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A numerical method for simulating the non-homogeneous irradiation effects in full-sized dispersion nuclear fuel plates

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ABSTRACT

For full-sized dispersion nuclear fuel plates under heterogeneous irradiation conditions, the three-dimensional large deformation incremental constitutive relations and stress update algorithms are built for the homogenized fuel meat and cladding in the co-rotational coordinate frame with a location-dependent irradiation-hardening effect in the cladding involved. The user subroutines to define the location-dependent thermo-mechanical constitutive relations are correspondingly developed and validated. Numerical simulation of the thermo-mechanical behaviors in a non-uniformly irradiated fuel plate is correctly realized. The obtained results indicate that (1) both the volumetric swelling and temperature distributions show remarkable non-uniform characters; (2) the maximum thickness variation appears in the strongly irradiated location at lower burnup, and it is not the case at higher burnup; (3) at the initial stage a stress concentration area in the cladding exists in the constrained plate corner; and with increasing burnup the highest Mises stresses exist at the locations with an enhanced irradiation condition.

1. Introduction

Plate-type dispersion nuclear fuel elements [1] are composed of metal cladding and a composite fuel meat with a certain volume fraction of fuel particles embedded in a non-fissionable metal matrix. Compared to the presently used nuclear fuel elements in the nuclear plants, they have a higher thermal conductivity and thus can achieve higher burnup, which makes them have a promising usage in the advanced nuclear reactors and disposal of nuclear wastes.

The thermo-mechanical behavior's evolution of nuclear fuel elements and assembly in an irradiation environment is one of the mostly concerned issues in their practical design. Recent researches on the thermo-mechanical behaviors in dispersion fuel elements with the finite element method (FEM) have become a development trend, and the numerical simulation method is expected to be an important way for their optimal design. Some finite element codes, such as FASTDART [2,3], PLATE [4,5], MAIA [6,7] and DART-TM [8], were developed with the attempt to study their thermal and thermal–mechanical behaviors. Van Duyn [9] treated the rod-like dispersion fuel pellet as a composite and established a three-dimensional model with the mutual interaction between the particles and matrix considered. Shurong Ding et al. [10,11] studied the thermal and mechanical behaviors and Qiming Wang et al. [12] studied the interfacial behaviors of the plate-type dispersion nuclear fuel elements based on the representative volume element (RVE) method. Marelle et al. [13] used a 2-D model to calculate the thermal–mechanical behaviors in UMo dispersion nuclear plates with the fuel meat treated as a homogeneous material, and it was pointed out that the mechanical calculation should be optimized with the constitutive laws improved.

In the demanding environment of nuclear reactors, irradiation swelling occurs in the nuclear fuel particles to result in large deformation in the fuel plate [14], and the thermal conductivity of fuel particles is degraded due to nuclear fissions; the metal materials within fuel elements experience irradiation damage effects due to being attacked by fast neutrons, such as irradiation hardening and creep [15]. Besides, a full-sized dispersion nuclear fuel plate is non-uniformly irradiated in a reactor core, with the neutron flux different in varied locations. Thus, the irradiation damage effects in the cladding are heterogeneous owing to the non-homogeneous distribution of fast neutrons. The heat generation rate as well as irradiation-induced swelling in the fuel particles is also location-dependent. The resultant temperature–time–location-dependent thermo-mechanical performances should be well taken into account in order to simulate the thermo-mechanical behavior's evolution in a full-sized fuel plate. An effective simulation method to allow for un-uniform irradiation conditions is waiting to be developed with the irradiation damage effects in the cladding considered.

In order to implement simulation of the irradiation-induced thermo-mechanical behavior's evolution in full-sized dispersion nuclear plates, it is critical to establish the three-dimensional constitutive relations with the above-mentioned irradiation effects

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involved. To achieve objectivity in large deformation problems, the three-dimensional constitutive relations and stress update algorithms are more convenient to be formulated in the co-rotational framework [16–18]. For some complex material constitutive relations, the corresponding stress update algorithms were able to be successfully built and implemented in ABAQUS with the user material subroutine UMAT [19–24]. The three-dimensional stress update algorithms suitable for nuclear materials can be similarly developed and performed in fem calculations.

In this study, based on micromechanics, an equivalent fuel meat is obtained with the homogenized thermo-mechanical material properties related to the ones of fuel particles and metal matrix. With the thermo-elastic and irradiation swelling effects in the equivalent fuel meat, and with the thermo-elasto-plastic and irradiation hardening behaviors included in the metal cladding, the respective three-dimensional thermo-mechanical constitutive relations and stress update methods are constructed. Assuming that the heat generation rate and fast neutron flux along the plate length direction are cosine-distributed with the maximums appearing in the middle location, a numerical simulation method is implemented through self-defined FORTRAN subroutines in ABAQUS. The material points have been given different constitutive relations according to their current temperatures, burnup and locations. The proposed numerical method is validated and the un-uniform thermo-mechanical fields are obtained and analyzed.

