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A mechanical constitutive model for the equivalent solid of fission gas bubbles in irradiated U-10Mo fuels

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Abstract: The internal pressure within fission gas bubbles (FGBs) in irradiated nuclear fuels drives mechanical interactions with the surrounding fuel skeleton. To investigate the micromechanical stress fields in irradiated nuclear fuels containing pressurized FGBs, a mechanical constitutive model for the equivalent solid of FGBs is developed and validated. This model is based on the modified Van der Waals equation, incorporating the effects of surface tension. Using this model, the micromechanical fields in irradiated U-10Mo fuels with randomly distributed FGBs are calculated during uniaxial tensile testing via the finite element (FE) method. The macroscopic elastic constants of the irradiated U-10Mo fuels are then derived using homogenization theory, and the influences of bubble pressure, bubble size, and porosity on these constants are examined. The key findings are as follows: (1) Adjacent FGBs exhibit mechanical interactions, which leads to distinct stress concentrations in the surrounding fuel skeleton; (2) The macroscopic elastic constants of irradiated U-10Mo fuels decrease with increasing macroscopic porosity, which can be quantitatively described with the Mori-Tanaka model. In contrast, bubble pressure and size have negligible effects on these constants. These results provide valuable insights into the micromechanical behavior of irradiated nuclear fuels and aid in further predicting of their mechanical performance under irradiation.

Key words: effective mechanical constitutive model; fission gas bubbles; finite element method; U-10Mo nuclear fuels, macroscopic elastic constants

During irradiation in reactors, both solid and gaseous products are generated in nuclear fuels through the fission process. Among these products, fission gases are of particular concern due to their significant impact on fuel performance. They induce changes in the microstructure, physical properties, stress fields, and swelling deformations of nuclear fuels [1-6]. On average, one fission gas atom (xenon or krypton) is produced for every four fission events [7,8]. These fission gas atoms tend to form fission gas bubbles (FGBs) due to their low solubility in the nuclear fuel matrix [9]. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) studies have revealed that FGBs are distributed both within the grains (intra-granular) and along the grain boundaries (inter-granular) of the nuclear fuel [10,11]. Meanwhile, the density of inter-granular bubbles evolves with burnup, and micrometer-sized FGBs are randomly distributed throughout the grains in high-burnup fuels [12].

The formation and growth of FGBs transform irradiated nuclear fuels into porous structures, thereby degrading their macroscopic thermal conductivity

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and elastic modulus. The evolution of these macroscopic properties can be described as functions of the macroscopic porosity of the irradiated fuels [2,3,9,13]. As FGBs become filled with fission gas atoms, internal bubble pressure develops within the bubbles. In irradiated U-Mo fuels, this bubble pressure ranges from several MPa to hundreds of MPa [14]. The pressure is determined by the temperature, volume of the FGBs, and the number of fission gas atoms, as described by the modified Van der Waals equation [15-18]. These pressurized FGBs mechanically interact with the surrounding solid fuel matrix and are also constrained by the surface tension of the bubbles [3,4].

In models of fission gas swelling, bubble pressure is typically expressed as the sum of surface tension and the macroscale hydrostatic pressure of the homogenized porous fuels [17,18]. However, the equivalent spherical shell model [18], which is based on a single bubble, cannot precisely capture the complex mechanical fields in irradiated fuels with numerous FGBs, although it can be used to estimate macroscale swelling strains. To address this limitation, X. Cao et al. [4] developed a pore pressure model for FGBs in UO_2 fuels, considering pore size characteristics and burnup conditions. They established a 2D finite element model of the fuel particle with non-uniformly distributed FGBs to calculate the stress fields in high-burnup UO_2 fuels. In their studies, bubble pressure was applied as a load boundary condition on the bubble surfaces within the UO_2 particle. However, this applied pressure remained constant and did not vary with the deformation of the fuel skeleton or the FGBs. To better reflect the relationship between bubble pressure and the deformations of the FGBs, it is necessary to develop an effective mechanical constitutive model for the FGBs. Jiang et al. [19] proposed a method for 3D simulation of internal gas effects on thermal-mechanical behaviors in nuclear fuel elements. In their approach, the internal gas volume was represented by an equivalent solid with a constant elastic modulus. However, this model does not satisfy the modified Van der Waals equation, which describes the relationship between the variation in pressure and the internal gas volume.

