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INTERACTION BETWEEN PRISMATIC AND GLISSILE DISLOCATIONS

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by

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ABSTRACT

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.

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1. Introduction

The clustering of excess vacancies due to rapid quenching of FCC metals from high temperature leads to the formation of prismatic dislocation loops (both perfect and imperfect), stacking fault tetrahedra, and helical dislocations.[1 to 4] In pure aluminum only perfect loops with Burgers vector $\frac{a}{2}$ <110> and stacking fault loops with Burgers vector $\frac{a}{3}$ <111> 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 FCC 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 $\frac{1}{d^2}$ 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 to 13]

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 Thompsons[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.)

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 $\vec{AD}$ 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 $\vec{AD}$ (or $\vec{DA}$) 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 $\vec{BC}$ or $\vec{CB}$ 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. Provided there are equal numbers of loops for each of the possible $\frac{a}{2}\langle 110\rangle$ 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 $\vec{BD}$ or $\vec{DC}$ (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_1M_2 will be formed which must lie along the intersection of the two glide surfaces as shown in Fig. 4.

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 $\vec{AB}$ or $\vec{AC}$ or their opposites as Burgers vector, 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.

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:

$$R_{min} = \frac{G b_s^2}{2\gamma} = \frac{G a^2}{12\gamma}$$

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/cm^2 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 the dislocation is given by a formula of the type:

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

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 mm^{-2} 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 FCC metals

All other quenched and aged FCC 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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Figure Captions

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

Fig. 2 Thompson tetrahedron.[15]

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

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).

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).

