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# A FRANK LOOP UNFAULTING MECHANISM IN fcc METALS DURING NEUTRON IRRADIATION

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# A FRANK LOOP UNFAULTING MECHANISM IN fcc METALS DURING NEUTRON IRRADIATION

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## ABSTRACT

The unfaulting mechanism whereby sessile Frank dislocation loops evolve into a complex tangle of glissile dislocations during irradiation of face centered cubic metals is not well understood. It is generally presumed that such loops grow by absorption of point defects until interactions develop which provide sufficient impetus for nucleation of an unfaulting event. The loops then become glissile, interact and form a dislocation network.

The present study identifies an alternate mechanism which has been observed to occur in an austenitic precipitation-strengthened commercial alloy irradiated in the EBR-II fast reactor. The mechanism requires an interaction between the sessile $\frac{a}{3}\langle 111\rangle$ Frank loop and a moving glissile $\frac{a}{2}\langle\bar{1}\bar{1}0\rangle$ perfect dislocation. An unfaulting $\frac{a}{6}\langle 112\rangle$ dislocation is created which, as it moves, eliminates the Frank loop and leaves only a perfect dislocation with the original $\frac{a}{2}\langle 110\rangle$ Burgers vector. This process is demonstrated by an example illustrated with transmission electron micrographs.

This alternate mechanism can have significant impact on the development of the dislocation microstructure in a metal undergoing irradiation creep. This impact will be discussed in relation to relevant irradiation creep models.

## INTRODUCTION

Irradiation creep is an important behavioral response which must be considered in the development of structural materials for fast breeder reactors. Irradiation creep occurs as a result of enhanced concentrations of point defects produced by bombardment with highly energetic neutrons. Increases in point defect concentrations lead to increased dislocation climb rates which in turn generally result in enhanced creep rates. Two approaches can be taken to quantify irradiation creep response. Creep tests can be performed in-reactor to obtain data for specific alloy conditions under specific test conditions(1) or, alternatively, irradiation creep response can be modeled mathematically and predictions can be made for various inputs, as test condition changes, to the model. The former approach is limited by the fact that every possible test condition cannot be tested and the latter approach is limited by inaccurate modeling due to oversimplification of the model and due to misinformation regarding controlling mechanisms. Ideally, a marriage of the two approaches is required to best predict irradiation creep response for any given application. The present work provides insight into an important aspect of the evolution of dislocation structure in an irradiation environment: the transition from a Frank loop dominated microstructure to one involving perfect dislocation networks. The impact of this process on irradiation creep response is then discussed.

## AUTOCATALYTIC FRANK LOOP UNFAULTING

It is generally presumed that the Frank loop unfaulting process can occur in an autocatalytic manner.(2-4) Once a given loop grows sufficiently large, it may intersect another microstructural feature which can generate sufficient localized stresses to nucleate an unfaulting dislocation loop of the type $\frac{a}{6}\langle 11\bar{2}\rangle$. This Shockley partial can then glide in the plane of the Frank loop and react with the Frank partial according to the equation

$$\frac{a}{6}[11\bar{2}] + \frac{a}{3}[111] = \frac{a}{2}[110] , \qquad (1)$$

thereby transforming the Frank loop into a perfect prismatic dislocation loop.

## PERFECT DISLOCATION/FRANK LOOP UNFAULTING

An alternate mechanism exists, however, which allows Frank loop unfaulting. It has been demonstrated to apply in the case of Frank loop unfaulting in quenched pure aluminum(5,6) and, as will be demonstrated, it is found to apply in a precipitation strengthened commercial alloy during irradiation creep. It differs from the above in that nucleation of an $\frac{a}{6}\langle 11\bar{2}\rangle$ dislocation loop is not required.