In this study, a mechanical constitutive model for the equivalent solid of FGBs is derived based on the modified Van der Waals equation, incorporating the effect of surface tension. Using this model, the mechanical response of the FGBs and the interaction between the FGBs and the surrounding fuel skeleton under varying external loads are calculated. Finite element simulations of uniaxial tensile tests are performed on irradiated U-10Mo fuels containing pressurized FGBs. The macroscopic elastic constants of these fuels are then determined using homogenization theory, based on the microscopic mechanical fields within the FGBs and the U-10Mo fuel skeleton. The effects of bubble pressure, bubble size, and porosity on the macroscopic elastic constants are systematically investigated. Additionally, the calculated macroscopic elastic constants are compared with the experimental data in reference and results from other theoretical models to validate the applicability of the proposed mechanical constitutive model for FGBs.

1 The effective mechanical constitutive model for the FGBs

Spherical models are generally used to describe the geometry of the FGBs [4,6,18,20]. The force analysis for a spherical fission gas bubble is shown in Fig.1. The constraint pressure of the surrounding fuel skeleton, bubble pressure, and surface tension satisfy the force balance equation as

$$P_b = P_s + \frac{2\gamma}{R} \tag{1}$$

where P_b is the current bubble pressure; γ is the surface tension of the fission gas bubble; R is the bubble radius; P_s is the constraint pressure exerted by the surrounding fuel skeleton, also termed as the effective hydrostatic pressure of the fission gas bubble in this study, which is the actual pressure subjected to the surrounding fuel skeleton.

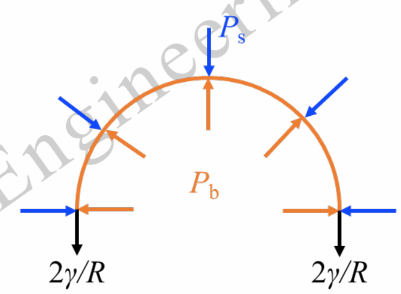

Fig.1 The force analysis of the fission gas bubble

According to the modified Van der Waals equation [5,17], the bubble pressure is determined by the temperature, the number of fission gas atoms, and the volume of fission gas bubble as

$$P_b\left(V - h_s b_v N\right) = NkT \tag{2}$$

where V is the bubble volume, with $V = 4\pi R^3/3$; N is the number of fission gas atoms in the fission gas bubble; k is the Boltzmann constant; b_v is the Van der Waals constant for Xe gas; h_s is the fitting parameter according to the hard sphere model.

In this study, a fission gas bubble (FGB) is modeled as an equivalent solid with the goal of developing an effective mechanical constitutive equation that describes the mechanical interactions between the FGBs and the surrounding fuel matrix. For given values of temperature and the number of fission gas atoms, it is necessary to establish the relationship between the volume change and the bubble pressure variation. According to the modified Van der Waals equation, the ratio of the current bubble volume V to the initial bubble volume V_0 can be expressed as

$$\frac{V}{V_0} = \frac{NkT/P_b + h_s b_v N}{N_0 kT_0/P_{b0} + h_s b_v N_0} \tag{3}$$

where P_{b0}, N_0 and T_0 denote the initial bubble pressure, the number of fission gas atoms and the temperature before the volume changes.

The volume ratio can also be expressed as a function of the volumetric strain as

$$\frac{V}{V_0} = e^{\varepsilon_{kk}} \tag{4}$$

where ε_{kk} depicts the first invariant of the logarithmic strain tensor, which refers to the volumetric strain relative to the reference configuration.

Combining Eq. (3) and Eq. (4), the current bubble pressure can be obtained as

$$\begin{aligned} P_\text{b} &= \frac{NkT}{e^{\varepsilon_{kk}}\left(N_0 kT_0 / P_{\text{b}0} + N_0 h_s b_v\right) - h_s b_v N} \\ &= \frac{c_1}{e^{\varepsilon_{kk}} c_2 - c_3} \end{aligned} \tag{5}$$

where $c_1 = NkT$; $c_2 = N_0 kT_0 / P_{\text{b}0} + N_0 h_s b_v$; $c_3 = N h_s b_v$.

According to Eq. (1) and Eq. (5), the effective hydrostatic pressure of the fission gas bubble is expressed as

$$P_\text{s} = \frac{c_1}{e^{\varepsilon_{kk}} c_2 - c_3} - \frac{2\gamma}{R_0 e^{\frac{1}{3}\varepsilon_{kk}}} \tag{6}$$

Thus, the effective mechanical constitutive equation for the equivalent solid of FGB is developed as

$$\sigma_{ij} = -P_\text{s}\delta_{ij} = \left(-\frac{c_1}{e^{\varepsilon_{kk}} c_2 - c_3} + \frac{2\gamma}{R_0 e^{\frac{1}{3}\varepsilon_{kk}}}\right)\delta_{ij} \tag{7}$$

For a given time increment, the stresses at the end can be calculated using the initial configuration as the reference one. Here, the volumetric strain represents the incremental strain relative to the initial state.