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

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

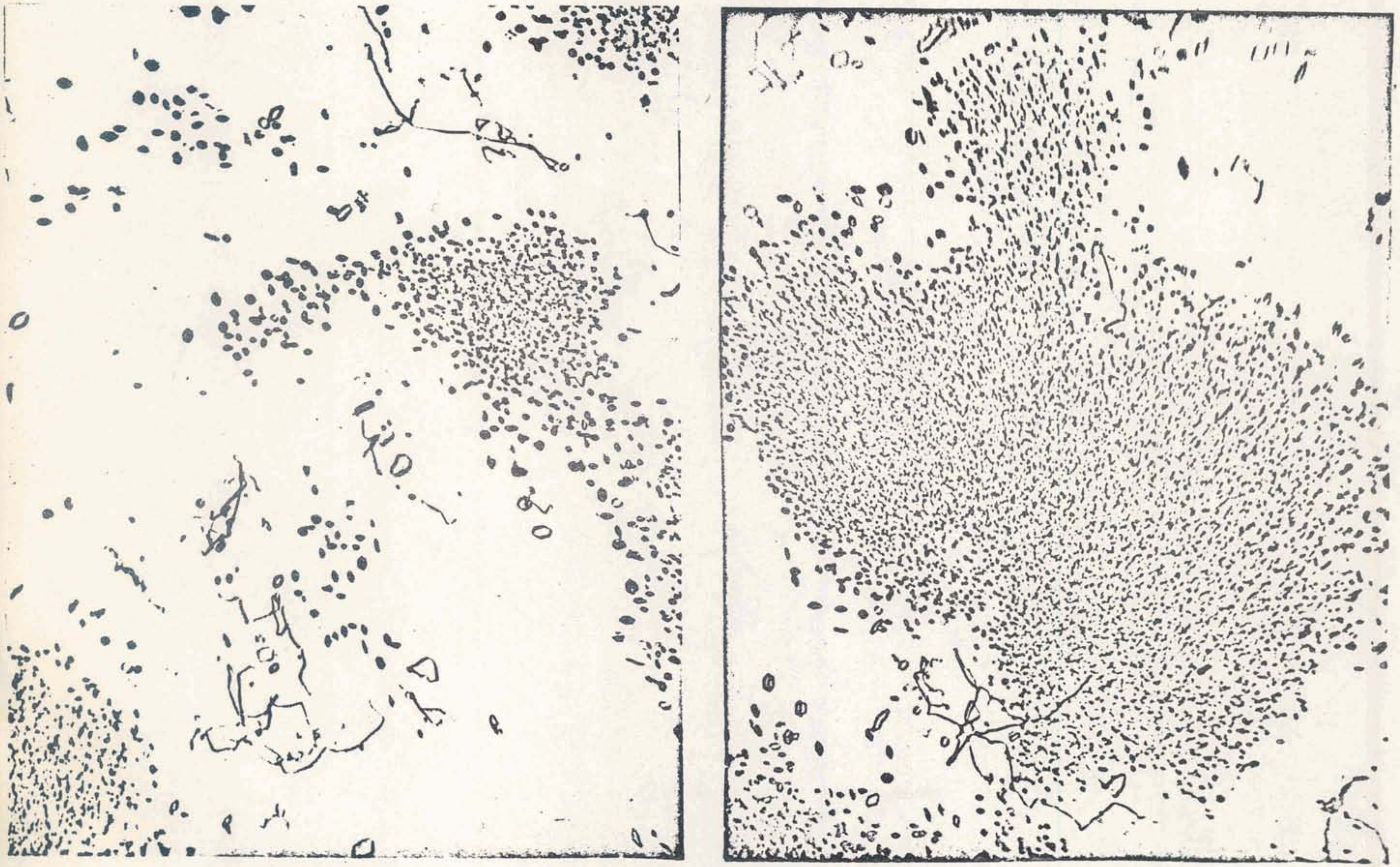

