Dynamic Fracture Behavior of High Burnup Fuel Particles Considering Fission Gas Release: Postprint

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Abstract

Ceramic fuels generate numerous fission gas pores under high burnup conditions, and the release of fission gas from these pores into crack cavities exerts substantial influence on crack propagation behavior. A dynamic crack propagation model under varying internal pressure was developed, achieving a dynamic fracture technique that couples the internal pressure within crack cavities with the crack propagation process. The magnitude of internal pressure varies with crack extension, while the fracture behavior is simultaneously affected by the pressure magnitude. This model was successfully applied to simulate cracking behavior within high-burnup structural ceramic fuel particles, investigating the mechanical effects of fission gas release on crack propagation. Based on global cohesive zone elements, the crack initiation and propagation processes were simulated, establishing a research methodology for investigating the mechanical effects of gas release on crack propagation, and analyzing the influence of gas pressure on crack initiation and propagation within fuel particles. The results demonstrate that, under constant total gas amount, gas release into crack cavities exerts an inhibitory effect on crack propagation based on gas pressure and crack geometric characteristics. For different initial gas pressure conditions, higher initial gas pressure leads to longer crack propagation lengths at crack arrest. This dynamic crack simulation technique provides an analytical method and numerical reference for accurately studying the failure of dispersed fuel matrices, and also offers a research approach for cases involving coupling between load and crack propagation.

Full Text

Preamble

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Introduction

Ceramic fuel pellets generate substantial fission gas during operation, leading to irradiation swelling and numerous microcracks. The cracking of ceramic fuel pellets represents the root cause of failure in dispersion fuel elements. Fission gas present in microcrack cavities creates internal pressure, while crack propagation behavior is simultaneously influenced by the magnitude of this pressure. Consequently, cracking in high-burnup ceramic fuel constitutes a coupled behavior between internal pressure effects and crack extension processes. Simulation studies considering fission gas pressure are therefore crucial for analyzing the failure mechanisms of dispersion fuel elements.

High-burnup ceramic fuel pellets exhibit porous geometries, with internal pressure in pores arising from fission gas accumulation. During failure, stress mismatch occurs in fuel pellets under the action of fission gas pressure in pores, and fission gas is released onto crack surfaces. Most existing studies have only considered fission gas effects simplistically. The global cohesive element method offers advantages for crack propagation analysis as it does not require pre-existing cracks, facilitating determination of crack location and size. This method is particularly suitable for analyzing crack propagation under complex loading conditions such as fluid pressure and can be applied to dynamic crack extension within pellets. By implementing a custom load subroutine within the finite element framework, the magnitude and position of loads on crack surfaces can be varied, enabling simulation of dynamic crack propagation under fission gas effects.

This study develops a dynamic crack propagation model under variable internal pressure based on the global cohesive element method, enabling exploration of how fission gas release behavior affects the mechanical failure of dispersion fuel matrices. Since fission gas pressure acts primarily on crack surfaces and varies with changes in crack geometry, crack propagation in ceramic fuel pellets under fission gas pressure represents a dynamic crack extension problem under variable internal pressure. Therefore, during crack propagation, the pressure in the crack cavity changes with crack extension dimensions, creating a coupled interaction between pressure magnitude and crack growth.

Variable Internal Pressure Crack Propagation Model

Fuel Pellet Structural Model

A spherical shell model of the fuel phase can represent pores of any size and location within fuel pellets and their surrounding fuel matrix structure. Under gas pressure, microcracks initiate around pores, with fission gas-induced pressure also present within crack cavities. As cracks extend under gas pressure, the pressure acting on crack surfaces changes with crack geometry, becoming the driving force controlling crack tip initiation and arrest. The initial gas pressure is calculated using a real gas equation of state under ultra-high pressure conditions:

$$p_0 = \frac{nRT}{V}$$

where n is the total fission gas amount (mol), V is the total gas volume (pore volume) (m^3), T is temperature (K), and R is the gas constant. The fission gas amount is determined by:

$$n = \frac{\rho \cdot \mathrm{BU} \cdot Y}{\mathrm{M}}$$

where ρ is the fuel phase density ($\mathrm{kg/m}^3$), BU is burnup (MWd/kgU), Y is the fission yield of fission gas (Kr, Xe) with a value of 0.25, and M is the molar mass.

Cohesive Zone Elements

Crack propagation surfaces are modeled with cohesive zone (CZ) elements whose constitutive relationship follows a bilinear law. The fracture energy G_c is characterized by the area under the traction-separation curve. When element traction increases, the traction force rises with opening displacement until reaching the specified fracture strength, after which damage initiates. The traction reaches its maximum value then decreases during the material damage evolution stage until dropping to zero when the element completely fails, at which point the fracture energy reaches its critical value G_c.