To compute the mechanical response of the equivalent solid for the FGBs using the FE method, the consistent stiffness modulus $D_{ijkl} = \frac{\partial \sigma_{ij}}{\partial \varepsilon_{kl}}$ is needed for the equilibrium iteration. According to Eq. (7), the corresponding consistent stiffness modulus can be derived as

$$D_{ijkl}^{g} = \left[\frac{c_1 c_2 e^{\varepsilon_{mm}}}{\left(e^{\varepsilon_{mm}} c_2 - c_3\right)^2} - \frac{2\gamma e^{\frac{1}{3}\varepsilon_{mm}}}{3R_0 e^{\frac{2}{3}\varepsilon_{mm}}}\right]\delta_{ij}\delta_{kl} \tag{8}$$

2 Verification of the effective mechanical constitutive equation for the equivalent solid of FGBs

The mechanical constitutive equation for the equivalent solid of FGBs, derived based on the modified Van der Waals equation and the effect of surface tension, provides a foundation for numerically calculating the thermo-mechanical behaviors in porous nuclear fuels. To validate the established constitutive equation, a spherical model containing the fission gas bubble and the U-10Mo fuel skeleton is constructed to simulate the mechanical response under the external pressure. Given the geometric and loading symmetry, 1/8 of the spherical model is selected as the finite element (FE) model, as shown in Fig. 2. The model is discretized into 96,876 elements using the C3D8R element type. Symmetric boundary conditions are applied to the surfaces at x=0, y=0, and z=0, which correspond to the symmetric planes of the 1/8 spherical model. An external pressure is applied to the outer surface of the model. Based on Ref. [14], the initial bubble pressure and bubble radius are set as 50 MPa and 0.2 μm, respectively. The volume fraction of the fission gas bubble f_b is set as 10%. The temperature and the number of fission gas atoms in the FE model are assumed to remain constant during the application of the external pressure. The FE simulation is performed using the commercial software ABAQUS, with the mechanical constitutive equation for the equivalent solid of FGBs implemented via a user-defined subroutine UMAT.

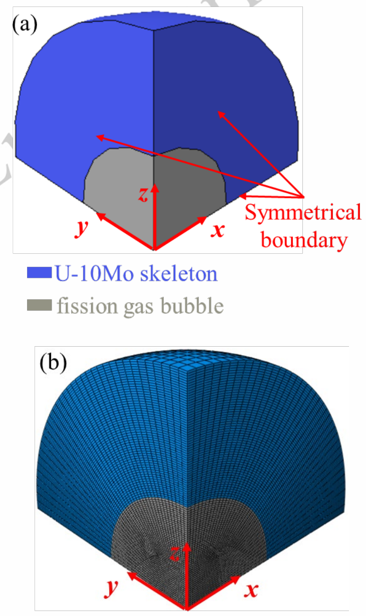

Fig.2 Diagrams of (a) the FE model containing the equivalent solid of fission gas bubble and the U-10Mo skeleton (b) the mesh grid

The hydrostatic pressure results of the FE model with the pressured fission gas bubble are shown in Fig. 3. The effective hydrostatic pressure of the fission gas bubble is approximately 40 MPa, which is lower than the initial bubble pressure of 50 MPa. This difference is attributed to the constraint effect of surface tension on the fission gas bubble. For a fission gas bubble with a radius of 0.2 μm, the equivalent constraint pressure due to surface tension is approximately 10 MPa, considering a surface tension γ of 1 N/m [17]. It should be mentioned that the initial effective pressure of the gas bubble is introduced into the equivalent solid as the initial stresses. It can be seen from Fig. 3 that the equivalent solid of the gas bubble exhibits mechanical interaction with the surrounding fuel skeleton even before the application of external pressure, as a result of the mechanical equilibrium that must be maintained. The hydrostatic pressures in the surrounding fuel skeleton are the same as those under the effective pressures applied to the inner surface of the shell model, as obtained with the analytical solutions in Ref. [13]. It is demonstrated that the effects of bubble pressure on the surrounding fuel skeleton can be effectively captured by the stresses in the equivalent solid of FGBs.

