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Simulation of the coupling behaviors of particle and matrix irradiation swelling and cladding irradiation growth of plate-type dispersion nuclear fuel elements

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ABSTRACT

Within plate-type dispersion nuclear fuel elements, besides irradiation swelling of fuel particles induced by nuclear fissions, the metal matrix and the cladding are attacked continuously by the fast neutrons released from the fuel particles. As a consequence, the matrix undergoes a bit irradiation swelling and the cladding takes on irradiation growth, which both might have remarkable effects upon the mechanical behaviors within fuel elements. In this paper, the three-dimensional large-strain constitutive relations for the fuel particles, the metal matrix and cladding are developed; based on them, the method of virtual temperature increase proposed by Ding et al. (2008) is further developed to model the irradiation swelling; the method of anisotropic thermal expansion is introduced to model irradiation growth of the cladding; and a method of multi-temperature-loadstep is proposed to simulate the coupling features of the irradiation swellings of both the metal matrix and the fuel particles together with the irradiation growth of the cladding. In order to clarify the critical factors that affect their mechanical performances and carry out optimal design, with the aid of the research thoughts of particle-reinforced composites, numerical simulations of the irradiation-induced mechanical behaviors are implemented with the finite element method in consideration of the micro-structure of the fuel meat. The obtained results indicate the effects of irradiation swelling of the matrix and irradiation growth of the cladding as that: (1) they might weaken the in-pile mechanical performances at the matrix to some extent; and (2) the former increases interfacial stresses between the fuel meat and the cladding, while the latter relatively relieve those interfacial stresses; and the interfacial mechanical strength might be improved by getting suitable irradiation growth mode of the cladding.

1. Introduction

The energy problem is becoming an urgent worldwide problem. The main energy resources at present are fossil fuel, including coal, petroleum and natural gas, which are non-renewable, and also give birth to tremendous greenhouse gases, such as CO_2, oxysulfide and oxynitride, which are responsible for the global warming and the acrid rain. In order to maintain a sustainable development, the new alternative energies are in great demand. Owing to the merit in environment friendliness and great power, the nuclear energy becomes a kind of feasible alternative energy. However, a great deal of nuclear wastes with high radioactivity will be generated in the nuclear reactors, which stems from the insufficient combustion of the internal nuclear fuels. For one thing, it is an enormous waste of energy; for another, great threats would be brought about. In order to make full use of the nuclear fuels and ensure nuclear safety, it is necessary to extend burnup of nuclear fuels and dispose of the nuclear wastes, especially the unirradiated U^{235} and Pu (e.g. Duyn, 2003) effectively.

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Dispersion nuclear fuel elements are composed of metal cladding and fuel meat, which is similar to a sandwich plate in the configuration; and the fuel meat is the same to the particle composite with the fuel particles dispersed within the metal matrix. As pointed out by Duyn (2003), owing to their high conductivity, the in-pile temperatures at the dispersion nuclear fuel elements are much lower than those at the traditional rod-like fuel elements and can achieve the high burnup goal. As a result, they are studied as an alternative to dispose of nuclear wastes. Moreover, the dispersion nuclear fuel elements have been widely used in the research and test reactors especially since the Reduced Enrichment for Research and Test Reactors (RERTR) program started in 1970s. This program has been tasked with the conversion of research reactors from high-enriched uranium (HEU) to low-enriched uranium (LEU) with a U^{235} content of less than 20%. In order to reach the requisite power density of the fuel element with low-enriched uranium, the needs to raise the density of the exiting fuels should be met. On account of the high uranium density (e.g. Duyn, 2003; Sinha et al., 2009), several kinds of dispersion fuel elements, such as the U_3Si_2 dispersion fuel, etc., are formally qualified for reactor usage and a good many research and test reactors have been converted to LEU fuels. And the related researches keep all the while, a number of irradiation tests (e.g. Huet et al., 2003, 2005; Ryu et al., 2003; Leenaers et al., 2004) are being carried out in order to improve performances of the current dispersion fuel elements.

