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MICRODAMAGE AND FRACTURE INITIATION IN THE MATERIALS SUBJECTED TO ION-IRRADIATION

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Summary In this work defects induced by ion-irradiation in the elastic-plastic materials are investigated by using the nano-indentation technique. Radiation induced damage level is expressed in terms of displacements per atom (dpa), afterwards, the radiation induced damage is defined in the framework of Continuum Damage Mechanics (CDM) to solve the problem of further evolution of damage fields under mechanical loads. The new mathematical relation between radiation damage (dpa) and porosity parameter is proposed. Deformation process experienced by the ion irradiated materials during the indentation test is then simulated by Gurson–Tvergaard–Needleman (GTN) model. Moreover, a novel material model with radiation induced damage based on nonlocal peridynamic theory is proposed to study of ion-irradiated materials. The peridynamic theory based on integro-differential equations without spatial derivatives is a powerful tool for the modelling of materials involving discontinuities. The conditions of fracture, the onset and the propagation of macro-crack are investigated.

INTRODUCTION

In general, radiation induced damage causes profound changes of the macroscopic response, reflected by progressive material degradation. Radiation damage creates the threats for structural components working under mechanical loads. Moreover, damage evolution causes degradation of mechanical properties and severely compromises the lifetime of structural components. Radiation-induced defects serve as strong obstacles to dislocation motion. Irradiation invariably renders a metal less ductile and leads to drastic modifications of mechanical properties, e.g., growth of porosity, fracture toughness and increase in yield stress. Depending on the degree of irradiation, fracture can have the brittle or ductile characteristics. A microcrack can rapidly propagate across the entire component, or it can occur as result of stress and or large plastic deformation.

IRRADIATION INDUCED POROSITY

The irradiation of metals by high energy particles leads to the interaction of energetic incident particles with lattice atoms. The pair of interstitial atom and vacancy in irradiated crystalline solids is known as the Frenkel defect. After the end of the collisional phase (cascade) the point defects (vacancies and interstitials) may migrate in the material leading to the formation of various forms of defect clusters: e.g. clusters of voids. In this way, the process of damage initiation is created. To evaluate radiation damage, a damage variable that characterizes the material degradation is required. Radiation induced damage level is expressed in terms of displacements per atom (dpa) parameter. The nature of radiation induced damage is close to porosity because of formation of clusters of vacancies. The porosity ξ of the material expressed by dpa function takes the form

$$\xi = q_c \frac{4}{3} \pi C (dpa)^n$$

where q_c is the density of vacancy clusters caused by irradiation, C and n are material parameters. The processes of the defects formation and initial clustering as well as the interaction between point defects which are the basis of the fracture are considered.

ELASTIC-PLASTIC DEFORMATION DURING INDENTATION

In the irradiated ductile materials, the plastic deformation is based on similar mechanisms like in the virgin materials. In particular, the main mechanism of plastic flow is still slip. However, due to the presence of radiation induced defects, like the groups of interstitial atoms or vacancy clusters containing impurities, strong hardening is usually observed. The motion of dislocations within the easy slip planes is hindered by numerous types of obstacles, causing substantial increase of the flow stress. The experimental characterization of the deformation process of the ion irradiated materials during the nano-indentation test is carried out (Fig.1).

a) b) c)

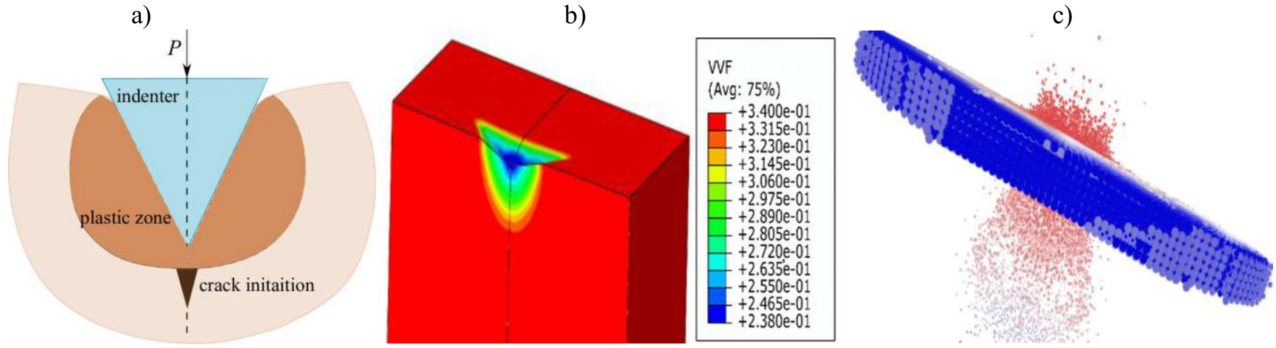

Figure 1. a) Indentation of an elastic-plastic solid by a rigid cone; b) Evolution of porosity in the damaged material subjected to indentation in the framework of CDM; c) Indentation test results of peridynamics simulation (PD)

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Afterwards, the radiation induced damage is defined in the framework of Continuum Damage Mechanics (CDM) and peridynamics theory (PD) to solve the problem of further evolution of damage fields under mechanical loads [1]. A novel material model based on nonlocal peridynamic theory is proposed to study of irradiated materials. The peridynamic theory is particularly powerful in modelling problems where spontaneous formation of discontinuities, like micro-damage, voids and cracks, occurs. Numerical simulation of indentation test results of PD is shown in Fig. 1c. Emphasis is placed on the macroscopic behaviour, like the evolution of damage and fracture through the plate.