For ceramic fuel materials, a simple bilinear constitutive law adequately describes cracking behavior. [FIGURE: $(# 图 $] illustrates the bilinear constitutive law for CZ elements. In the CZ element properties, the damage initiation stress t_0^0 equals the material fracture strength σ_f, which can be calculated from the material’ s fracture toughness K_{IC}. The damage failure displacement δ_f is determined by:

$$\delta_f = \frac{2G_{IC}}{t_0^0}$$

The damage initiation displacement δ_0 and CZ stiffness K are calculated as:

$$K = \frac{t_0^0}{\delta_0} = \frac{\sigma_f}{\delta_0}$$

Dynamic Cracking Behavior and Results

Basic Model and Parameters

This study focuses on dynamic crack propagation under variable internal pressure. For single pore initiation, the following assumptions are made: the pore is circular and uniform, and a rectangular region of the surrounding fuel phase is selected to provide sufficient geometric space for dynamic crack initiation and arrest. The meshed model contains over 10,000 elements, with 120 CZ elements. The mesh size of 0.1 mm yields acceptable errors within acceptable limits.

Loading and boundary conditions are shown in [FIGURE: A]. The pore applies pressure to the surrounding fuel phase, while pressure also acts on crack surfaces as they extend. To prevent separation of the model' s upper and lower portions, appropriate constraints are applied.

UO_2 is a common ceramic nuclear fuel used in light water reactors, heavy water reactors, and experimental reactors, offering advantages including low thermal neutron capture cross-section, high melting point, isotropic behavior below melting point, and good irradiation stability. Therefore, UO_2 fuel pellet material properties are adopted.

The elastic modulus E of fuel pellets is a function of temperature and burnup. Based on experimental data, the following fitted relationship is obtained:

$$E = 2.2 \times 10^{11} \cdot \left[1 - 0.5\left(\frac{T - 300}{1720}\right)\right] \cdot [1 - 0.2 \cdot \mathrm{BU}]$$

where T represents temperature (K) and the elastic modulus unit is Pa.

The fracture strength σ_f of UO_2 material is calculated by:

$$\sigma_f = 170 \cdot \exp\left(-\frac{T - 300}{573}\right)$$

Using the high-burnup fuel elastic modulus E and fracture strength σ_f from the above equations, the damage failure displacement δ_f can be calculated.

The global cohesive element model is applied to the UO_2 fuel pellet geometry shown in [FIGURE: A]. The crack arrests after extending approximately 0.5 mm, with the numerical results in [FIGURE: @] and physical field values matching engineering reality.

[FIGURE: J] shows the gas pressure variation with crack extension length. When gas change effects are considered, the stress field and crack length in fuel pellets change significantly. The crack tip stress field under variable pressure is notably reduced, and crack extension length decreases. The coupling between gas pressure and crack propagation thus inhibits crack extension, producing a crack arrest effect. Clearly, considering fission gas release into crack cavities has a non-negligible impact on crack propagation.

Microscopic analysis of dispersion fuel failure after high-temperature irradiation indicates that when cladding begins to blister, cracks have already appeared within fuel pellets. Some cracks penetrate through the pellets, while others only enter the surface layer. In later blistering stages, cracks propagate out of fuel pellets into the matrix. Therefore, microcracks within pellets constitute the root cause of fuel pellet cracking, arising from internal tension exceeding the material’ s capacity as fission gas pressure increases. The variable internal pressure-crack propagation coupling model developed in this study more accurately simulates microcrack extension in ceramic fuel pellets because the fracture criterion in CZ elements is established based on fracture toughness. The resulting physical fields for cracked fuel pellets are more realistic, and this method can be readily extended to similar systems with variable pressure crack propagation.

Effect of Initial Fission Gas Pressure on Cracking Behavior

The initial pressure of fission gas significantly influences crack propagation. This section investigates models with different initial gas pressures. Initial pressures of 50 MPa, 100 MPa, and 150 MPa are considered.

[FIGURE: !] shows gas pressure variation with crack extension length for different initial pressures. [TABLE: #] summarizes crack initiation behavior for different initial pressure models.

[TABLE: #] Crack initiation behavior for different initial gas pressure models

Initial Pore Pressure (MPa)	Crack Arrest Length (mm)
50	0.42
100	0.51
150	0.63

Results demonstrate that as initial gas pressure increases, the final crack extension length increases. However, crack extension length is reduced by gas pressure changes, indicating that gas release inhibits crack propagation. The gas pressure at crack arrest decreases with increasing initial gas pressure. Since initial fission gas pressure correlates with burnup, this relationship enables further investigation of the connection between burnup and dispersion fuel matrix failure.

Conclusions

This study developed a cracking model under variable internal pressure-crack propagation coupling and applied it to dynamic simulation of fuel pellet cracking. Using the global cohesive element method, numerical simulations were conducted on single-pore models in high-burnup fuel pellets considering gas release into crack cavities. The effects of fission gas pressure on dynamic crack processes (initiation and arrest) were analyzed. The main conclusions are:

1. A fuel cracking behavior model under conditions of variable location and magnitude of complex gas loads can be established through user-defined subroutines, effectively simulating gas load-dominated cracking processes in high-burnup ceramic fuel pellets.
2. The developed variable internal pressure-crack propagation coupling model provides more accurate simulation of microcrack extension in ceramic fuel pellets, as the fracture criterion is based on fracture toughness. The resulting physical fields for cracked fuel pellets are closer to realistic values.
3. As initial gas pressure increases, the final crack extension length increases, but gas release inhibits crack propagation. The gas pressure at crack arrest decreases with increasing initial pressure, demonstrating the significant influence of fission gas release on crack propagation dynamics.

References

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Note: Figure translations are in progress. See original paper for figures.

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