Journal of Nuclear Materials 399 (2010) 41–54

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Research on the interfacial behaviors of plate-type dispersion nuclear fuel elements

Qiming Wang, Xiaoqing Yan, Shurong Ding *, Yongzhong Huo

Department of Mechanics and Engineering Science, Fudan University, Shanghai 200433, China

ARTICLE INFO

Article history:
Received 21 July 2009
Accepted 1 January 2010

ABSTRACT

The three-dimensional constitutive relations are constructed, respectively, for the fuel particles, the metal matrix and the cladding of dispersion nuclear fuel elements, allowing for the effects of large deformation and thermal-elastoplasticity. According to the constitutive relations, the method of modeling their irradiation behaviors in ABAQUS is developed and validated. Numerical simulations of the interfacial performances between the fuel meat and the cladding are implemented with the developed finite element models for different micro-structures of the fuel meat. The research results indicate that: (1) the interfacial tensile stresses and shear stresses for some cases will increase with burnup, but the relative stresses will decrease with burnup for some micro-structures; (2) at the lower burnups, the interfacial stresses increase with the particle sizes and the particle volume fractions; however, it is not the case at the higher burnups; (3) the particle distribution characteristics distinctly affect the interfacial stresses, and the face-centered cubic case has the best interfacial performance of the three considered cases.

1. Introduction

Dispersion nuclear fuel elements are widely used in the research and test nuclear reactors because of their high thermal conductivity and high burnup, and they consist of fuel meat and cladding [1]. The fuel meats are similar to particle-reinforced composites in the configurations, distinguished by having a fissile material (such as compounds of uranium or plutonium) dispersed as small particles through a non-fissile matrix of metal, ceramic or graphite. The cladding is made of metal alloy [2,3], such as the aluminum alloy, the zircaloy or the stainless steel.

In the nuclear reactors, the dispersion nuclear fuel elements are subjected to complex loadings: (1) nuclear fissions in the fuel particles lead to heat generation within them, the generated heat is taken away by the flowing coolant water through heat exchanges mainly at the two plate surfaces and the steady-state temperature of the coolant water keeps about 573 K in pressurized-water reactors; (2) solid and gaseous fission products will induce fuel particle swelling; (3) the fission gases would migrate to the free volumes with rise of burnup, and they would form the bubble nucleus if caught by flaws, dislocation, and cavity on the grain boundary, then the bubbles would grow with absorption of the liberated fission gas [4]. The nuclear experiment [5] showed that the mini-flaws which were formed at the interface between the fuel meat and the cladding in the production of the nuclear fuel element would develop with the fuel swelling and fission gas release. Consequently, the interfacial facture or delamination between the fuel meat and the cladding is a typical damage form of the dispersion fuel element, in which the irradiation swelling and the fission gas release are the important factors. Furthermore, it was obtained by the nuclear experiment [6] that the interfacial mechanical performance of dispersion nuclear elements were intensely affected by the sizes, the volume fractions and the distribution forms of the fuel particles. Adding to the complexities mentioned above, the fuel particles might not be evenly distributed, which makes the structures of dispersion fuels very complicated and further increases the research difficulty.

Besides the experimental research, numerical simulation is becoming an important tool to explain the experimental results and carry out optimal design. Recently, the relative researches on the dispersion fuel plate with the finite element method (FEM) came forth and some specific codes for the thermal and thermal–mechanical analysis were developed and were being upgraded, including FASTDART [7,8], PLATE [9,10], MAIA [11,12] and DART-TM [13] and so on. In these studies, the dispersion fuel meat was generally treated as homogeneous and the modeling was two-dimensional, that is, the mutual actions between the fuel particles and the matrix, and the mutual actions among fuel particles were not taken into account. Van Duyn [14] studied the PuO_2–Zr dispersion rod-like fuel element with FEM, taking account of the distribution of the fuel particles more actually, while the simulation was relatively simple. Shurong Ding [15,16] studied the thermal and mechanical behaviors of the plate-type dispersion nuclear fuel element, but did not draw the actual cladding structure into consideration. And the study of the effects of the micro-structures on the thermal–mechanical behaviors and the interfacial behaviors is limited.

* Corresponding author.
E-mail address: dsr1971@163.com (S. Ding).

0022-3115/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2010.01.001

For the dispersion nuclear fuel plates, the thermal–mechanical behaviors of the fuel elements are induced by the high temperature differences between the steady-state temperature and the room temperature at the initial stage of burnup; and with increasing burnup, the irradiation swelling of the fuel particles will result in intense mechanical interaction between the fuel particles and the matrix. Thus, in numerical simulation of the in-pile mechanical behaviors of dispersion nuclear fuel elements, the effects of large deformation and thermal-elastoplasticity should be introduced in the used three-dimensional constitutive relations.

In this study, the three-dimensional constitutive relations are constructed, respectively, for the fuel particles, the metal matrix and the cladding, allowing for the effects of large deformation and thermal-elastoplasticity. According to the constitutive relations, the method of modeling the irradiation behaviors of dispersion nuclear fuel elements in ABAQUS is developed and it is validated through comparison of the obtained numerical results with the theoretical ones. Besides, considering the micro-structures of plate-type dispersion nuclear fuel elements, the three-dimensional Representative Volume Element is chosen to act as the research object, which might simulate not only the micro stress and strain fields but also the macro deformation along the thickness and the interfacial stresses between the fuel meat and the cladding. In order to clarify the cracking mechanism of the interface and carry out optimal design, numerical simulations of the interfacial mechanical behaviors induced by the irradiation swelling together with the thermal effects are performed with the developed finite element models for different micro-structures of the fuel meat (such as the particle size, the particle volume fraction and the particle distribution forms). And the effects of the micro-structures of the fuel meat on the interfacial stresses are investigated.