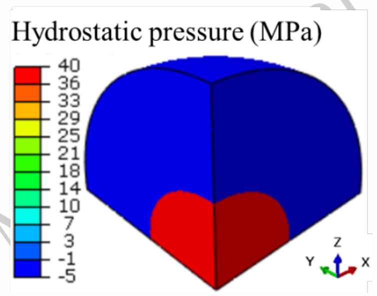

Fig.3 The contour plots of the hydrostatic pressure in FE model with the pressured fission gas bubble before applying the external pressure

While applying external pressure to the spherical model containing the fission gas bubble, both the volume of the model and that of the fission gas bubble decrease. It is known that the bubble pressure should vary with the volume of the fission gas bubble in accordance with the modified Van der Waals equation. Fig. 4 presents the evolution of bubble pressure with the volume of the fission gas bubble, calculated using both the FE method and the modified Van der Waals equation. The current volume of the fission gas bubble is calculated as $V_0 e^{\varepsilon_{kk}}$, and the FE results of bubble pressure are calculated as $\frac{1}{3}\sigma_{kk}+\frac{2\gamma}{R_0 e^{\varepsilon_{kk}/3}}$. As shown in Fig. 4, the evolution of bubble pressure calculated using the FE method aligns well with that predicted by the modified Van der Waals equation, thereby verifying the reliability of the established mechanical constitutive equations for the equivalent solid of FGBs.

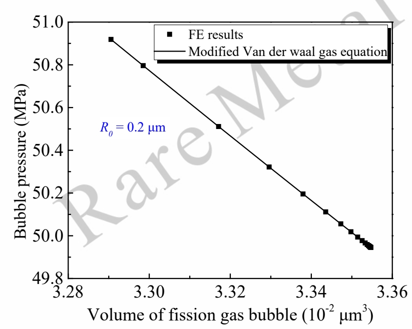

Fig.4 The comparison of the bubble pressure evolution results along with the volume of the fission gas bubble calculated by FE method and the modified Van der Waals equation respectively, while applying the external pressure

3 Calculation of the macroscopic elastic constants of irradiated U-10Mo fuels using the proposed mechanical constitutive model for the equivalent solid of FGBs

Macroscale elastic constants (homogenized elastic constants) are key material properties of porous nuclear fuels, directly influencing their mechanical interactions with the cladding in fuel elements. During irradiation, these elastic constants degrade with increasing macroscopic porosity [3,13]. The uniaxial tensile test is a standard method for measuring the macroscopic elastic constants of materials [21]. Therefore, a uniaxial tensile FE simulation based on a representative volume element (RVE) with randomly distributed FGBs in the U-10Mo fuel skeleton is performed, as shown in Fig. 5. The FGBs are assumed to have identical bubble radii and bubble pressures. To implement the uniaxial tensile test, periodic displacement boundary conditions are applied to the opposite surfaces of the RVE to account for its geometric asymmetry. Displacement constraints are applied to nodes numbered 0, 1, 2, and 3 to restrict rigid body movement and rotation of the RVE. The uniaxial tensile simulation is performed at a fixed temperature of 373 K, and the number of fission gas atoms is assumed to remain unchanged during the tensile process in this study.

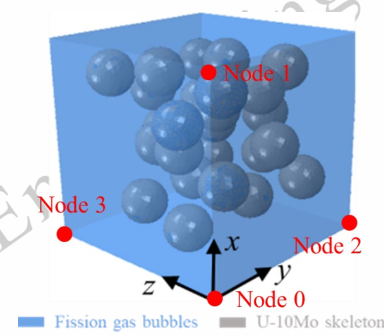

Fig.5 The RVE of irradiated U-10Mo fuels with randomly distributed FGBs

According to the homogenization theory, the macroscopic Young's modulus is expressed as

$$\bar{E}=\frac{\bar{\sigma}_x}{\bar{\varepsilon}_x} \tag{9}$$

where $\bar{\sigma}_x$ and $\bar{\varepsilon}_x$ are the effective stress and strain components in the x direction (the tensile direction).

The macroscopic Poisson's ratio is calculated as

$$\bar{\mu}=-\frac{1}{2}\left(\frac{\bar{\varepsilon}_y}{\bar{\varepsilon}_x}+\frac{\bar{\varepsilon}_z}{\bar{\varepsilon}_x}\right) \tag{10}$$

where $\bar{\varepsilon}_y$ and $\bar{\varepsilon}_z$ are the effective strain components in the y and z directions, which are perpendicular to the tensile direction.

