Finite Element Analysis of Inner and Outer Contracts of LMFBR Fuel Elements

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Summary

Structural mechanics problems associated with gap closure and opening are among the characteristics of the core components in general, in comparison e. g. to the plant components, and of the fuel elements in particular.

Inside the cladding the possible contact with pellets (PCMI) and its implication for the structural integrity of the cladding are a well recognized problem for the most pin types.

For the fuel pin in a subassembly with grid spacing system consideration has to be given also to the contacts on the outer side, i. e. with the grid-cell straps. In addition to further thermal and mechanical loads for the cladding during the in core service, the outer contacts could imply permanent deformations and so increase the traction force later necessary for the pin disassembly from the grid system.

The subject of this paper is the theoretical analysis of the pin cladding structural response in such contact situations through the finite element code IAFETIN. The analysis procedure, including a model for the thermostructural behavior of the fuel is shortly mentioned and the application to the case of the cladding contact to a spark eroded spacing grid under steady state conditions is presented.

1 Introduction

Structural mechanics problems associated with gap closure and opening are among the characteristics of the core components in general, in comparison e. g. to the plant components, and of the fuel element in particular. On the inner side the influence of the gap changes on the temperature distribution, the possible pellet-cladding contact (PCMI) and its implication for the structural integrity of the cladding are a well recognized problem for the most pin types.

For the fuel pin in a subassembly with grid spacing system consideration has to be given also to the contacts on the outer side, i. e. with the grid-cell straps. In addition to further thermal and mechanical loads for the cladding and the grid during the in core service, the outer contacts could imply permanent deformations and so increase the traction force later necessary for the pin disassembly from the grid system.

To investigate such contact cases in more detail than through integral fuel pin modelling codes a procedure was developed and incorporated in IAFETIN / 1 /, a finite element code with 6 node isoparametric triangular elements for 2-dimensional thermal and inelastic analysis.

This procedure consists principally in the following two ingredients:

- an algorithm to handle the problem of the time dependent contact with frictional conditions, based on the use of orthotropic gap elements and on the identification of the contact areas through the non positive values of the Jacobian in the gap elements / 2 /, and

- a model for the fuel thermostructural behavior aiming primarily at the determination of the pellet deformations and its global stiffness in the cracked state at the time of the contact.

2 Cladding-Grid Contact

The main objective of this analysis is the structural response of the clad coming into contact with the spacer grid cell straps as a result of differential swelling and creep, fission gas pressure and temperature differences. In the case considered here the fuel pin has a

7.6 mm outside diameter and a 0.5 mm tickness and the spacer grid is the advanced type, i. e. spark eroded grid, with 8.8 mm pitch, candidate for the fuel subassemblies of a demonstration LMFBR core (Fig. 1a).

In the 2-D analysis a plane stress situation is assumed and for symmetry reasons only a region corresponding to three 60°-sectors of adjacent cells of the cladding grid cross-section (Fig. 1b) is used for analysis and schematized with finite elements.

All the displacements are referred to the central point C (Fig. 1c). The points on the lines AB, BC and CD are constraint to remain on the respective line while displacing, i. e. the lines AB, BC, CD translate so that the equal-sided triangle ABC has an isotropic expansion as dictated by symmetry. The following loading conditions are assumed:

- Uniform temperature of 500 °C for the cladding and 470 °C for the grid
- Uniform neutron flux $\overline{E}\emptyset = 2.06 \cdot 10^{15}$ MeV/cm² sec
- Fission gas pressure increasing linearly with the time at a rate of $\sim$ 0.06 bar/EFPD.

The material of both the cladding and the grid is the stainless steel 1.4970 cw, but maximal and minimal swelling and creep are assigned to the cladding and to the grid, respectively.

The IAFETIN results showed a contact beginning at 315 EFPD. This contact time may be postponed by designing an adequate initial gap between pin and grid cell. The clad deflection from the circular form, i. e. the difference δR (Fig. 1d) between the outer radius in the undisturbed zone and that at the mid point in the contact zone, increases with time up to the value of 27 µm after 830 EFPD.