ELASTIC-PLASTIC DAMAGE MODEL OF INDENTATION OF THE ION-IRRADIATED MATERIAL

The nature of radiation induced damage is close to porosity because of formation of clusters of vacancies and helium bubbles. For this reason, the models describing the porosity evolution appear most suitable. The kinetics of radiation induced damage involves essentially two models describing the evolution of porosity in the materials: the Gurson–Tvergaard–Needleman (GTN) model and - for comparison – the Rice and Tracey (R-T) model [2]. Both of them address the evolution of porosity in the form of spherical or ellipsoidal voids in a different way. GTN proposed a constitutive model of porous materials including the micro-voids. The porosity rate is controlled by the appropriate GTN yield function. Moreover, the GTN kinetics is accompanied by the yield surface that retracts in the course of increasing porosity. On the other hand, the R-T model predicts the evolution of radius of spherical void as a function of triaxiality and the plastic strain. The R-T model is expressed in the form of a differential equation and has, therefore, implicit character. Main drawback of the R-T model consists in the fact, that there is no full coupling between the plasticity and the damage. The reasons for which the GTN kinetics appears far better for the irradiated materials are as follows:

- the nature of radiation induced damage is close to porosity because of formation of clusters of voids, without generation of cracks,
- the GTN model represents a dilatational constitutive model based on the yield function formulated for a porous solid, with the volume fraction of voids reflecting randomly distributed spherical voids,
- the void growth in the GTN model is driven by the volumetric plastic strain rate, combined with type GTN yield surface,
- the current porosity value is computed and can be easily converted to damage parameter.

The numerically obtained loading-unloading curves were imposed on the experimental data in order to verify their consistence, both for the loading and for the unloading stages. The curves were corrected for the initial stage of the indentation process, where the indenter cuts through the surface layer and the hardware adjustment takes place (Fig. 2). Quite good agreement between the numerical and the experimental curves is obtained, which confirms validity of the GTN model.

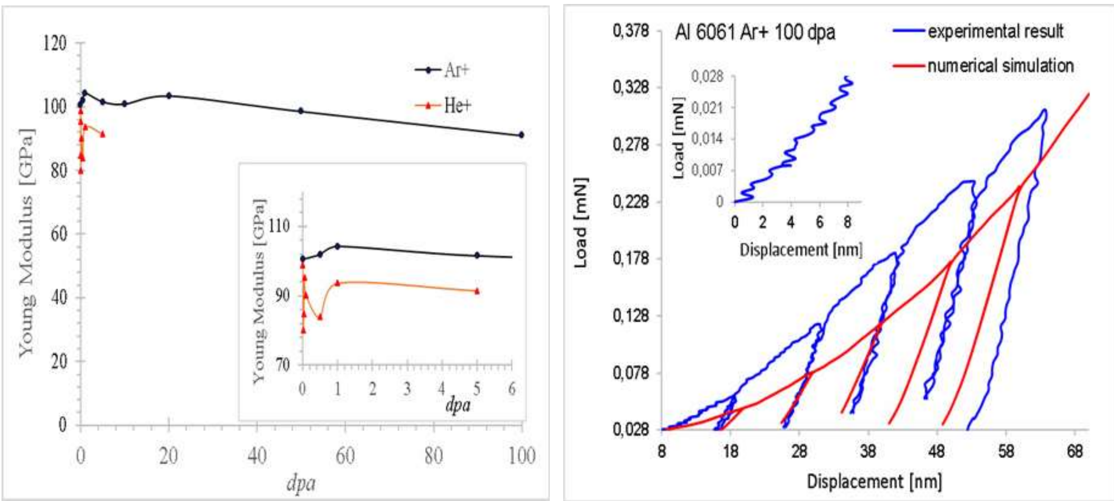

Figure 2. Young's modulus as a function of the irradiation dose; Load-indentation depth curves - experimental results and numerical simulations

THE ONSET OF FRACTURE AND THE MACROCRACK PROPAGATION

In view of the above model of irradiated elastic-plastic material, the conditions of fracture are to large extent determined by the radiation induced porosity. This phenomenon largely affects the conditions of the onset and the evolution of macrocrack, that depend on the level of irradiation (porosity). Therefore, the conditions of fracture, including the fracture toughness as well as the propagation of the micro-crack, are investigated. A criterion of the macro-crack initiation is proposed and implemented.

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