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Impact of alloy composition on one-dimensional glide of small dislocation loops in concentrated solid solution alloys

Shi Shi[a,*], Hongbin Bei[b], Ian M. Robertson[a,c]

[a] Department of Engineering Physics, University of Wisconsin-Madison, Madison, WI 53706, USA
[b] Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[c] Department of Materials Science and Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA

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ABSTRACT

One-dimensional glide of loops during ion irradiation at 773 K in a series of Ni-containing concentrated solid solution alloys has been observed directly during experiments conducted inside a transmission electron microscope. It was found that the frequency of the oscillatory motion of the loop, the loop glide velocity as well as the loop jump distance were dependent on the composition of the alloy and the size of the loop. Loop glide was most common for small loops and occurred more frequently in the less complex alloys, being highest in Ni, then NiCo, NiFe and NiCoFeCr. No measurable loop glide occurred in the NiCoCr, NiCoFeCrMn and NiCoFeCrPd alloys.

1. Introduction

The evolution of the defect microstructures produced by irradiation is modified by the diffusion of interstitials and vacancies and clusters based on them. The small interstitial clusters produced by electron irradiation [1–7] as well as the vacancy clusters in Au [8] produced by quenching from elevated temperatures have been reported to undergo one-dimensional glide. The glide distance as well as the frequency of observation depends on the loop size, observation temperature, and alloy purity. Both the distance and the frequency decrease with increasing size of the dislocations loops [3,4], decreasing observation temperature, and impurity content of the material [1–3,9,10]. For example, interstitial loops in Fe with a diameter in the range of 20–30 nm have been reported to undergo one-dimensional glide at elevated temperature [11]. Interestingly, in this study it was reported that the Burgers vector of the dislocation loop could change, which enabled a change of the glide direction. Arakawa et al. compared the frequency of one-dimensional loop glide in Fe and Fe-9Cr alloy under 1 MeV electron irradiation as a function of temperature, 110–680 K, and on thermal annealing, 295–960 K [1]. They found that the presence of Cr had an insignificant effect on the frequency of one-dimensional glide during the electron irradiation at 390 K but reduced it on thermal annealing. The duality of the effect of the Cr was attributed to Cr-vacancy complexes being attracted to the interstitial loops such that the Cr was deposited on the loops whereas this did not occur during electron irradiation at 390 K. One-dimensional glide of interstitial loops produced by deuterium ion irradiation of a Fe-Cr-W alloy has been reported to occur at 400 K, and this was attributed to the deuterium on the loop causing a modification of the strain field [2].

In this paper, the loop mobility is revealed during 1 MeV ion irradiation at 773 K in a transmission electron microscope for different Ni-containing concentrated solid solution alloys. Specifically, the materials investigated included Ni, and alloys with each element being present in an equiatomic ratio: NiCo, NiFe, NiCoCr, NiCoFeCr, NiCoFeCrMn and NiCoFeCrPd. In these alloys, the elements themselves as well as the atomic size impact the local environment each ion experiences and, additionally, the atomic displacements mean that the lattices are actually FCC-like.

2. Experimental procedures

Face-centered cubic Ni-containing solid solution concentrated alloys were used. The alloy ingots were prepared by arc-melting together appropriate amounts of pure Nickel, Cobalt, Iron, Chromium, Manganese and Palladium (> 99.9% purity). These alloys were developed by Oak Ridge National Laboratory [12]. All but the five element alloys were [001] oriented single crystals, the five element alloys were polycrystalline with an average grain size of a few millimeters.

Thick disks were cut from the as-received material and polished mechanically to a thickness of 150 μm. Standard 3 mm disks were punched out from these disks and thinned to electron transparency using an electrolyte of 10% perchloric acid + 90% ethanol under the

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[*] Corresponding author.
E-mail address: sshi42@wisc.edu (S. Shi).

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following conditions: temperature = 253 K, voltage = 15 V, current = 40 mA.

The electron transparent foils were irradiated with 1 MeV Kr^{++} using the Intermediate Voltage Electron Microscope (IVEM) – Tandem facility at Argonne National Laboratory. The irradiation conditions were: dose rate ~ 1×10^{11} ion cm $^{-2}$ s $^{-1}$; dose ≤ 2 dpa; and temperature of 773 K. The sample was tilted 15° with respect to the electron beam such that the sample surface was normal to the ion beam. The accumulation of damage was monitored in real time with a capture rate of 15 frames per second. This enabled the motion of defects to be followed during the ion irradiation.

3. Results

Details of the accumulation of damage as a function of ion dose are reported elsewhere [13]. In summary, the accumulation of damage decreased in the following order Ni, NiCo, NiFe, NiCoCr, NiCoFeCr, NiCoFeCrMn and NiCoFeCrPd. It was also determined that the loop form was dependent on alloy composition as well as dose. Small loops are prevalent in all alloys, but larger elliptical perfect and Frank loops appear more commonly in the alloys at a lower dose than in pure Ni. In this case, neither the loop nature (i.e. interstitial or vacancy) nor the location of the loop within the electron transparent foil was determined.