This unfaulting mechanism is initiated by the interaction of a sessile $\frac{a}{3}\langle 111\rangle$ Frank loop with a glissile $\langle\bar{1}\bar{1}0\rangle$ perfect dislocation. A reaction results by which an $\frac{a}{6}\langle\bar{1}12\rangle$ dislocation is created according to the equation

$$\frac{a}{2}[\bar{1}\bar{1}0] + \frac{a}{3}[111] = \frac{a}{6}[\bar{1}\bar{1}2] \ . \qquad (2)$$

The Shockley partial created can sweep across the Frank loop, remove the stacking fault and react with the opposite side of the Frank loop according to the equation

$$\frac{a}{6}[\bar{1}\bar{1}2] + \frac{a}{3}[\bar{1}\bar{1}\bar{1}] = \frac{a}{2}[\bar{1}\bar{1}0] \ . \qquad (3)$$

The process diagramed in Figure 1 shows the interaction of a Frank loop in the plane of the figure and a perfect dislocation moving on some other plane and intersecting the loop. Thus, the Frank loop can be annihilated, the only remnant being a coil in the $\frac{a}{2}[\bar{1}\bar{1}0]$ dislocation approximately on the Frank loop {111} plane. Thus, the unfaulting product of a perfect dislocation/Frank loop interaction immediately becomes part of the perfect dislocation network but the autocatalytic unfaulting product consists of an individual prismatic dislocation loop.

## EXPERIMENTAL DEMONSTRATION

A pressurized tube specimen of solution treated Nimonic PE16 (specimen AV75) was irradiated to a fluence of 2 x $10^{22}$ n/$cm^2$ ($E > 0.1$ MeV) at 545°C under a hoop stress of 167 MPa.(1) Nimonic PE16 is a commercial gamma prime [$Ni_3(Al,Ti)$] precipitation strengthened austenitic superalloy. The specimen was examined by transmission electron microscopy and found to contain a partially unfaulted dislocation structure. In many regions of the specimen, unfaulting had not occurred and only Frank loops were present. In other regions, however, Frank loops had been almost completely replaced by a perfect dislocation network. In the transition regions, many examples of crescent-shaped stacking fault features were found, and several of these were observed to be connected to the perfect dislocation network.

