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Kinetics of evolution of radiation induced micro-damage in ductile materials subjected to time-dependent stresses

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ABSTRACT

The present paper aims at predicting evolution of radiation induced damage in the solids subjected to mechanical loads beyond the yield stress. Moreover, the evolution of radiation induced damage is combined with the evolution of mechanically induced damage within the common framework of Continuum Damage Mechanics (CDM). An additive formulation with respect to damage parameters (tensors) has been postulated. Multiscale constitutive model containing strong physical background related to the mechanism of generation of clusters of voids in the irradiated solids has been built. The model is based on the experimental estimation of concentration of lattice defects (interstitials, di-interstitials, interstitial clusters, vacancies, di-vacancies, vacancy clusters) in Al as a function of *dpa* (displacement per atom), and comprises the relevant kinetics of evolution of radiation induced damage under mechanical loads. Two kinetic laws of damage evolution were taken into account: the Rice & Tracey model and – for comparison – the Gurson model. As an application, estimation of lifetime of a cylindrical shell (coaxial target embedded in a detector of particles) subjected to combination of irradiation and mechanical loads, has been carried out. It is demonstrated that the number of cycles to failure depends strongly on the accumulation of micro-damage due to irradiation. The lifetime of irradiated components has been expressed as a function of two parameters: maximum *dpa* and axial stress amplitude on cycle.

1. Introduction

One of the crucial problems in design of particle detectors consists in taking account of degradation of material properties and failure of metal components as a result of intensive irradiation. A beam penetrating target produces the secondary particles flux that reaches detector components located in direct proximity of the target. The target-detector configuration is often characterized by coaxial configuration, comprising a cylindrical target aligned with the beam trajectory and a cylindrical thin-walled shell belonging to a magnetic lens called "horn". In such a configuration, high intensity secondary particles flux emitted by the target interacts with the shell causing evolution of local micro-damage fields and leading to inevitable failure of detector components. It is of vital importance to understand the mechanisms of production and evolution of micro-damage

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and to predict the lifetime of components exposed to pulsed irradiation combined with the mechanical loads, and this for a wide range of temperatures related to detector service conditions.

During irradiation, energetic particles penetrating a lattice displace the atoms from their original positions. Exposure to a flux of particles leads inevitably to creation of clusters of defects in the material, provided that the energy of incident particles is large enough. Such a process is often termed the "atomic displacement damage process" because the atoms are moved from their lattice positions to the neighborhood, thus becoming the interstitial atoms.

Thus, as a result of the cascade process, the pairs of interstitial atoms and vacancies (the so-called Frenkel pairs) are massively created (Fig. 1).

It is worth pointing out, that the vacancies making part of the Frenkel pairs often accumulate in clusters by means of diffusion. Each cluster may be qualified as a spherical or ellipsoidal void of the size of several nanometers. The elastic collisions with the lattice atoms (elastic scattering) are produced by heavy particles, such as the protons or the neutrons, carrying energies ranging from a few MeV to approximately 1 GeV. A group of such voids constitutes specific type of damage, coexisting in the material with the natural micro-damage of mechanical origin (Carroll et al., 2012; Li et al., 2012; Krasnikov et al., 2011). A relationship between the production of Frenkel pairs and the kinetic energy carried by primary knock-on atoms (PKAs) was for the first time described by Kinchin and Pease (K–P) (1955). This was one of the first theoretical assessments of the production of irradiation defects. On the basis of experimental results, the K–P approach was supplemented by Norgett et al. (1975) in order to calculate the number of atomic displacements produced in a damage cascade by a primary knock-on atom of known energy. It has been subsequently revised by Norgett et al. (1975) to work out a standard formula for the displacements per atom (*dpa*) in irradiated metals.

A short and comprehensive introduction to the physics of radiation damage has been presented by Ullmaier and Carsughi (1995). In particular, a classical definition of *dpa* has been formulated. The *dpa* number corresponds namely to stable displacement from their lattice sites of all atoms in the material during irradiation near absolute zero.

However, the problem of radiation induced damage requires deep insight from experimental, theoretical and computational points of view. It certainly belongs to the group of problems of multiscale nature, comprising the range from discrete atomic scale via micro- and meso, to the continuum macro scale. Multiscale models describing the accumulation of radiation induced damage and the corresponding effects on material microstructure were presented by Wirth et al. (2004). The atomic scale modelling (ASM) has been widely used to study the irradiation effects in metals (Bacon et al., 2000, 1999). The computational methods developed to investigate dynamics of dislocation–defect interactions were presented by Li et al. (2014) and Ghoniem et al. (2002). Another model for irradiated materials, using the internal variables formalism and coupling between mobile dislocation density and dislocation loops, was proposed by Pokor et al. (2004). The mechanism of radiation induced hardening was analyzed by Singh et al. (2002). Mathematical models that take into account the radiation induced damage as a function of the dose were developed and applied by Verbiest and Pattyn (1982). The radiation damage was expressed by the concentrations of interstitials, vacancies, di-interstitials, di-vacancies, as well as the cluster of interstitials and vacancies and their average sizes. The irradiation dose has been expressed in term of concentration of interstitials or vacancies created in the lattice. On the other hand, the recombination process has not been taken into account.

In order to calculate the critical void growth rates and the critical damage levels, the Gurson and the Rice & Tracey models were used by Pardoen et al. (1998) and Chen and Ghosh (2012). The Gurson model (1977), developed further by Needleman and Tvergaard (1984), is certainly more accurate in the case of porous materials. It incorporates well the mechanisms of nucleation and growth of voids under the hydrostatic stress.

Nahshon and Hutchinson (2008) proposed extension of the Gurson model in order to describe failure in shear. The extension retains isotropy of the original Gurson model and incorporates damage growth under low triaxiality straining for

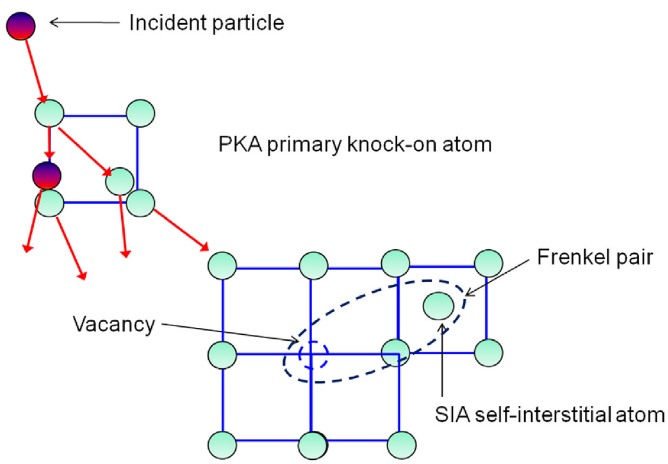

Fig. 1. Displacement cascade and formation of Frenkel pairs.