COMPARISON OF A MICROSTRUCTURE EVOLUTION MODEL WITH EXPERIMENTS ON IRRADIATED VANADIUM – S. Sharafat and N.M. Ghoniem (University of California at Los Angeles)

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Extended Abstract

Interaction of high-energy neutrons with fusion reactor materials will result in simultaneous production of displacement damage and helium atoms. Subsequent reactions between helium and defect clusters determine, to a large extent, most physical and mechanical properties of irradiated materials. Thus, microstructure evolution of neutron-irradiated BCC and FCC metals in the presence of helium has been the focus of research over the past 2 decades. Vanadium and its alloys are now considered as candidate structural materials in fusion reactors, because of their low neutron activation and high-temperature capabilities. Development of a mechanistic understanding for the influence of helium on microstructure evolution of irradiated vanadium can help in tailoring its microstructure by thermomechanical processes for maximum resistance to radiation damage. One of the main themes of current interest is the origin of the asymmetry in the flow of vacancies and interstitials to various microstructures. The asymmetry in vacancy/interstitial flow to microstructural features determines the rate of their evolution. In particular, the growth of voids in irradiated materials was explained in terms of an *"Absorption Bias (AB)"* of dislocations towards interstitials, thus leaving excess vacancies to flow into already nucleated voids. Recently, however, another form of asymmetry has been proposed, in which the fraction of free vacancies produced in collision cascades is higher than that of free interstitials. This type of *"Production Bias (PB)"* can also lead to cavity growth in irradiated materials, and when combined with *AB*, can explain qualitative differences in the swelling behavior of BCC and FCC metals. These arguments, however, are based on the notion that cavities have already nucleated in the material, and that their growth phase dominates subsequent evolution. In the presence of helium production, especially the high levels anticipated under fusion neutron conditions, this scenario might be incomplete. Continuous production of helium in the matrix can result in very long nucleation transients of bubbles. Under these conditions, separation of distinct nucleation and growth phases may not be so clear. During the process of bubble nucleation, helium is trapped in free vacancies to form substitutional sites, from which further agglomeration is possible. If helium production rates are large, the fraction of occupied vacancies, which are tied up with helium-vacancy complexes, can be quite substantial. Thus, the balance between free vacancy and interstitial fluxes arriving at those bubbles to allow their growth can be greatly disturbed by helium trapping. This physical scenario can result in an additional complication to the "bias" idea, in which continuous nucleation of helium bubbles can lead to another type of symmetry breaking for free point defects. We will label this effect as the *"Nucleation Bias (NB).*

A kinetic rate theory model, which includes helium generation and the formation of cascade-induced clusters (CIC), is presented. Comparison of the model to ion irradiation data on vanadium reveals the effects of helium generation and cascade-induced interstitial and vacancy clusters on microstructure evolution. The model includes rate equations for clustering of helium bubbles, immobile vacancy clusters, glissile interstitial clusters, sessile dislocation loops, as well as bubbles on precipitates and in grain boundaries. It is shown that helium transport to dislocations, bubbles and grain boundaries is strongly transient because of coupling between the nucleation and growth modes of bubble evolution. Helium agglomeration in vacancy clusters is shown to reduce the excess vacancy flux for growing matrix and precipitate-affixed bubbles. The direct formation of vacancy and interstitial clusters leads to enhanced nucleation of matrix bubbles, and a corresponding reduction of their growth rate. In addition to the dislocation and production bias mechanisms, a new mechanism of "helium nucleation bias" is shown to exist under high helium generation rates, and to lead to reasonable agreement with experiments. The present model for the evolution of bubble, dislocation and defect microstructure in irradiated vanadium reveals the delicate balance between rate processes, which control the speed of microstructure evolution. It is clear that bubble nucleation in irradiated vanadium under conditions of high helium generation rates evolves on a long time scale. Strong coupling between the nucleation and growth phases of the microstructure is achieved under these conditions. The presence of helium as additional specie to intrinsic point defects results in a reduction in the concentration of freely migrating vacancies. The growth rate of nucleated bubbles is thus reduced by this form of natural bias dictated by the presence of helium. Comparison with ion irradiation data shows the necessity to include the direct formation of CIC's in rate theory models, and the need to couple both nucleation and growth phenomena.