The effective stress and strain components are the volume-averaged results of the U-10Mo fuel skeleton and the equivalent solid of FGBs. The effective strain component in the x direction is obtained by

$$\bar{\varepsilon}_x=\frac{\sum_{i=1}^{n_\mathrm{m}}\varepsilon_{x,i}^{\mathrm{m}}V_i^{\mathrm{m}}+\sum_{j=1}^{n_\mathrm{b}}\varepsilon_{x,j}^{\mathrm{b}}V_j^{\mathrm{b}}}{\sum_{i=1}^{n_\mathrm{m}}V_i^{\mathrm{m}}+\sum_{j=1}^{n_\mathrm{b}}V_j^{\mathrm{b}}} \tag{11}$$

where n_m and n_b are the number of the integration points for all the elements of U-10Mo skeleton and the equivalent solid of FGBs respectively; $\varepsilon_{x,i}^{\mathrm{m}}$ and $\varepsilon_{x,j}^{\mathrm{b}}$ are the strain components along the x direction for the *ith* integration point of the U-10Mo skeleton and the *jth* integration point for the equivalent solid of FGBs, respectively; V_i^{m} and V_i^{b} are the volume of the *ith* integration point for the U-10Mo skeleton and that of the *jth* integration point for the equivalent solid of FGBs, respectively. The other effective stress and strain components are calculated similarly.

A representative case with an initial bubble pressure of 50 MPa, a bubble radius of 0.2 μm, and a porosity of 15% for the FGBs is selected to analyze the stress field results of irradiated U-10Mo fuels during the uniaxial tensile test. The von Mises stress contour plots on the cross-section in the tensile direction, both before and after loading, are shown in Fig. 6. Even in the absence of external loading, a non-uniform distribution of von Mises stress exists within the fuel skeleton, as illustrated in Fig. 6(a). This uneven stress distribution arises from the effects of the stresses in the equivalent solid of the FGBs. Regions with a higher density of FGBs exhibit elevated von Mises stress due to the interactions between adjacent bubbles. The von Mises stress within the FGBs themselves is zero, as shown in Fig. 6. This indicates that the stress tensors in the equivalent solid of FGBs are spherical ones, representing the effective pressures of FGBs. Upon the application of external loading, the von Mises stress in the U-10Mo fuel skeleton evolves continuously, as depicted in Fig. 6(b).

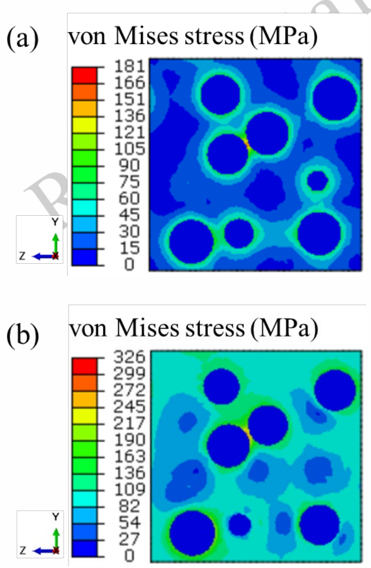

Fig.6 The contour plots of the von Mises stress on the cross section in the x direction of the RVE (a) before loading and (b) after loading

The macroscopic Young's modulus is derived from the stress-strain curve of the uniaxial tensile test, based on the slope in the elastic region. Fig. 7 presents the effective stress-strain curve of the RVE in the tensile direction during the uniaxial tensile process. It is evident that the effective strain of the RVE increases linearly with effective stress. According to Eq. (9), the calculated macroscopic Young's modulus of the RVE is ~63 GPa, which is lower than the Young's modulus of dense U-10Mo fuel before irradiation (~85 GPa). The effective stress component of the RVE in the tensile direction starts at zero, as shown in Fig. 7. This indicates that the effective stress component of the RVE is zero before the external load is applied, despite the non-uniform microscopic stress field within the RVE. This suggests that the stress field is self-balanced inside the RVE prior to the application of the external load.