The stresses remain everywhere quite small ($\sigma_{equ.} \leq 123$ N/mm^2), the highest values arising in the cladding at the contact region.

Through removing the thermal loading and reducing the fission gas pressure to the room temperature value, the permanent cladding deformation can be obtained and used to enter an experimental curve giving the fraction force necessary for disassembling.

Fig. 1c and d show the plots of the initial geometry (t = 0) and of the deformed geometry (t = 830 EFPD).

3 Cladding-Pellet Contact

The analysis of the contact between the cladding and the (U, Pu)O_2 pellet (PCMI) requires the modeling of the thermal and mechanical fuel behavior and thus becomes a quite complex problem because of the number and the nature of the single phenomena herein involved. The usual practice of handling the PCMI through one dimensional models of the integral pin codes (e. g. the INTERATOM-IAMBUS), while mostly adequate for design and licensing purposes, could result insufficient for particular problems in complex geometries. A complementary tool for localized analysis helps getting more insight in the cladding structural behavior.

The IAFETIN approach to the PCMI-study presents the following features:

- two dimensional (r-z or r-Θ) finite element model,
- gap temperature interaction,
- time dependent contact with frictional conditions,
- fuel structural model to determine pellet deformations and pellet overall stiffness with 4 regions / 3 /
  . completely brittle,
  . semibrittle,
  . ductile with plastic strains,
  . ductile with plastic and creep strains,
- input from integral pin analysis results, i. e. fission gas pressure and composition, actual fuel porosity and stochiometry, central void radius.

For the brittle regions the cracked state can be simulated locally through fictitious orthotropic element materials and reduced E-Moduli. The plastic strains of the semibrittle and ductile regions are calculated on the basis of a bilinear σ-ε curve. The latter is determined through the fracture and flow characteristics of the UO_2 (ultimate tensile stress, proportional limit, total plastic strains) observed in mechanical property tests.

For the detailed analysis of the cladding structural behavior under PCMI conditions two geometrical models, namely the axisymmetrical (radial-axial geometry) and the plane (radial-circumferential geometry) model, can be used to focus the axial and the circumferential effects, respectively.

In the axisymmetrical model a pin zone large enough to include all the bending effects in the cladding, needs to be considered, i. e. axially extending up to a distance from the contact region of at least $2{,}5 \sqrt{R \cdot t}$ (R = radius, t = thickness of the clad). For that it is normally sufficient to consider the zone corresponding to two fuel pellets and for symmetry reasons to schematize with axisymmetric finite elements only the part corresponding to half a pellet (i. e. between pellet interface plane, pellet midplane and axis).
The finite element mesh is chosen particularly fine at the region where pellet clad contact is expected. As boundary conditions a plane strain state (i. e. identity of axial displacements) must be specified for the points on the pellet mid plane and on the cladding ends and a plane stress state for the points at the pellets interface.

In the plane modell it is usual to assume a certain number of radial cracks in the pellet and to schematize with finite elements only half the sector comprised between two cracks with the corresponding displacement conditions on the boundary points.

To investigate the PCMI effects during a transient situation, e. g. an overpower transient or the ramps of a power change, the chosen loading histogram is assumed to begin at a certain time point of the power history and the actual values of the fuel and fission gas properties are derived from integral pin analysis results.

The frictional conditions can be simulated through adequate values (E_t) of the E-Modulus of the fictitious orthotropic material of the gap elements in the direction tangential to the opposing surfaces. E_t can be infinitesimal or equal to the E-Modulus in the normal direction for the limit cases of fritionless sliding or stick condition, respectively.

The analysis of a specific case of PCMI during power ramp conditions is at the time of writing in progress.

4 Concluding Remark

The presented analysis procedure of inner and outer contacts of the cladding represents an attempt to a complementary and more detailed treatment of the cladding structural mechanics than that with integral pin modeling codes.

Its disadvantage of large computer costs is therefore compensated by the more realistic information on the clad high strain concentration, presumed to contribute largely to impairment of the clad integrity.