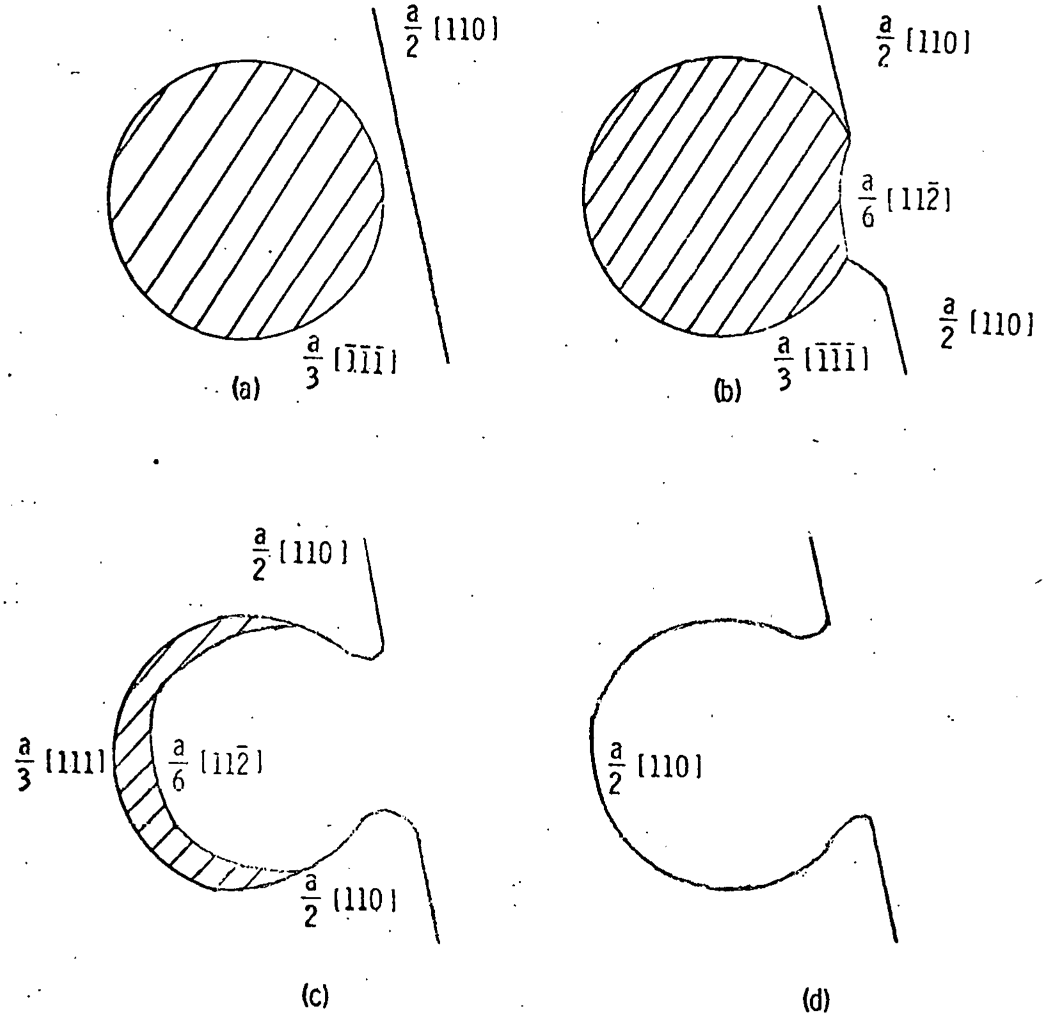

FIGURE 1. The Frank Loop Unfaulting Mechanism Which Requires the Interaction of a Perfect Dislocation With the Frank Loop.

An example is given in Figure 2 which shows such a transition region in a (112) foil imaged using $11\bar{1}$ dislocation contrast so that (1) stacking fault fringes for three of the four sets of Frank loops can be seen (the fourth appearing edge-on) and (2) half of the perfect dislocations are in contrast. Locations in the micrograph where perfect dislocation/Frank loop interactions were confirmed by stereo examination are indicated by arrows. Analysis of the $\frac{a}{3}\langle 111\rangle$ and $\frac{a}{2}\langle 110\rangle$ Burgers vectors involved in such interactions demonstrated that the reaction of equation (2) was responsible for the unfaulting. Several examples can also be found where large dislocation coils have developed in the perfect dislocation network identifying locations where Frank loops have recently been annihilated.

Figure 3, a low magnification montage of a whole grain, demonstrates the localized effects of the unfaulting behavior. In this example, the specimen is in an (011) foil orientation, again imaged using $11\bar{1}$ dislocation contrast so that two sets of Frank loops are steeply inclined and appear edge-on, and two sets are more circular in shape. Several large regions, generally elliptical in shape, can be found which are unfaulted, one of which is so labeled. Sources of unfaulting response can be identified in this figure as being either grain boundaries or large blocky precipitates (which have punched-out matrix dislocations as a result of quenching strains).

Therefore, it is found that in the case of Nimonic PE16 irradiated under stress at 545°C, Frank loop unfaulting occurs as a result of interactions with perfect dislocations. Perfect dislocations are present even in highly annealed material, produced by quenching strains around large blocky precipitates or associated with grain boundaries. In fact, the dislocation generation capability of grain boundaries during cold working(7) appears to apply for irradiation creep response as well. However, the motion of these perfect dislocations will reflect an externally applied stress, for those dislocations oriented for optimum motion under stress will move most rapidly. This is demonstrated in Figure 3 by the noncircular unfaulted regions. As the irradiation proceeds, the area swept out by the perfect dislocations becomes larger and larger until almost the entire Frank loop population has been annihilated.