Fig. 1

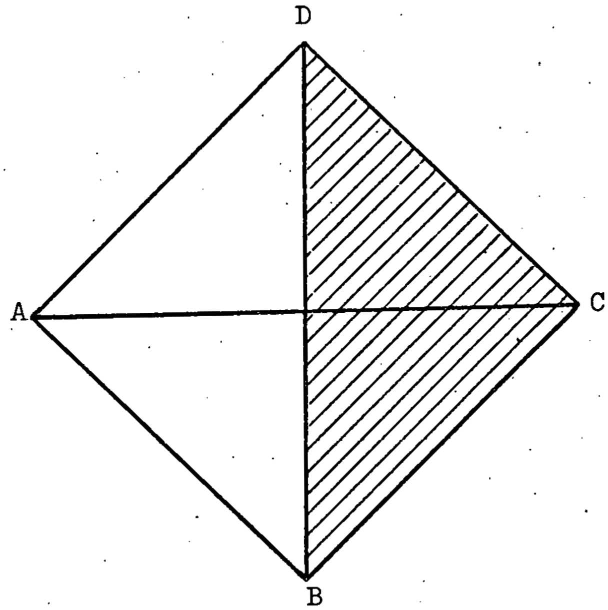

Fig. 2

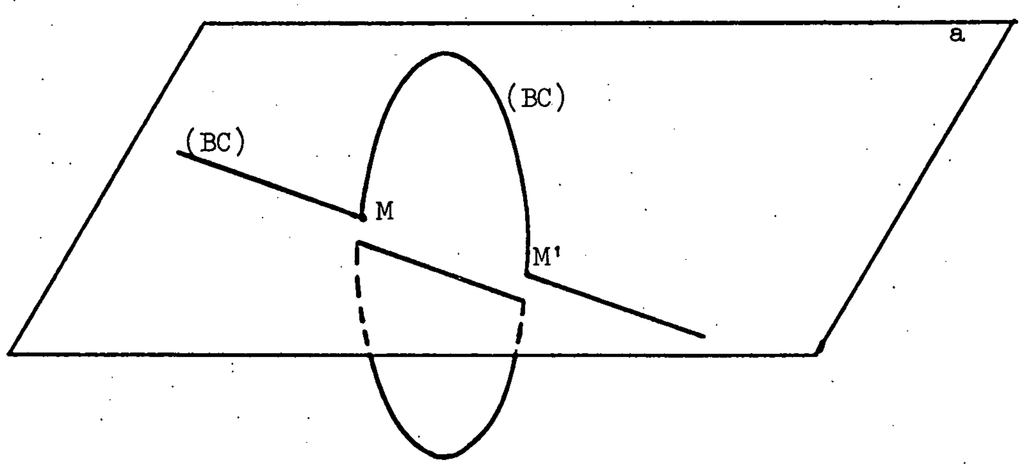

Fig. 3

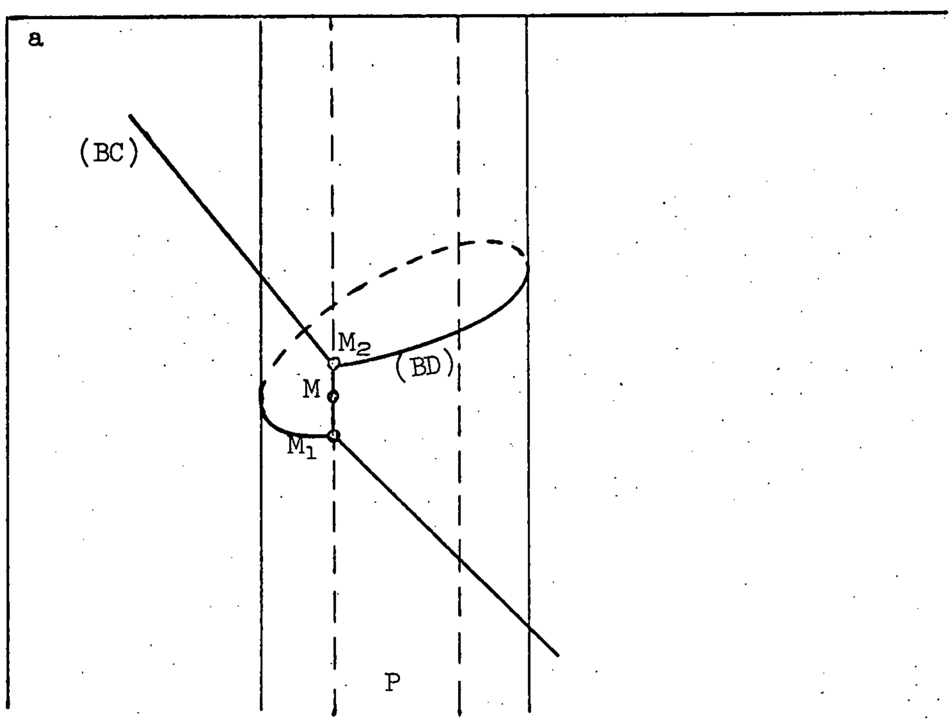