Literature

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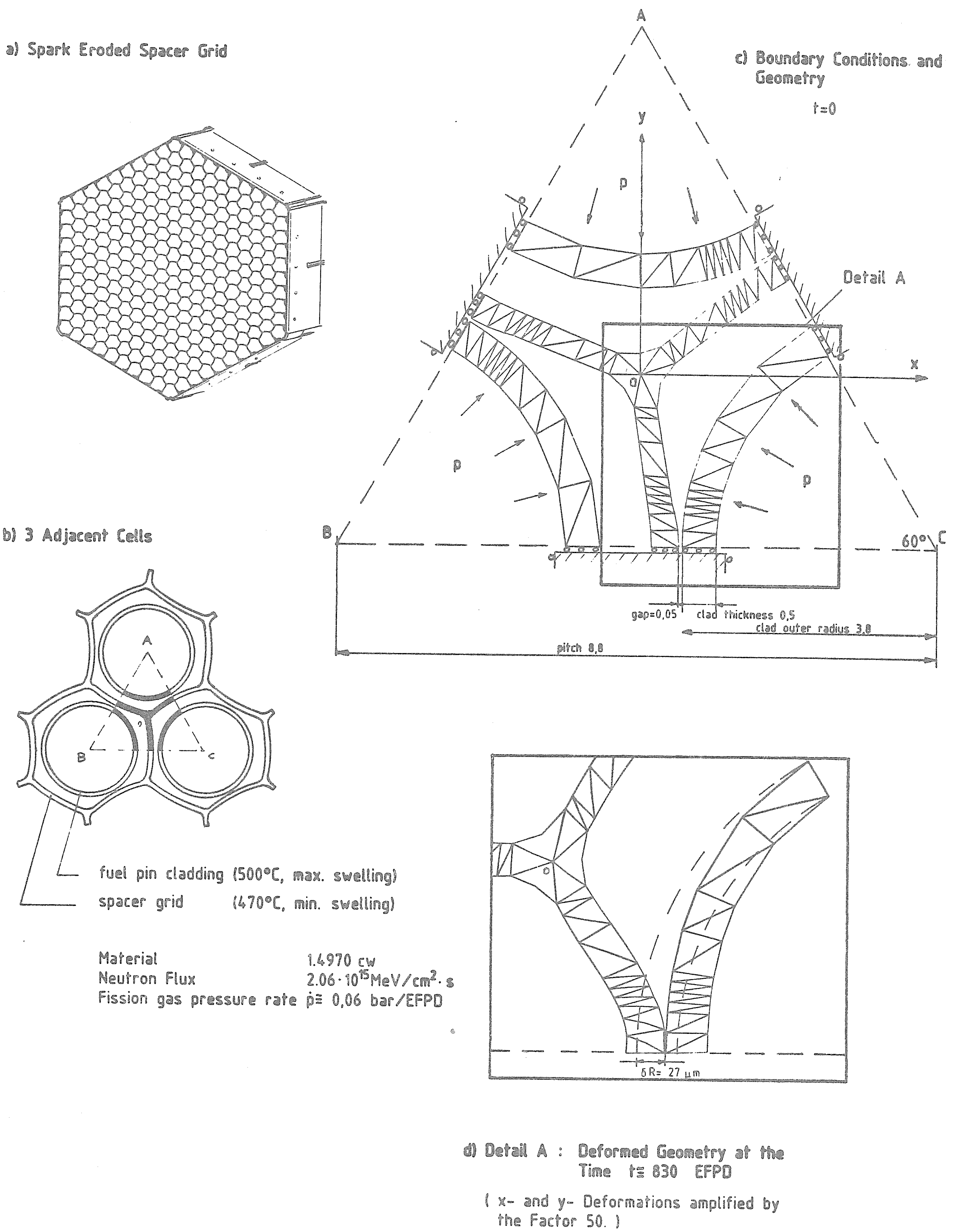

Fig. 1 - Fuel Pin Cladding-Spacer Grid Contact Analysis