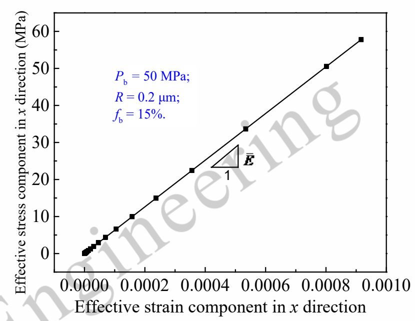

Fig.7 The effective stress-strain curve of the RVE in the tensile direction during loading

Fig. 8 presents the evolution of the effective strain components in the y and z directions relative to the effective strain component in the x direction of the RVE. As the effective strain in the x direction increases, the effective strain components in the y and z directions decrease linearly, a behavior attributed to the Poisson effect. The trends of the effective strain components in the y and z directions are nearly identical. According to Eq. (10), the calculated macroscopic Poisson's ratio of the RVE is ~0.316, which is lower than that of the dense U-10Mo fuel before irradiation (~0.34).

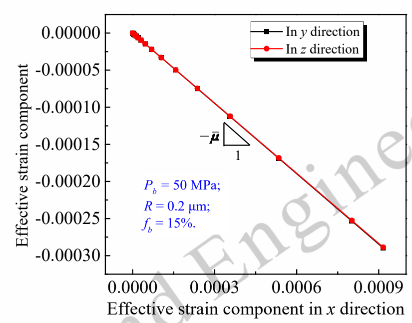

Fig.8 The evolution curve of the effective strain in the y and z directions versus the effective strain in the x direction during loading

The volume fraction of FGBs inside irradiated U-10Mo fuels increases with irradiation exposure. The bubble pressure and size of the FGBs also vary with the local state histories of the irradiated U-10Mo fuels, such as local temperature, hydrostatic pressure, and grain size. According to the study of Li et al.[13], the macroscopic elastic constants of irradiated U-10Mo fuels can be described with the Mori-Tanaka model based on the average volume fraction of inter-granular bubbles. However, the effects of bubble pressure and bubble size on the macroscopic elastic constants of irradiated U-10Mo fuels were not discussed in their study due to limitations in modeling FGBs. In their approach, FGBs were modeled as solids with a small constant elastic modulus, thereby excluding the effects of bubble pressure and surface tension of the FGBs. Based on the proposed mechanical constitutive equation for the equivalent solid of FGBs in this study, the macroscopic elastic constants of irradiated U-10Mo fuels with different bubble pressures, sizes, and volume fractions of FGBs are further investigated through simulations of the uniaxial tensile test.

Fig. 9 shows the macroscopic elastic constants of irradiated U-10Mo fuels with varying bubble pressures and volume fractions of FGBs. The bubble pressure ranges from 20 to 120 MPa, while the volume fractions of FGBs vary from 5% to 25%, with a constant bubble radius of 0.2 μm. The macroscopic elastic constants calculated using the FE method are compared with those obtained from the Mori-Tanaka model and experimental data [3]. It can be noted that the macroscopic elastic constants of irradiated U-10Mo fuels are similar across different bubble pressures, indicating that bubble pressure has a negligible effect on these constants. The results calculated by the FE method, based on the proposed mechanical constitutive equation for the equivalent solid of FGBs, are in good agreement with those from the Mori-Tanaka model and experimental data.

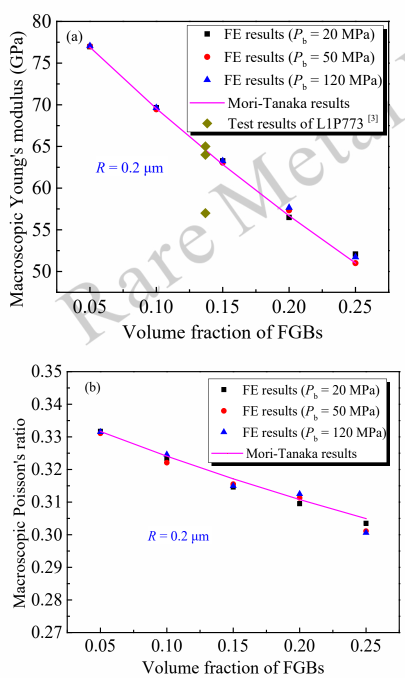

Fig.9 The macroscopic elastic constants of irradiated U-10Mo fuels with different bubble pressure and volume fractions of FGBs (a) macroscopic Young's modulus and (b) macroscopic Poisson's ratio

Fig. 10 shows the macroscopic elastic constants of irradiated U-10Mo fuels with different sizes and volume fractions of FGBs. The uniform bubble radius ranges from 0.1 to 1 μm, while the bubble pressure is held constant at 40 MPa. The results indicate that bubble size also has negligible effects on the macroscopic elastic constants of irradiated U-10Mo fuels. The effective elastic constants calculated by FE simulation for fuels with different bubble sizes and volume fractions are consistent with those obtained from the Mori-Tanaka model and experimental data.

