EFFECTS OF IRRADIATION DAMAGE LEVELS ON ACTIVATION VOLUME AND DEFORMATION MECHANISMS IN IRRADIATED GOLD THIN FILMS USING IN SITU TEM STRAINING

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Abstract

The plastic deformation mechanisms of ultrafine grained gold thin films (average grain size of 150 nm) irradiated with 2.8 MeV Au+ ions at three different levels (0.1, 1 and 5 dpa) have been studied using quantitative *in-situ* transmission electron microscopy (TEM) nanomechanical testing. This technique allows for the simultaneous observation and comparison of the active deformation mechanisms, measurement of mechanical properties and true activation volume. Some of the observed deformation mechanisms include dislocation nucleation at grain boundaries (GB), dislocation pinning/de-pinning at irradiation induced defects, and stress-induced GB migration. During the early stages of deformation, dislocation nucleation and GB migration occur simultaneously. However, the dense populations of irradiation-induced defects prevent transgranular dislocation motion. As the deformation levels increase, GB migration leads to defect-free zones which then provide avenues for unimpeded dislocation glide. The true activation volume increases from ~10b^3 in unirradiated specimens, to ~22b^3 in irradiated specimens at 1dpa, for flow stresses ranging from 400 to 550 MPa. The experimentally measured activation volume values are compared with values determined from atomistic simulations (grain size ~10 nm) for different unit dislocation processes to determine the controlling deformation mechanism, using a framework based on Conrad's model. This model provides a Hall-Petch-type relationship of grain size dependent activation volume.

Results

This *in situ* TEM nanomechanical testing technique allows for simultaneous observation of the active deformation mechanisms and measurement of stress/strain and true activation volume V^*. Gold specimens were irradiated at room temperature at Sandia National Laboratory's Ion Beam Lab (IBL) with 2.8 MeV Au^{4+} ions at a fluence of 5.5×10^{13} ions cm^{-2} to ~0.1, 1 , and 5dpa (displacement per atom). The initial microstructure of the non-irradiated specimens (Fig. 1a) shows that the majority of grains are defect free, with a few of the largest grains containing lattice dislocations and/or twin boundaries. The initial microstructure of the irradiated specimens (at 1 dpa) is shown in Fig. 1b, where 'black-spot' radiation damage can be observed within all the grains. The radiation damage can be seen in more detail at higher magnification in Fig. 1c.

Fig. 1e shows the monotonic tensile stress-strain curves for a non-irradiated and irradiated specimen at a strain rate of 10^{-4} s^{-1}. The monotonic response of the irradiated specimen shows evidence of brittle behavior with a linear elastic stress increase followed by quick failure after the ultimate tensile strength (UTS) of 663 MPa. In contrast, the non-irradiated counterpart yields at ~480 MPa (0.2% offset) and reaches an UTS of 520 MPa, which is followed by a gradual decrease in stress and eventual failure at strain $\varepsilon = 6.7\%$.

Repeated stress-relaxation experiments have been conducted to measure the true activation volume V^* for both irradiated and non-irradiated specimens (Fig. 1e). Across all stress levels (200-600 MPa), V^* is larger for the irradiated specimens and exhibits a strong stress-dependence (decreasing V^* with increasing stress). At higher stress levels (σ > 400 MPa) once the stress-dependence is minimized, the average $V^* = 22 \pm 6\ \mathrm{b}^3$ for irradiated specimens. Non-irradiated specimens show only a slight stress dependence with an average V^* across all stress levels of $10 \pm 4\ \mathrm{b}^3$. The difference in sample-level activation volume is indicative of different governing mechanisms, which will be discussed in light of atomistic simulations and an existing model linking sample-level activation volume to intragrain and grain boundary mediated mechanisms.

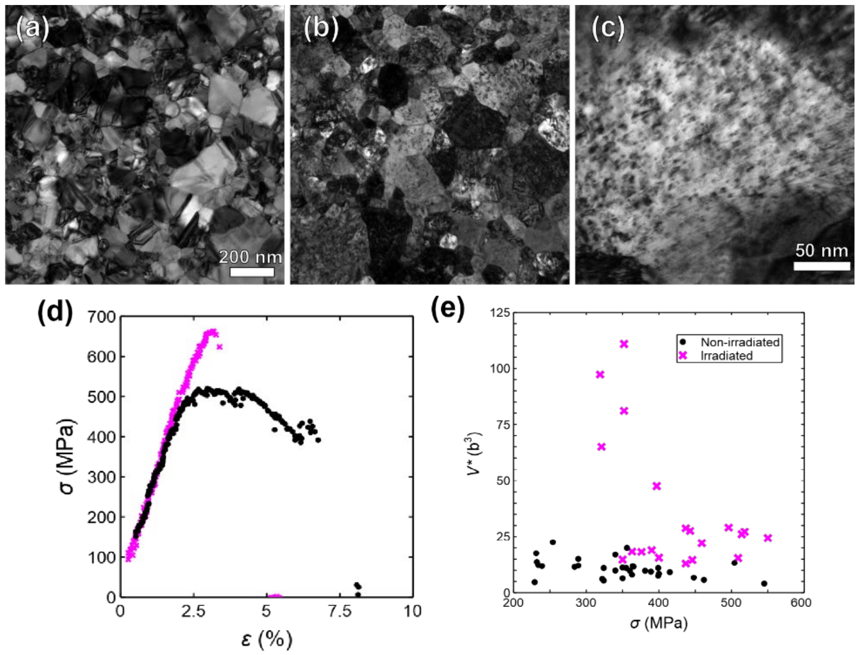

Fig. 1. Initial microstructure and tensile properties of irradiated and non-irradiated UFG Au films. TEM micrographs of (a) non-irradiated Au films and (b) irradiated Au film with most grain interiors contain 'black-spot' radiation damage. Scale bar is the same as in (a). (c) Bright-field TEM micrograph of a grain interior of irradiated film to exhibit radiation damage. (d) Stress-strain curves from in situ TEM tensile tests of non-irradiated (black circles) and irradiated (magenta crosses) specimens. Both were conducted at a strain rate of ~10^{-4} s^{-1}. (e) True activation volume measurements for multiple non-irradiated and irradiated specimens.

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