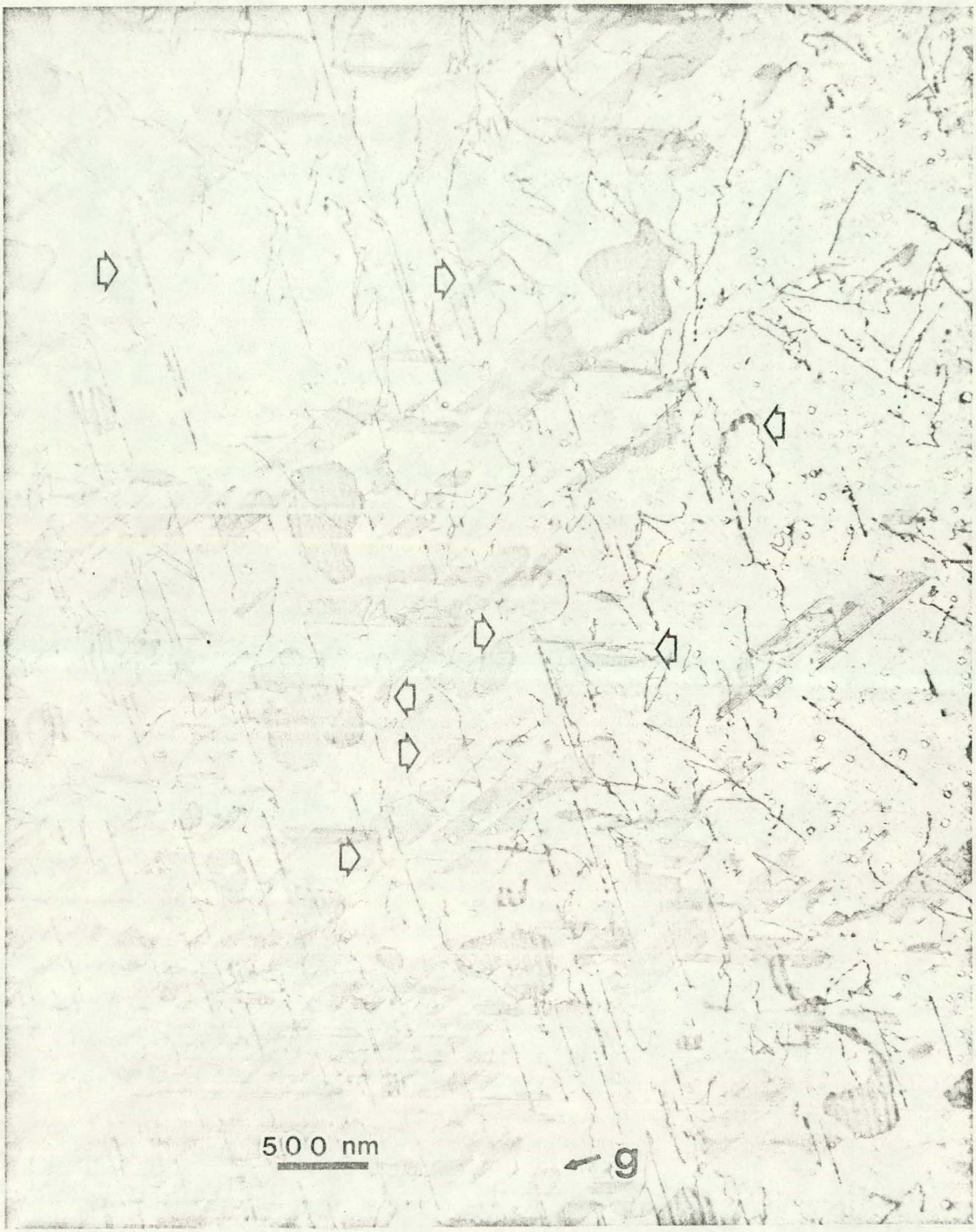

FIGURE 2. Dislocation Structure in a Specimen of Solution Treated Nimonic PE16 After Irradiation to 2.0 x $10^{22}$ n/cm$^2$ (E >0.1 MeV) at 545°C Under a Hoop Stress of 167 MPa Showing a Region Undergoing Frank Loop Unfaulting. Arrows identify locations where perfect dislocation/Frank loop interactions are confirmed by stereoscopic examination.