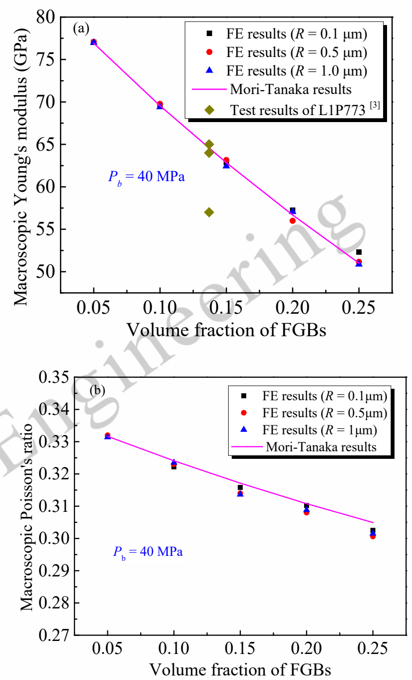

Fig.10 The macroscopic elastic constants of irradiated U-10Mo fuels with different sizes and volume fractions of FGBs (a) macroscopic Young's modulus and (b) macroscopic Poisson's ratio

4 Discussion

Fig. 11 shows the contour plots of radial stress in the surrounding fuel skeleton before the application of external pressure. It can be seen that the radial stress in the fuel skeleton adjacent to the fission gas bubble is equal to the hydrostatic stress (negative hydrostatic pressure) of the equivalent solid of the fission gas bubble. The radial stress in the surrounding fuel skeleton decreases with increasing distance from the fission gas bubble. To accurately capture the evolving mechanical interaction between the fuel skeleton and the fission gas bubbles under changing irradiation conditions and stress fields, it is essential to establish a mechanical constitutive model for the equivalent solid of FGBs.

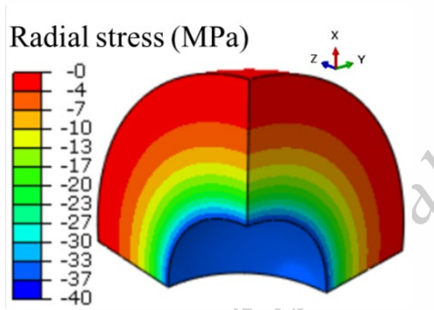

Fig.11 The contour plots of radial stress of the surrounding fuel skeleton before the application of external pressure

According to the homogenization theory, the effective stress components in the x-direction of the RVE in Fig. 5 can be expressed as $\bar{\sigma}_x = (1-f_b)\bar{\sigma}_x^m + f_b\bar{\sigma}_x^b$. The components $\bar{\sigma}_x$, $\bar{\sigma}_x^m$ and $\bar{\sigma}_x^b$ correspond to the effective stresses for the RVE, the fuel skeleton and the equivalent solid of FGBs, respectively. Fig. 12 illustrates the evolution results of $\bar{\sigma}_x$, $\bar{\sigma}_x^m$ and $\bar{\sigma}_x^b$ throughout the uniaxial tensile process. The FGBs are initialized with a volume fraction of 15%, an average bubble pressure of 50 MPa, and a radius of 0.2 μm. As shown in Fig.12, before applying the external tensile stress, $\bar{\sigma}_x^m$ is ~ 7 MPa, whereas $\bar{\sigma}_x^b$ is -40 MPa. The zero value of $\bar{\sigma}_x$ demonstrates that the compressive stress contribution from the equivalent solid of FGBs is balanced by the tensile stress contribution from the fuel skeleton. During the tensile process, both $\bar{\sigma}_x^m$ and $\bar{\sigma}_x^m$ increase linearly with the effective strain in the tensile direction of the RVE, while $\bar{\sigma}_x^b$ remains substantially unchanged. Similar trends in the evolution of $\bar{\sigma}_x$ are observed for the cases with different average pressures and radii of FGBs. This indicates that the U-10Mo fuel skeleton is the primary load-bearing component under external tensile stress. The variation in $\bar{\sigma}_x$ is predominantly influenced by $\bar{\sigma}_x^m$ and the macroscopic porosity, rather than the average bubble pressure and radius of the FGBs. Thus, it can be concluded that the macroscopic elastic constants of irradiated U-10Mo fuels are primarily determined by the elastic properties of the U-10Mo fuel skeleton and the macroscopic porosity. This finding emphasizes the critical influence of the fuel skeleton on the overall mechanical response of irradiated nuclear fuel.