2. Development of the three-dimensional constitutive relations

At the initial stage of burnup, the thermal–mechanical behaviors are mainly induced by the high temperature differences. This will result in existence of plastic deformations at the metal matrix and cladding, however, the total deformations remain small. So, at this stage the thermal-elastoplastic constitutive behaviors for small deformation can be adopted for the metal matrix and the cladding, while the thermal-elastic constitutive relation is suitable for the fuel particles.

With increasing burnup, at higher burnups the relative volumetric variations of the particles due to the fission products can reach 20%. Then the mechanical interactions between the fuel particles and the matrix will be enhanced and large deformation can appear. In the three-dimensional constitutive relations for the fuel particles, the matrix and the cladding, finite strain forms should be considered. Besides, when the volumes of the fuel particles enlarge, the configuration of the fuel element will also change accordingly, for example, the plate thickness will increase. This will lead to variations of the heat transfer coefficient between the plate surface and the coolant water and variations of the temperatures within the fuel element. Based on the above reasons, the thermal strain component should be involved in the large-deformation constitutive relations.

For the fuel particles, the internal large strain is mainly induced by the swelling strain and the thermal strain; for the metal matrix or the cladding, their internal large strains mainly result from the plastic component and the thermal component. Therefore, the Prantle–Reuss theory [17] can still be used here. The total deformation rate within the fuel particle is assumed to be the sum of the elastic one, the swelling one and the thermal one; and the deformation rate within the metal matrix or the cladding is supposed to consist of the elastic one, the plastic one and the thermal one. The three-dimensional constitutive relations at higher burnups are deduced in this section; besides, the material parameters needed in the thermal–mechanical analysis are also given. Firstly, the empirical formulas for the particle swellings are given as follows.

2.1. The empirical formula for irradiation swelling of the fuel particles

The fuel particle swelling is usually characterized by the relative volume variations. A kind of swelling coefficient β_V can be introduced as the volumetric swelling rate by

$$SW(BU) = \frac{\Delta V}{V_0} = \int_0^{BU} \beta_V d(BU) \tag{1}$$

where V_0 is the reference volume, ΔV is the volume variation measured after a period of fission reactions. *BU* is called burnup with the unit % FIMA which is defined as the ratio of the number of the fissioned *U* atoms to the original number of *U* atoms, being widely used to characterize the extent of the fission reactions in the nuclear fuel.

The swelling rate β_V (swelling per % FIMA) has three contributions from the fission gas-bubbles β_V^{gs}, the solid fission products β_V^{ss} and the fission densification β_V^{ds}. Namely,

$$\beta_V = \beta_V^{gs} + \beta_V^{ss} + \beta_V^{ds} \tag{2}$$

All the swelling rates have been studied extensively in the literatures and are generally rather complicated. For our FEM calculations, the following simplified relations [18–20] for UO_2 in PWRs will be used.

$$\beta_V^{gs} = 1.122 \times 10^3 \exp(-1.645 \times 10^4/(T - 100)) \tag{3}$$

$$\beta_V^{ss} = 6.4 \times 10^{-3} \tag{4}$$

$$\beta_V^{ds} = -[0.51 \exp(-59.9 \times BU) + 4.76 \times 10^{-2} \exp(-10.07 \times BU)] \tag{5}$$

where *T* is the temperature in Kelvin. Note that β_V^{gs} is temperature-dependent and β_V^{ds} is burnup-dependent.

2.2. The three-dimensional constitutive relation for the fuel particles

Considering the temperature variation, the total deformation rate within the fuel particle is assumed to be the sum of the elastic one, the swelling one and the thermal one as

$$d_{kl} = d_{kl}^{e} + d_{kl}^{sw} + d_{kl}^{th} \tag{6}$$

where d_{kl}^{sw} is the swelling deformation rate. In fact, it is the instantaneous variation rate of the swelling true strain at the current configuration. Because the irradiation swelling only brings volumetric variation without shape changes, the swelling strain is similar to the thermal expansion strain for the isotropic material. That is, only the normal strain e^{sw} which is the same along all directions exists without the shear strain.

According to the definition of irradiation swelling as Eq. (1), the swelling at time *t* can be expressed as

$$SW(t) = SW[BU(t)] = \frac{\Delta V_t}{V_0} = \frac{V_t - V_0}{V_0} \tag{7}$$

Then the volume at time *t* is obtained as

$$V_t = [1 + SW(t)]V_0 \tag{8}$$

The variation rate of the absolute volume is

$$\dot{V}_t = \frac{dV_t}{dt} = \frac{dSW(t)V_0}{dt} = \frac{\partial SW(BU)}{\partial(BU)}\frac{dBU(t)}{dt}V_0 = \beta_V(BU)\cdot \dot{BU}\cdot V_0 \tag{9}$$