2. Material properties

In order to simulate the thermo-mechanical behavior's evolution in a full-sized fuel plate, the composite fuel meat is homogenized as an equivalent one without considering the interactions between the fuel particles and metal matrix, as illustrated in Fig. 1. In the following sections, the used material models for the cladding and the equivalent fuel meat are given.

2.1. The thermo-mechanical parameters of the Zircaloy cladding

(1) Thermal conductivity [25]

$$k = 7.51 + 2.09 \times 10^{-2}T - 1.45 \times 10^{-5}T^2 + 7.67 \times 10^{-9}T^3 \quad (1)$$

where k in W/m K is the thermal conductivity and T in K denotes the temperature.

(2) Thermal expansion coefficient [25]

The coefficient of thermal expansion is set at $5.58 \times 10^{-6}/K$ and the application range of temperature is from 273 K to 1500 K.

(3) Young's modulus and Poisson's ratio

Fisher model [26] is adopted to get the elastic parameters expressed as

$$E = [9.9 \times 10^5 - 566.9 \times (T - 273.15)] \times 9.8067 \times 10^4 \quad (2)$$

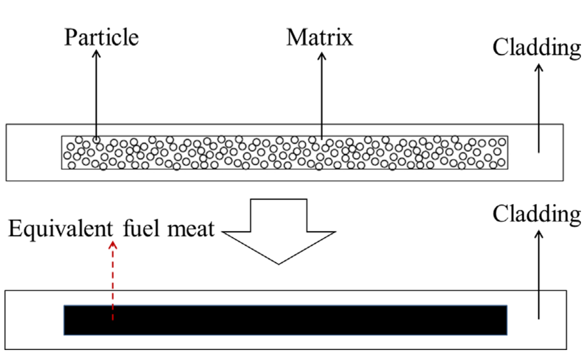

Fig. 1. Cross section of a dispersion nuclear fuel plate.

$$\nu = 0.3303 + 8.376 \times 10^{-5}(T - 273.15) \quad (3)$$

where E in Pa is Young's modulus and ν is Poisson's ratio, T represents temperature in K. Attacked by the fast neutrons in the reactor core, the Zircaloy cladding will experience an irradiation hardening effect. The expression of Young's modulus is revised as

$$E = [9.9 \times 10^5 - 566.9 \times (T - 273.15)] \times 9.8067 \times 10^4 / k_1 \quad (4)$$

$$k_1 = 0.88 + 0.12\exp\left(-\frac{\phi \cdot t}{10^{25}}\right) \quad (5)$$

where $\phi \cdot t$denotes the fast neutron fluence in n/m^2.

(4) The irradiation hardening plasticity model

The strain–hardening curve of unirradiated Zircaloy is described as [27]

$$\sigma = K\varepsilon^n\left(\frac{\dot{\varepsilon}}{10^{-3}}\right)^m \quad (6)$$

where σ in Pa is the true stress, ε is the true strain and $\dot{\varepsilon}$ is the true strain rate. If $\dot{\varepsilon} < 10^{-5}/s$, set $\dot{\varepsilon} = 10^{-5}/s$. The parameters K, n and m in Eq. (6) separately denote the strength coefficient, strain-hardening exponent and strain rate sensitivity exponent, respectively. Their expressions are given as

$$K = 1.17628 \times 10^9 + T(4.54859 \times 10^5 + T(-3.28185 \times 10^3 + 1.72752T)) \quad (7)$$

$$n = -9.49 \times 10^{-2} + T(1.165 \times 10^{-3} + T(-1.992 \times 10^{-6} + 9.588 \times 10^{-10}T)) \quad (8)$$

$$m = 0.02 \quad (9)$$

where T is the temperature in K ranging from 300 K to 730 K.

Due to the irradiation hardening effect, the strain hardening exponent is described by multiplying the coefficient k_2 given as

$$k_2 = 1.369 + 0.032 \times 10^{-25}\phi \cdot t \quad (10)$$

The strength coefficient under irradiation is given by adding the value as

$$k_3 = 5.54 \times 10^{-18}\phi \cdot t \quad (11)$$

In Eqs. (10)–(11), $\phi \cdot t$ is the fast neutron fluence in n/m^2; ϕ is the fast neutron flux, which is location-dependent due to the heterogeneous irradiation condition in this study.

2.2. The thermo-mechanical parameters of the equivalent fuel meat

The fuel meat is treated as a kind of particle composite with the particle volume fraction denoted as V_f. The homogenization theory [28–31] and the mean field model [32] have been adopted to determine its effective thermo-mechanical parameters as follows:

(1) Thermal conductivity

According to the mean field model by Maxwell [32], the conductivity of the equivalent meat $k(T, t, X)$ can be described as

$$k(T, t, X) = \frac{k_m(2k_m + k_p - 2V_f(k_m - k_p))}{2k_m + k_p + V_f(k_m - k_p)} \quad (12)$$

where k_m and k_p separately represent the conductivity of the matrix and the particles used in Ref. [21], and k_m decreases with irradiation time induced by the internal accumulated fission products.

(2) Thermal expansion coefficient

$$\alpha_c(T) = 5.84 \times 10^{-6} + 1.9 \times 10^{-7}$$