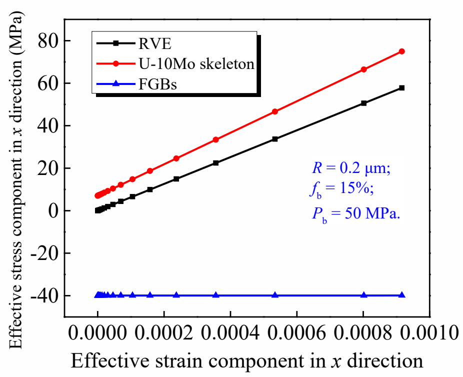

Fig.12 The contour plots of radial stress of the surrounding fuel skeleton before the application the external pressure

It is important to note that the volume change of the FGBs due to the elastic deformation of the U-10Mo fuel matrix is minimal. The primary mechanisms contributing to the growth of FGBs involve plastic deformation and creep deformation of the fuel skeleton [5,22], corresponding to the microscale vacancy diffusion and dislocation motion. When accounting for the time-integration effects of creep deformation during irradiation, the increase in the number of fission gas atoms within the FGBs must also be considered. From Eq. (5), it is known that the variations of the number of fission gas atoms [17,23,24] and temperature can also be taken into account. Consequently, the developed mechanical constitutive model for the equivalent solid of FGBs can also be utilized in thermo-mechanical coupling analyses during prolonged irradiation. This application will offer a more comprehensive understanding of bubble growth behavior and the underlying mechanisms driving this growth.

5 Conclusion

In this study, an effective mechanical constitutive model for the equivalent solid of FGBs in irradiated nuclear fuels is derived based on the modified Van der Waals equation, considering the surface tension effect. Three-dimensional FE simulations of uniaxial tensile tests for irradiated U-10Mo fuels are performed to obtain the macroscopic elastic constants, incorporating the established effective mechanical constitutive model. The main conclusions are as follows:

(1) The bubble pressure induces non-uniform stress fields in the fuel skeleton, even in the absence of external loading. The maximum von Mises stress is prone to appear in the regions with closely spaced bubbles due to stress interactions between adjacent FGBs.

(2) The macroscopic elastic constants of irradiated U-10Mo fuels are found to be minimally affected by bubble pressure and bubble size; instead, they are predominantly determined by the macroscopic porosity. This dependency aligns with the predictions of the Mori-Tanaka model.

The proposed effective mechanical constitutive model for the equivalent solid of FGBs provides a method to calculate the micromechanical fields inside irradiated nuclear fuels with pressured FGBs. This model can also be utilized in the thermo-mechanical coupling analyses for nuclear fuels during irradiation. Such analyses are crucial for predicting the long-term performance of nuclear fuels and ensuring their safety and reliability in nuclear reactors.

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辐照后的 U-10Mo 燃料裂变气泡的等效固体力学本构模型

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摘　要：辐照后的核燃料裂变气泡存在内压，导致周围的燃料骨架内部产生应力。为了计算含压裂变气泡所引起的辐照后核燃料的微观力学场，本研究基于修正的范德华方程，考虑气泡的表面张力效应，建立并验证了裂变气泡的等效固体力学本构模型。将裂变气泡等效为固体，建立了含随机分布裂变气泡的辐照 U-10Mo 燃料的有限元模型，基于所发展的等效固体力学本构模型、算法及程序，对辐照后燃料的单轴拉伸试验过程进行了有限元模拟，获得了微观力学场的分布及演化结果。根据均匀化理论，获得了辐照 U-10Mo 燃料的宏观弹性常数，并研究了气泡压力、气泡尺寸和孔隙率对宏观弹性常数的影响。研究发现：（1）相邻的裂变气泡之间存在力学相互作用，导致周围骨架产生局部应力集中；（2）辐照后 U-10Mo 燃料的宏观弹性常数随宏观孔隙率的增加而减小，两者之间的定量关系可以采用 Mori-Tanaka 模型描述；气泡压力和尺寸对宏观弹性常数的影响可以忽略。本研究为辐照后核燃料的微观力学行为、进一步预测其在堆内辐照工况下的力学行为提供了有效的基础性模型和数值计算方法。

关键词：等效力学本构模型；裂变气泡；有限元方法；U-10Mo核燃料；宏观弹性常数