Then a resultant dislocation $M_1 M_2$ will be formed which must lie along the intersection of the two glide surfaces as shown in Fig. 4.

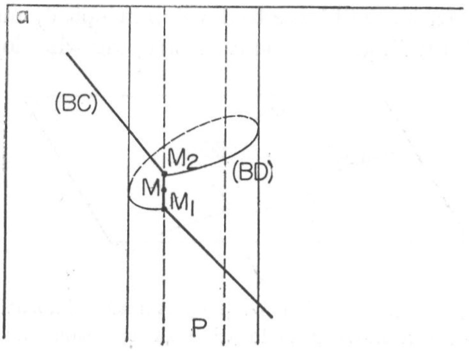

Fig. 4 Junction reaction at the intersection of a dislocation moving in its glide plane and a perfect prismatic dislocation (glide plane parallel to axis of glide cylinder).

Assume first that the prismatic loop P lies in a {111} plane. The increase in length and the gain in energy cannot be evaluated with high precision, but the reaction should occur. If the configuration is as depicted in Fig. 4, there will be a tendency for the loop to rotate toward the plane normal to its Burgers vector. If this happens, it can be seen that the length of the junction dislocation may shrink to zero because it would then cause too much increase in the total length of dislocation.

d) Finally, if the prismatic loop has $\overrightarrow{AB}$ or $\overrightarrow{AC}$ or their opposites as Burgers vector,

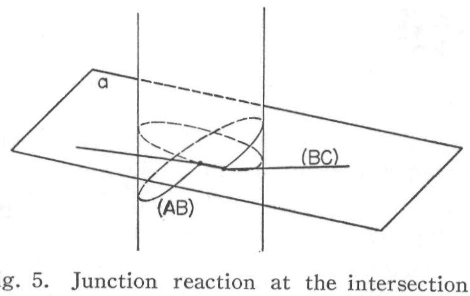

Fig. 5. Junction reaction at the intersection of a dislocation moving in its glide plane and a perfect prismatic dislocation (glide plane at an angle to axis of glide cylinder).

the intersection of the glide plane of the moving dislocation with the glide cylinder of the loop is an ellipse. It can be seen from Fig. 5 that the junction reaction can occur.

It also seems likely that in some cases the prismatic loop can be pushed by the moving dislocation so as to rotate to plane a. If this happens or if the loop lies originally in plane a and near enough to the glide plane of the moving dislocation, then the reaction shown in Fig. 6 will occur when there is attraction. The result is a change in the Burgers vector of the loop. It can be seen that the energy gained by this process can be very large, of the order of $\mu b^2 R$, where R is the radius of the loop.

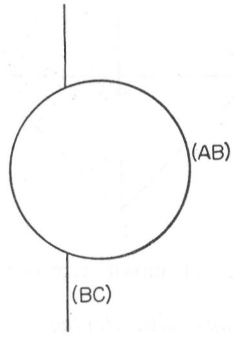

Fig. 6. Change in the Burgers vector of a prismatic loop due to interaction with a moving dislocation.

3.2 *Interaction of a Moving Dislocation with Stacking Fault Loops*

a) Two different cases exist. First, assume that the loop lies in plane a or plane d having $A\alpha$ or $D\delta$ as its Burgers vector respectively. If the moving dislocation comes in contact, either by intersecting a loop on plane d or by cross-slip contacts a loop on plane a, then it is possible for the partials to recombine and split into two new Shockley partials in the plane of the stacking fault that will sweep away the fault. The final result is the same as that shown in Fig. 6; two nodes on the moving dislocation line connected by curved dislocation segments that do not lie in the glide plane. For a loop lying in plane d the two opposite sides of the loop become segments having Burgers vectors BD and DC. This configuration should act as a strong anchor point on the moving dislocation.

b) The second case occurs when the loop has $C\gamma$ or $B\beta$ as its Burgers vector and lies in plane c or b respectively. In this case the moving dislocation can also dissociate in the plane of the stacking fault but the result is a Frank sessile dislocation and a Shockley partial[2]. The loop is then separated into two parts. The stacking fault is swept away in only one of the parts and the dislocation line acquires a curved segment that does not lie on the original glide plane. This large jog may glide away conservatively in the direction of the Burgers vector. Therefore, both perfect and imperfect loops can be swept away by moving dislocations.

If the stacking fault loop is smaller than a critical size, neither of these interactions can occur because the increase in line energy of the Shockley partial associated with sweeping away the stacking fault is greater than the energy of the fault[16),17),18]. The critical radius to which a Shockley partial can be bent by the force exerted by the stacking fault is given approximately by:

$$R_{\min}=\frac{Gb_s^2}{2\gamma}=\frac{Ga^2}{12\gamma}$$

where G, a, and γ are the shear modulus, the lattice constant, and the stacking fault energy respectively.

If γ is taken as 150 ergs/cm² for aluminum, then $R_{\min}$ is 25Å. Therefore, loops smaller than 50Å in diameter will be effective barriers to moving dislocations. In order to pass through, the moving dislocation must produce a step in the stacking fault as previously described by Thompson.[15] It is of special interest to the theory of strain hardening and quench hardening that prismatic loops that are possibly too small to be easily observed by transmission electron microscopy may still be important barriers to the motion of dislocation.