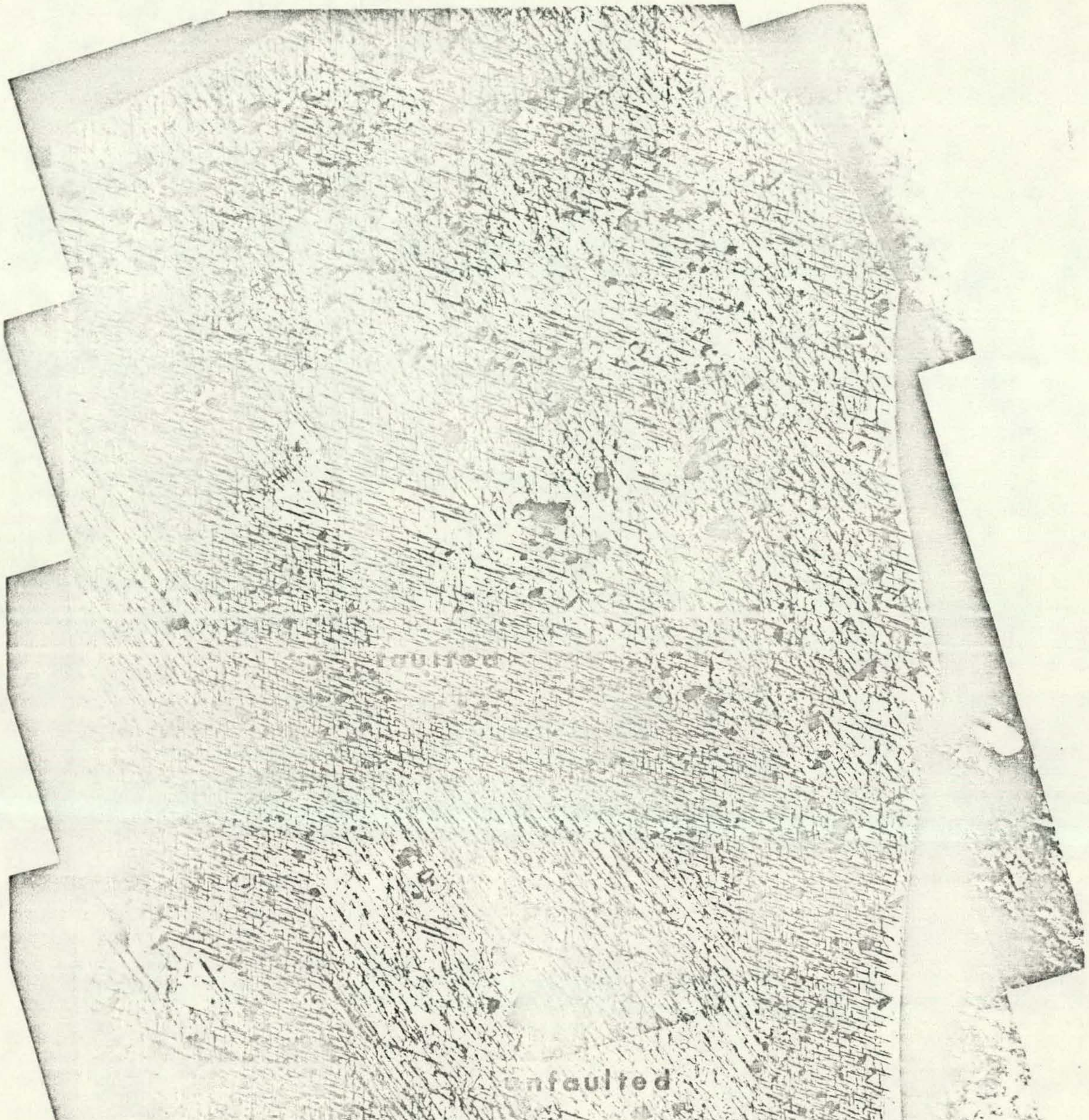

FIGURE 3. Montage Showing Variations in the Dislocation Microstructure of a Single Grain in a Specimen of Nimonic PE16 ST After Irradiation to 2.0 x $10^{22}$ n/cm$^2$ (E >0.1 MeV) at 545°C Under a Hoop Stress of 167 MPa.

