Mechanics of Materials 77 (2014) 14–27

Contents lists available at ScienceDirect

Mechanics of Materials

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

A new method to simulate the micro-thermo-mechanical behaviors evolution in dispersion nuclear fuel elements

Xin Gong [a], Yunmei Zhao [a], Shurong Ding [a,b,*]

[a] Department of Mechanics and Engineering Science, Fudan University, Shanghai 200433, China
[b] Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institution of China, Chengdu 610041, Sichuan, China

ARTICLE INFO

Article history:
Received 27 January 2014
Received in revised form 17 May 2014
Available online 24 June 2014

Keywords:
Dispersion nuclear fuel element
Incremental constitutive relations
Stress update algorithm
Irradiation effect
UMAT
UMATHT

ABSTRACT

The large-deformation constitutive relations and stress update algorithms in a co-rotational framework are formulated respectively for the fuel particles, the matrix and cladding in dispersion nuclear fuel elements undergoing irradiation, with the main irradiation-induced effects within them considered. Their specific consistent tangent stiffness moduli are also developed. Correspondingly, the user subroutines UMAT have been programmed for definition of their mechanical constitutive relations. Besides, the user subroutines UMATHT have been written to define their thermal constitutive relations, in which degradation of the thermal conductivity of fuel particles are involved. An efficient method is established for modeling the irradiation-induced micro-thermo-mechanical behaviors evolution in dispersion nuclear fuel elements. The developed methodology is validated with the simulation results of the thermo-mechanical behaviors in fuel elements under an assumed irradiation condition. This study lays a foundation for optimal design of dispersion fuel elements.

1. Introduction

A dispersion nuclear fuel element comprises of a dispersion nuclear fuel meat encapsulated in the alloy cladding, and in the composite meat the fissile fuel particles are dispersively distributed in the non-fissile matrix. Compared to the current nuclear fuel elements in the nuclear plants, the dispersion nuclear fuel elements (Holden, 1967; Neeft et al., 2003) can be subject to much higher burnup. They are widely used in the research and test reactors and have a promising prospect (Xu, 2003; Duyn, 2003; Lombardi et al., 2008) to be used in the advanced nuclear reactors and disposal of nuclear wastes. UMo/Al dispersion nuclear fuel plates (Kim and Hofman, 2011) have the potential to displace the highly-enriched Uranium fuel elements in the research and test reactors, because of their high density and stable irradiation performances. PuO_2/Zircaloy dispersion nuclear fuel rods (Duyn, 2003) were studied to be used in the commercial power water reactors in order to burn the weapons-grade or reactor-grade plutonium. Plate-type PuO_2/Zircaloy dispersion nuclear fuel elements should also be an alternative and are waiting to be studied. Dispersion fuels containing the minor Actinides (Ding et al., 2013) are the dedicated fuels in the future ADS systems.

The lifetime of dispersion nuclear fuel elements is directly related to the micro-structure of the fuel meat (Neeft et al., 2003; Duyn, 2003; Vatulin et al., 1999; Schram and Klaassen, 2007). It is of significance to investigate the effects of micro-structures of the fuel meat on the in-reactor performances of fuel elements. Owing to the fact that the irradiation experiments are of long time

* Corresponding author at: Department of Mechanics and Engineering Science, Fudan University, Shanghai 200433, China. Tel./fax: +86 021 65642587.
E-mail address: dsr1971@163.com (S. Ding).

http://dx.doi.org/10.1016/j.mechmat.2014.06.004
0167-6636/

with high cost and hard to be in situ examined, it is very necessary to develop the appropriate theoretical models and numerical simulation methods to assess the irradiation-induced behaviors and lifetime issues. Simulation research on the micro-scale irradiation behaviors in dispersion nuclear fuel elements was paid great attention (Meyer, 2001; Verwerft, 2007).

In the extreme irradiation environment of nuclear reactors, a dispersion nuclear fuel element experiences complex irradiation behaviors (Duyn, 2003; Suzuki and Saitou, 2005): (1) in the fuel particles fission heat is generated; the produced solid and gaseous fission products result in irradiation swelling, which leads to the strengthened mechanical interaction between the fuel particles, the matrix and cladding so that large deformation occurs within them; simultaneously, the thermal conductivity of fuel particles is degraded with burnup; (2) especially, the metal matrix and cladding undergo the irradiation damage effects (Rodriguez et al., 1984; Rowcliffe et al., 2009; Rodriguez and Fellow, 2005) induced by the high-energy fission fragments and fast neutrons, including the irradiation-hardening, irradiation creep and irradiation growth effects for Zircaloy (MATPRO-09, 1976). It is most critical to build the special thermal and mechanical constitutive relations considering the synergic irradiation effects within the fuel particles, the metal matrix and cladding.