4. Application to Quench Hardening of Aluminum

The typical substructure shown in Fig. 1 contains both imperfect and perfect loops of various sizes. It is also made complex by the grouping of loops into colonies[19] with loop-free regions between. For this reason, an accurate analysis of the hardening effect of the substructure would be difficult. However, an order of magnitude estimate can be made.

It has been shown that half of the large imperfect loops and all imperfect loops that are smaller than about 50Å in diameter will be strong barriers and that two-thirds of the perfect loops will also interact with a given moving dislocation to produce strong locking points.

Friedel[7] has analyzed in some detail the way in which a moving dislocation behaves by zig-zagging through randomly distributed loops (Fig. 7). The stress required to move

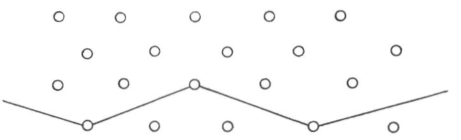

Fig. 7. Zig-zagging dislocation (following Friedel[8]).

the dislocation is given by a formula of the type:

$$\sigma=\frac{\mu b}{\beta}N^{2/3}R$$

where β is about 4, N is the number of loops per unit volume and R is the average radius of the loops. This stress will be temperature independent.

For a sample quenched from 600°C, N is of the order of 10^{15} and the average value of R is of the order of 200Å. Therefore, $\sigma\simeq 370$ g/mm² which is of the order of magnitude of the experimental results of Maddin and Cottrell[5].

A temperature dependent stress arises from the creation of jogs and we expect the total flow stress to vary in the same way as for work hardening. These two facts are in good agreement with the experimental results of Maddin and Cottrell[5] and Tanner and Maddin[20].

The hardening due to loops must gradually disappear during plastic deformation as loops are destroyed by the interactions described in sections *3.1 b* and *3.2 b*.

The analysis has been applied specifically to the loop substructure produced by quenching and aging. However, elongated prismatic loops or dislocation dipoles are formed within an active slip band. Therefore the same interactions may be more generally important to the theory of strain hardening; particularly when two or more slip systems are simultaneously active.

5. Application to Other F.C.C. Metals

All other quenched and aged f.c.c. metals that have been investigated experimentally contain stacking fault tetrahedra.[2] These should be even stronger barriers to moving dislocations than stacking fault loops. It is possible that defects of this type can also be created by irradiation, or even by plastic deformation, that are too small to be easily detected by transmission electron microscopy and yet large enough to be strong barriers to moving dislocations.

Acknowledgment

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DISCUSSION

Thomson, R.: Do you have any data on the growth of the prismatic loops? This kind of data would furnish information on such things as jog formation and pipe diffusion.

Washburn, J.: It is possible to observe directly the shrinkage of prismatic loops in thin foils. However, in pure aluminum it is probably not possible to observe growth because of the nearness of the external surfaces that are efficient sinks for excess vacancies.

Wilsdorf, H.G.F. and Kuhlmann-Wilsdorf, D.: Besides the possible mechanisms for the elimination of prismatic dislocation loops and for dislocation tangling by pure slip processes, so ably outlined by Dr. Washburn, thermally activated processes do definitely take place in dislocation tangling. Actually, vacancy-dislocation interactions are responsible. This is proven in two ways: (i) Tangling does not occur in electron transparent foils when observed in the electron microscope. In this case pipe diffusion allows the vacancies to escape to the free surfaces. (ii) Tangling ceases at very low temperatures.—In addition to the above two points, much supporting evidence has been accumulated in the course of the past few years showing that indeed vacancy-dislocation interactions are the cause for dislocation tangling. Several papers dealing with this problem have either been published already or are in the press.

Washburn, J.: When moving dislocations sweep away the loop substructure during plastic deformation a system of irregular subgrain boundaries or regions of relatively high dislocation density are formed. The final subgrain structure is the same as that forms during plastic deformation of a crystal that initially contains no loops. It was these irregular subgrain boundaries that I referred to as tangles. I believe you have in mind a more specific definition of tangling.

Brandon, D.G.: Should there not be a critical size of loops below which the interaction occurs by short range pipe diffusion rather than by a dislocation reaction?

Washburn, J.: I believe this is correct. Even for larger loops short range diffusion at nodes may result in some local climb.

Mitchell, J.W.: In our work on single crystals of silver halides containing glass spheres, D. A. Johnes and I (Phil. Mag. **3** (1958) 1) observed many examples of interactions between dislocations of unknown Burgers vectors with stress generated prismatic and helical prismatic dislocations with $1/2\, a\langle 110\rangle$ Burgers vectors. It was not possible to present these observations effectively in a publication on account of the number of photographs. These observations demonstrated very clearly the effectiveness of prismatic and helical prismatic dislocations in impeding the motion of glide dislocations through the crystals.

Washburn, J.: I want to thank Prof. Mitchell for his comments. We have also considered briefly the interaction of moving dislocations with helical dislocations in the original text of our paper (Lawrence Radiation Laboratory Report #10213). However due to limitation of space this could not be included in the Proceedings.

Kiritani, M.: We observed the cross slip of ordinary glide dislocations caused by the quenched-in Frank sessile dislocation loops. This might be one of the mechanisms of hardening. Have you observed such phenomena?

Washburn, J.: I am very glad to hear of your observations. We have not been fortunate enough to obtain clear examples of this kind of interaction in thin foils. In the text of our paper we have suggested that cross-slip should occur when a moving dislocation passes close to a loop.