disks but not of three-dimensional aggregates. In many alloys, on the other hand, vacancies are bound to the substitutional atoms, and conditions would be completely different from those discussed here, but the profuse multiplication of dislocations in crystals originally almost free of dislocations might in some cases be due to the phenomena discussed.

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NATURE OF RADIATION DAMAGE IN NICKEL*

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The problem of radiation damage by neutrons has been reviewed recently by various authors.[1,2] The evidence for the damage in metals obtained by resistivity measurements, x-ray techniques, tests of mechanical properties, and others cannot be interpreted unambiguously. In order to attempt a better understanding of the processes involved, a more direct experimental approach was sought by investigating irradiated metal foils by transmission electron microscopy. This method has been used for directly studying dislocations, stacking faults,[3-5] and dislocation loops produced by the condensation of vacancies.[6] Also, it is a most sensitive tool to detect lattice misorientations which may be as small as 1 minute of arc. The disadvantage of the method is that, at present, it does not permit tests below room temperature. However, since many metals show a considerable increase in yield strength after neutron exposure at pile temperature[7-9] the described experiments appeared to be suitable for investigating the nature of radiation damage that can be produced in this temperature range. The tests were made with nickel specimens of 99.999% purity which had been irradiated as foils 1000 A to 2000 A thick as well as with thicker specimens. The latter had to be thinned after radiation treatment for their examination. The transparent areas were obtained by electrolytic polishing from rolled strip.

Stimulated by the theoretical work on displacement spikes,[10] and by the theory that possibly very small dislocation loops might be produced by a knock-on,[11] foils in the thickness range of 1000 A were exposed to neutrons. All specimens were sealed in evacuated (10^{-5} mm Hg) quartz tubes and irradiated in the Brookhaven reactor.[12] The same areas were examined at magnifications between 40 000× and 65 000× before and after irradiation with an integrated flux of 10^{16} *nvt* or 10^{19} *nvt*. Even the most careful scrutiny of the many specimens investigated failed to reveal any consistent structural changes in the foils. At this point it seems to be safe to conclude that the neutron bombardment of thin nickel foils at pile temperature does not produce dislocations or stacking faults, nor regions of misfit as predicted for displacement spikes. Since the lattice strains around a vacancy or a vacancy cluster supposedly are too small to cause a noticeable contrast in the electron image, no statement can be made as to the presence or absence of these lattice defects. Further, the high jump frequency of vacancies at pile temperature makes it very unlikely that foils 1000 A thick contain vacancies after irradiation.

For these reasons, and in order to test the hypothesis derived from the above result that the interactions of the first glide dislocations with vacancies or vacancy clusters result in obstacles to slip, the following experiment was conducted. Nickel foils approximately 0.1 mm thick were subjected to a neutron flux of 10^{19} *nvt*, then deformed about 2%, and subsequently polished to a thickness of 1000 A and examined. Figure 1 is typical for the results obtained. The micrograph exhibits tangles of intricately kinked dislocations and dislocation loops with diameters between 50 A and a few hundred angstroms. This may be compared with a corresponding micro-

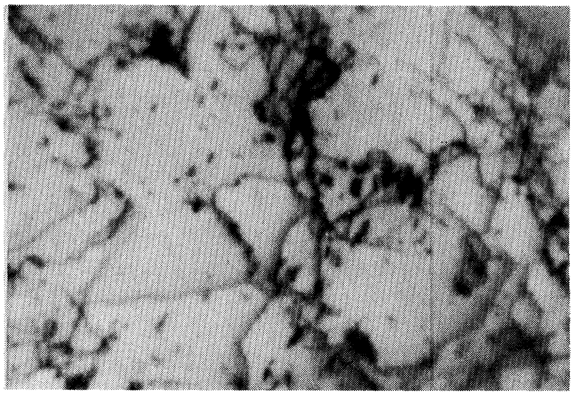

FIG. 1. Electron micrograph of irradiated nickel specimen (10^{19} *nvt*) deformed before thinning to 1000 A thickness. Lines represent dislocations, dark spots small dislocation loops. 40 000:1.