Fig. 4

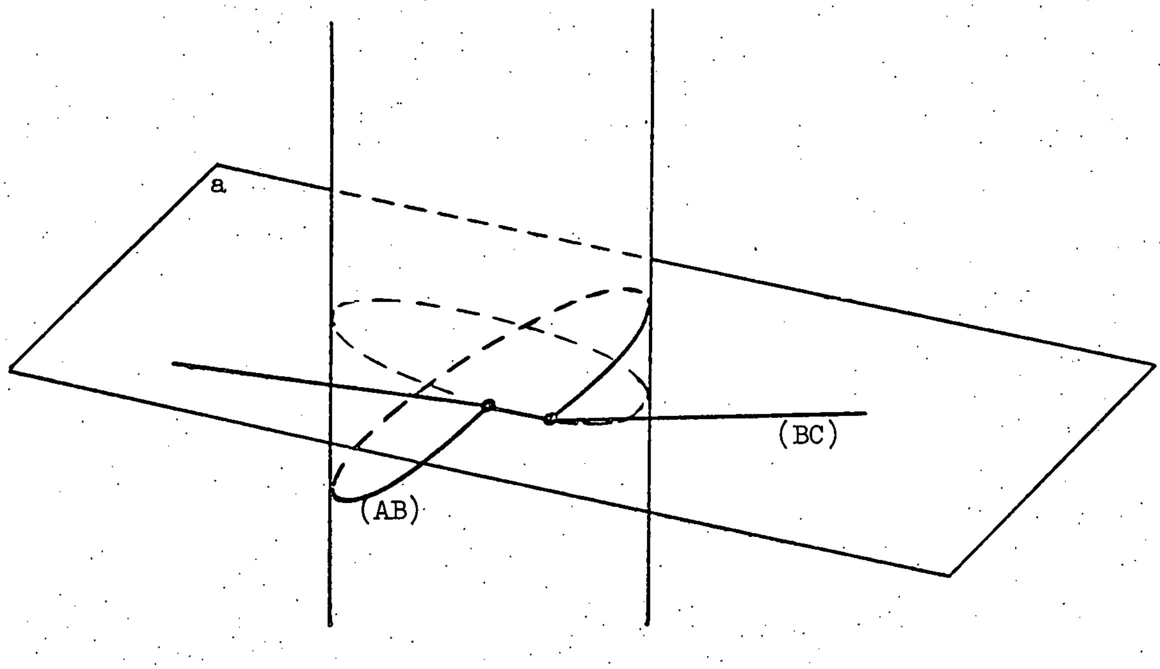

Fig. 5

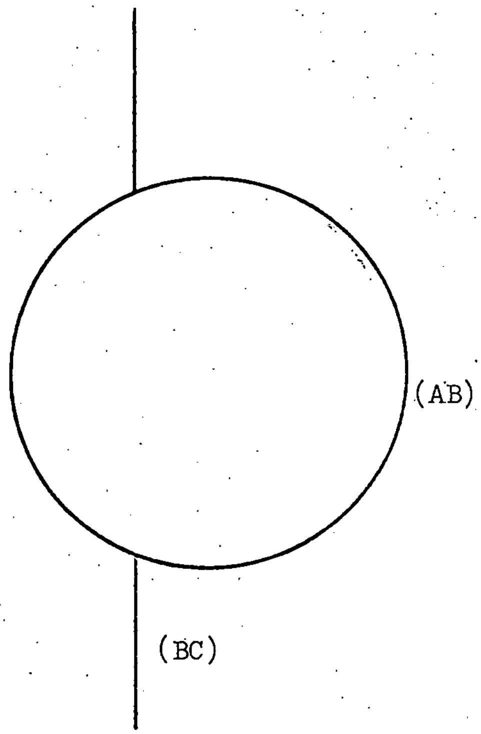

Fig. 6

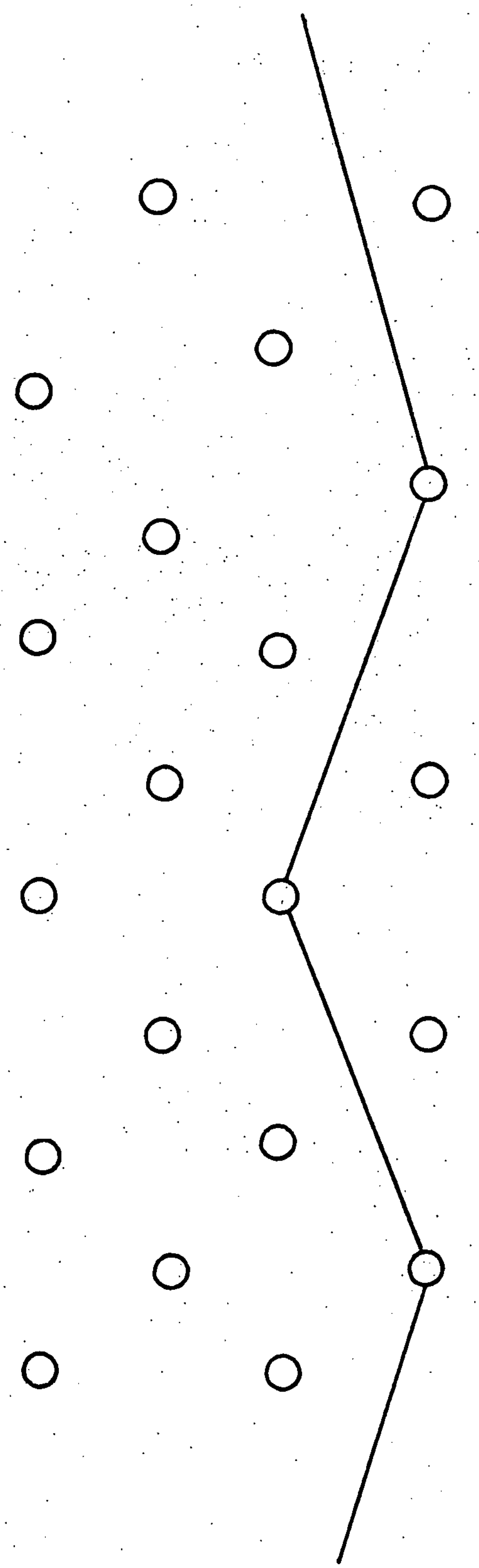

Fig. 7