For the in-reactor thermo-mechanical behaviors evolution in dispersion nuclear fuel elements, some new theoretical models and simulation methods have been found in the references Duyn (2003), Rest and Hofman (1999), Taboada et al. (2002), Saliba et al. (2003) and Marelle et al. (2004). In these studies, the constitutive relations for the nuclear fuels and the metal structural materials were simplified and should be improved with the irradiation effects involved. In our previous works, some simulation methods were developed. The irradiation hardening effect in the matrix and cladding and the irradiation growth effect in the cladding were gradually realized with the virtual temperature increase method (Ding et al., 2008, 2009; Wang et al., 2011; Jiang et al., 2011), where the irradiation-time dependant mechanical constitutive behaviors were regarded as the virtual temperature dependant behaviors. Because the real temperature variations after the initial stage were ignored, the simulation method were further improved (Gong et al., 2013) with several simple user subroutines in ABAQUS programmed for simulation of the irradiation swelling and degradation of the thermal conductivity in the fuel particles, irradiation hardening and creep effects in the matrix and cladding. For the heterogeneous irradiation condition (Kim and Hofman, 2011), the above simulation method is still inconvenient since the time–temperature-dependent Young's modulus of the metal matrix and cladding has to be discretized with the defined field variables. As in the references Roh and Bae (2010), Nanthikesan and Shyam Sunder (1995) and Mashayekhi et al. (2007), the special constitutive relations should be better to be defined in the user subroutines UMAT.

In this study, for the PuO_2/Zircaloy dispersion nuclear fuel elements, the stress update algorithms and the consistent tangent stiffness moduli are derived out based on the incremental constitutive relations for large deformation problems in the co-rotational reference frame (Andrade-Campos et al., 2006; Belytschko et al., 2000; Voyiadjis et al., 2006; Simo and Hughes, 1998; Ponthot, 2002), with the irradiation effects involved. Accordingly, the user subroutines UMAT are programmed to define the mechanical constitutive behaviors of the fuel particles, the matrix and cladding. And the user subroutines UMATTH are written to define their thermal constitutive behaviors, considering degradation of the thermal conductivity of fuel particles. The effectiveness of the subroutines is validated through the fem calculation results of an assumed plate-type element in the power water reactor.

2. The material models in an irradiation environment

As the material performances of PuO_2 are similar as the ones of UO_2 (Duyn, 2003), the thermo-mechanical properties of UO_2 are used to represent the ones of PuO_2 in this study.

2.1. The thermo-mechanical properties for fuel particles

2.1.1. Thermal conductivity

The thermal conductivity of UO_2 improved by Lucuta et al. (1996) consists of five contributions and can be expressed as

$$K_{UO2} = K_0 \cdot FD \cdot FP \cdot FM \cdot FR \tag{1}$$

where K_0 is Harding's expression for the thermal conductivity of unirradiated UO_2; FD quantifies the effect of dissolved fission products; FP describes the effect of precipitated solid fission products; FM is the modified Maxwell factor for the effect of the pore and fission-gas bubbles; FR characterizes the effect of radiation damage.

$$k_0 = \frac{1}{0.0375 + 2.165 \times 10^{-4} T} + \left[\frac{4.715 \times 10^9}{T^2}\right] \exp\left(-\frac{16361}{T}\right) \tag{2}$$

$$FD = \left[\frac{1.09}{B^{3.265}} + \frac{0.0643}{\sqrt{B}}\sqrt{T}\right] ar\tan\left[\frac{1}{\frac{1.09}{B^{3.265}} + \frac{0.0643}{\sqrt{B}}\sqrt{T}}\right] \tag{3}$$

$$FP = 1 + \left(\frac{0.019B}{3 - 0.019B}\right)\left[\frac{1}{1 + \exp\left(\frac{1200-T}{100}\right)}\right] \tag{4}$$

$$FM = \frac{1-P}{1+(s-1)P} \tag{5}$$

$$FR = 1 - \frac{0.2}{1 + \exp\left(\frac{T-900}{80}\right)} \tag{6}$$

where T represents the temperature in Kelvin, B is the burnup in at.%, P is the volume fraction of the pores and bubbles; s is the pore shape factor (with a value of 1.5 for spherical bubbles in the absence of other data).