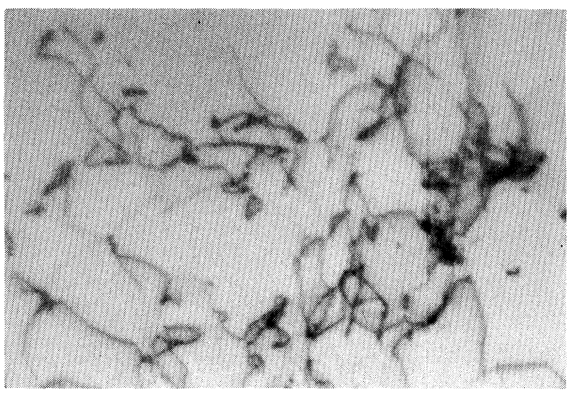

FIG. 2. Transmission micrograph of deformed non-irradiated speciman. 40 000:1.

graph of an unirradiated deformed specimen, Fig. 2, which shows a similar dislocation pattern but on a coarser scale, and practically no small dislocation loops as represented by the dark spots in Fig. 1.

The following interpretation of these findings is suggested. The vacancies produced through irradiation in 0.1-mm thick specimens form larger or smaller vacancy aggregates. On plastic deformation the first glide dislocations moving through the lattice cause the transformation of vacancies into condensed layers by a mechanism described elsewhere.[13] These loops are nucleated either in the neighborhood of dislocations, or in direct contact with them, in the latter case causing irregular kinks in the dislocation lines as visualized by Kimura, Maddin, and Kuhlmann-Wilsdorf for quenched-in vacancies in copper.[14] In this way numerous condensed loops are formed, distributed throughout the deformed specimen, and many kinkėd and intertwined dislocations. The greatly increased yield strength of irradiated nickel specimens at room temperature then is not directly caused by vacancies and vacancy clusters as present in the metal after irradiation but is due to the anchoring of the dislocations through loops and kinks nucleated at them. After their passage along a certain minimum number of slip planes, an appreciable portion of the excess vacancies will have been eliminated from the regions between these slip planes. Thus, paths will have been cleared for later dislocations which may originate from suitable loops or kinks, and consequently a low rate of work hardening may be expected for irradiated metals, as indeed has been observed.

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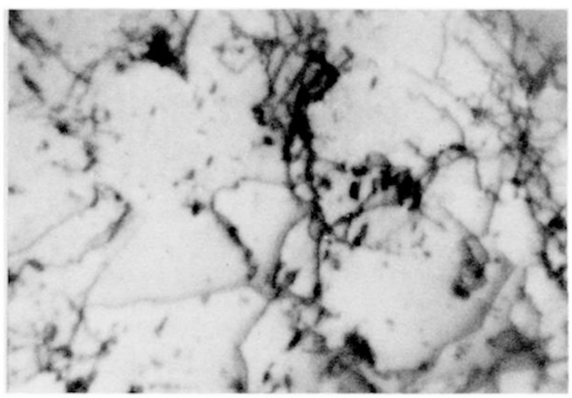

FIG. 1. Electron micrograph of irradiated nickel specimen (10^{19} *nvt*) deformed before thinning to 1000 A thickness. Lines represent dislocations, dark spots small dislocation loops. 40 000:1.

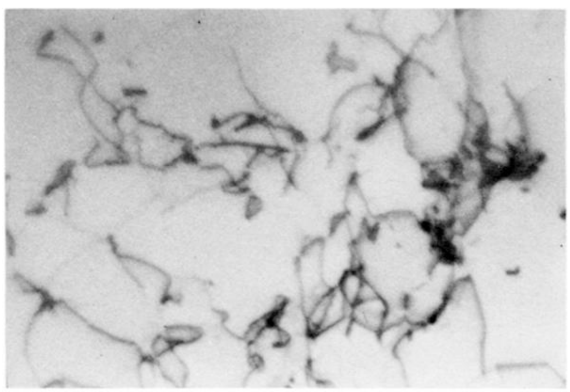

FIG. 2. Transmission micrograph of deformed non-irradiated speciman. 40 000:1.