In reviewing the movies captured during the accumulation of damage it was observed that some loops disappeared, others grew in size, and others oscillated between locations. The magnitude of the projected shift in position of a loop, the frequency of its oscillatory motion, and the loop glide velocity were dependent on the alloy composition and the size of the loop. Both the magnitude of the glide distance, the glide velocity as well as the oscillation frequency decreased with increasing alloy complexity and loop size. In the following figures, examples of loop glide in the different alloys are presented. To reveal the motion, a difference image was formed by superimposing a negative image of the initial position on a positive image of the final position. The resultant difference image shows weak contrast in regions in which no change has occurred, above background contrast for features that were present in the final image but absent in the initial image, and below background contrast for features present in the initial image and absent in the final image.

One-dimensional loop glide was observed most frequently in Ni and the glide distance was the largest. The series of weak-beam dark field images presented in Fig. 1 shows two examples of one-dimensional glide of a small (< 10 nm) dislocation loop in pure Ni. To make this loop shift easier to visualize, Fig. 1c and f were built by superimposing a negative image of the initial loop position on a positive image of the final position. The shift in both cases is evident in the difference image, which shows that the loops have moved projected distances of 8 nm and 67 nm, respectively. A section of the video capturing the motion of the loop shown in Fig. 1 is presented in the supplemental information, Video 1.

Larger loops, ones with a diameter ≥ 20 nm also exhibited one-dimensional glide, although the projected glide distance was significantly less than that for the smaller loops. An example of one-dimensional glide of a large loop is shown in Fig. 2. Here the projected loop glide distance is in the order of 5 nm; a section of the video showing the mobility of this large loop is provided in the supplemental material, Video 2.

An example of the oscillatory motion of a loop in Ni is shown in the series of time resolved images presented in Fig. 3; a section of the movie showing this oscillatory behavior is provided in the supplementary material, Video 3.. The motion of the loop in one direction is shown in Fig. 3a and b, with the positional shift revealed in the difference image presented in Fig. 3c; the arrow indicates the direction of motion. The loop glides a projected distance of 52 nm. The images presented in Fig. 3d and e show the loop moving in the opposite direction. Again, the difference image reveals the reverse motion more clearly and the arrow indicates the direction of motion. In this case, the reverse jump distance is only 8 nm. However, the loop may continue to move in this direction with time. The obstacle blocking the motion of this loop was not identified.

Loop glide was observed in the binary alloys and an example in the NiCo alloy is presented in Fig. 4. This example also shows that the glide direction is not necessarily restricted to a single direction but it can change direction; this change in glide direction was not a common observation. A section of the movie showing the glide direction changes is provided in the supplementary material, Video 4.. To illustrate the oscillatory motion as well as the change in glide direction, difference images were formed by superimposing a negative image of the initial position on a positive image of the final position and these are presented in Fig. 4f–i. The loop moves back and forth along respective arrow heads with a distance of 10, 8, 8 nm as in Fig. 4f–g, and in the

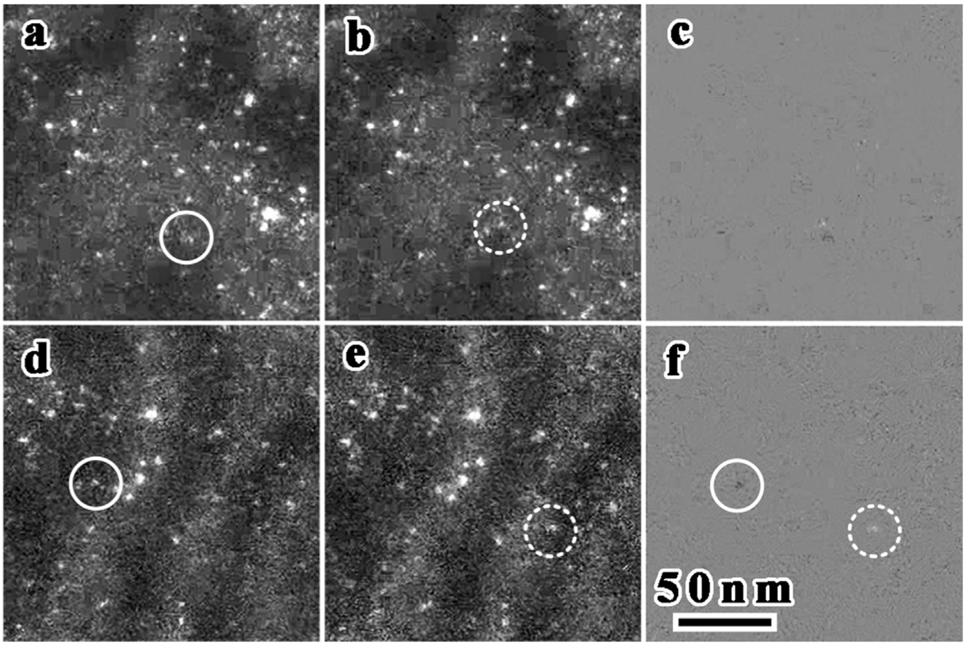

Fig. 1. Examples of one-dimensional glide of loops in Ni. a and b show the initial and final position of the loop and c shows a difference image created by superimposing a negative image of a on a positive image of b. d and e show the initial and final position of the loop, and f shows a difference image created by superimposing a negative image of d on a positive image of e.