The thermal and mechanical behaviors within dispersion nuclear fuel elements are very complex. At first, the nuclear fissions of the fuel particles produce tremendous fission heat resulting in the inhomogeneous temperature field within the fuel element. Also, the fuel particles bring about a lot of solid and gas fission products, which lead to irradiation swelling of the fuel particles. At the same time, irradiation experiment by Harbo-itle (1980) indicates that the metal matrix of the fuel element continually attacked by the fast neutrons released by the fuel particles undergoes relative irradiation swelling. Other irradiation experiments (e.g. Rogersom, 1988; Fidleris, 1988) show that the cladding of the fuel element, which is also attacked by the fast neutron, experiences obvious irradiation growth. These properties might greatly influence the in-pile mechanical performances of dispersion nuclear fuel elements, and thus lead to the bubbling, damage and fracture of the elements. In order to assess the lifetime of the dispersion fuel elements and optimize their microstructures, the effects of the above-mentioned irradiation effects on their in-pile mechanical behaviors should be investigated and evaluated.

It is a fact that the experimental researches of dispersion fuel elements are so time-consuming and costly that it is impossible to carry out tests for all kinds of parameters in optimal design. So, besides the relative experimental researches, as revealed by Snelgrove et al. (1997), the numerical simulations are playing a more and more important role in explaining the experiment results and in the optimal design. Recently, the relative researches on the dispersion fuel plate with the finite element method (FEM) appeared and some specific codes for the thermal and thermal–mechanical analysis were developed and were being upgraded, including FASTDART (e.g. Taboada et al., 2002; Rest, 1995), PLATE (e.g. Hayes et al., 2002, 2003), MAIA (e.g. Marelle et al., 2004, 2007) and DART-TM (e.g. Saliba et al., 2003) and so on. In these studies, the dispersion fuel meats were generally treated as homogeneous and the modeling was two-dimensional, that is, the interactions between the fuel particles and the matrix, and the interactions among fuel particles are not taken into account. Böning and Petry (2009) simulated the irradiation swelling of the full-sized U_3Si_2–Al fuel plate, whose meat was regarded as a homogeneous one, revealing that the dispersion fuel plate with only about 20% volume fraction presented a remarkable swelling ratio.

Furthermore, it was obtained by the nuclear experiment of Oh et al. (2006) that the in-pile mechanical performances of dispersion nuclear fuel elements were intensely affected by the micro-structures of the fuel meat. And thus, the interactions between the fuel particles and the metal matrix should be considered in order to optimize the fuel meat. Duyn (2003) 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 in-pile mechanical behaviors were simplified. Ding et al. (2008, 2009) studied the thermal and mechanical behaviors of the plate-type dispersion nuclear fuel elements with considering the interactions between the fuel particles and the metal matrix, but the actual cladding structure is not drawn into consideration. Ding et al. (2010), Wang et al. (2010a,b,c) further studied the in-pile mechanical performances with allowing for the mechanical interactions between the fuel meat and the cladding, while without taking account of irradiation swelling of the metal matrix and irradiation growth of the metal cladding.

In this study, with the aid of the research thoughts of particle-reinforced composites, the three-dimensional representative volume element (RVE) is chosen to act as the research object, which could model the in-pile stress–strain fields together with macro-deformation along the thickness. Apart from the irradiation swelling of the fuel particles, the irradiation swelling of the matrix together with the irradiation growth of the cladding are taken into account. Considering the above irradiation effects, the large-strain constitutive relations for the fuel particle, the metal matrix and cladding are developed, respectively. Based on the deduced three-dimensional constitutive relations, the flexible methods are put forward to model simultaneously the multi-type irradiation effects in the commercial software-ANSYS. The effects of irradiation swelling of the matrix and irradiation growth of cladding with burnup are investigated.

2. The material models

This study is conducted on one kind of typical dispersion fuel element, with an alloy cladding and a meat with the fuel particles being dispersively embedded in a metal matrix. Owing to the easy acquirement of the material parameters of uranium dioxide (UO_2) and zircalloy, UO_2 and zircalloy are set as the materials for the fuel particles and metal matrix (and the cladding), respectively.