The same mechanism for Frank loop unfaulting likely applies in the case of AISI 316, a solid solution strengthened austenitic stainless steel. Brager et al(8) showed that when perfect dislocations and Frank loops were able to coexist, the Frank loop size was governed by the mean spacing between dislocations. Thus, loop unfaulting occurred as a result of interactions with the perfect dislocation network and not by an autocatalytic process.

## CONSEQUENCES

The evolution of the dislocation network during irradiation creep has generally been envisioned as follows. Interstitial atoms preferentially coalesce to form Frank loops. Anisotropy in the loop populations develops in proportion to the deviatoric normal stress on the given plane.(8-10) The loops grow initially primarily as a result of increased interstitial capture efficiencies of the small loops.(9) The loops continue to grow in response to the irradiation induced point defect fluxes until they unfault in some autocatalytic manner, thereby forming individual prismatic loops. The prismatic loop populations are presumed to retain the anisotropy observed in the Frank loop populations. Thus, the irradiation creep rate continues unaffected. The prismatic loops grow into a dislocation network and a steady state microstructure finally develops.

The present results demonstrate that an autocatalytic unfaulting process does not control development of a perfect dislocation network in Nimonic PE16 at a temperature of 545°C. Also, there is strong evidence that a steady state dislocation network develops in a similar manner in AISI 316 both in the solution treated and cold worked conditions. As perfect dislocation interactions appear to control the Frank loop unfaulting process in both Nimonic PE16 and AISI 316 and as these two materials constitute the major source of irradiation creep data, irradiation creep modeling must allow for the consequences of this unfaulting process.

A major consequence of a perfect dislocation/Frank loop interaction mechanism for controlling loop unfaulting is that anisotropy in the Frank loop populations generated by irradiation creep will not necessarily be retained after unfaulting. A given Frank loop can be unfaulted by any one of three perfect dislocation Burgers vectors out of the six possible. As the Frank loop contains opposing Burgers vectors on opposite sides of the loop, the sign of the unfaulting perfect dislocation is unimportant: the reaction will either take place on one side of the Frank loop or the other. Thus, a given Frank loop can be unfaulted by half of the perfect dislocation Burgers vectors available. Furthermore, it is possible to annihilate all Frank loops in a given area using perfect dislocations having only two of the six possible Burgers vectors because each perfect dislocation can unfault two sets of Frank loops (or half the population). Whereas it has been previously assumed that the distribution of perfect dislocation Burgers vectors must be fairly uniform, at most reflecting the anisotropy produced in Frank loop populations by irradiation creep, it is now apparent that much larger variations in the distribution of Burgers vectors representing perfect dislocations may be produced. This could lead to much larger macroscopic shape changes during irradiation creep.

The present work also indicates that the perfect dislocation sources which effect the Frank loop unfaulting reaction during irradiation creep are one and the same as those for the low temperature plastic deformation case. Grain boundary ledges and precipitate particle interfaces emit the perfect dislocations which primarily control dislocation network evolution. It is the perfect dislocation network which is responsible for steady state irradiation creep at high fluences.

However, a major difference exists between Frank loop unfaulting during cold working(5,6) as opposed to during irradiation creep. During irradiation creep, climb plays a significant role in dislocation mobility whereas during cold working only glide is important. Washburn and coworkers have demonstrated that unfaulting of a Frank loop can occur by an alternative interaction mechanism, one involving a perfect dislocation capable of gliding on the plane of the Frank loop. (The product of the reaction at the loop perimeter is a perfect dislocation with a Burgers vector different than that of the unfaulting dislocation.) Evidence for this alternative reaction has not been identified in irradiation creep specimens. The reason is thought to be due to the enhanced climb mobility available for dislocation motion during irradiation creep. Much stronger interaction forces are available for the unfaulting mechanism defined by equation (2) and this reaction therefore dominates the unfaulting response during irradiation creep.

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