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Mechanical behavior simulation of oxidized fuel cladding

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ABSTRACT: A model of deformation behavior of oxidized fuel cladding which allows to take into account the effects of oxide shell cracking and strengthening due to oxidation is presented. The proposed model is the base of the deformation behavior module of SVECHA package.

1 MODEL DESCRIPTION

Zircaloy oxidized cladding is considered as multilayer cylindrical shell (see Fig.1) that includes four layers: internal layer, β-Zr, α-Zr(O) and external ZrO_2 extending from inside to outside in the order listed. These layers are not allowed to change their position with respect to each other, but some of them may be absent. The β-Zr layer is assumed to be free of oxygen, material of this layer may be α-phase, β-phase or mixture of these two phases. The α-Zr(O) layer material is β-phase, oxygen stabilized α-phase or mixture of these phases. The external ZrO_2 layer is assumed to be monoclinic, tetragonal or cubic oxide phase. It is assumed that each oxide phase is stoichiometric ZrO_2 with constant oxygen concentration. The ZrO_2 is considered as an elastic material whereas β-Zr and α-Zr(O) have visco-elastic properties. The internal layer is considered as an incompressible liquid.

The factors that impact the mechanical response of the cladding are the internal (in the gap between fuel pellets and cladding wall) and external (in the channel of the coolant) pressures, and volumetric expansion of the material due to oxidation and temperatures. Temperature variation in the radial direction is considered, but each layer is assigned a uniform temperature.

It is assumed that each layer can be described as a thin-wall cylinder. Hence its dimensions can be characterized with the help of a middle radius R, thickness t and height h. The three-dimensional stress state of the thin-wall cylinder can be obtained in the following way:

$$(1) \qquad \sigma_r = -\frac{1}{2}(P_{\text{int}} + P_{ext}); \qquad \sigma_\theta = P_{\text{int}}\frac{R_{\text{int}}}{t} - P_{ext}\frac{R_{ext}}{t}; \qquad \sigma_z = \frac{N}{t},$$

where R_{int}, R_{ext} - the internal and external layer radii; $t = R_{ext} - R_{\text{int}}$ - the layer thickness; P_{int}, P_{ext} - the internal and external layer pressures; N - the layer axial force per circumference unit length; r,θ,z - the directions of cylindrical coordinate system.

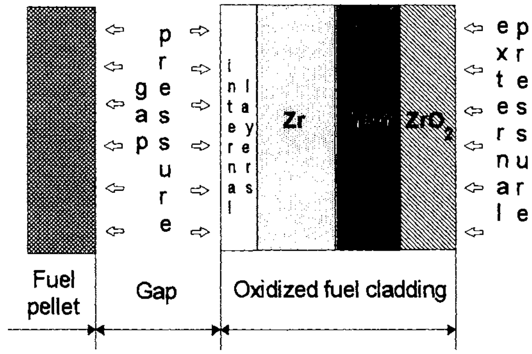

Fig. 1 Analyzed fuel cladding structure

The total strain in a given layer is taken to be the sum of elastic, creep and temperature strains:

(2) $$\varepsilon_\chi = \varepsilon_\chi^e + \varepsilon_\chi^{cr} + \varepsilon_\chi^T,$$

where $\varepsilon_\chi^e, \varepsilon_\chi^{cr}, \varepsilon_\chi^T$ - elastic, creep and temperature layer strains, correspondingly; index $\chi = r, \theta, z$.

Elastic strains are written with the help of Hook's law.

Thermal strains can be written as:

(3) $$\varepsilon_r^T = \varepsilon_\theta^T = \varepsilon_z^T = \alpha^T (T - T_{ref}),$$

where α^T - the mean coefficient of thermal expansion; T_{ref}, T - the initial temperature and the current temperature of the layer, correspondingly.

Using assumption that stresses do not change significantly due to dimensions changes during time interval dt, creep strains increments are given by:

(4) $$d\varepsilon_\chi^{cr} = \frac{3 d\varepsilon_{\text{int}}^{cr}}{2\sigma_{\text{int}}} (\sigma_\chi - \sigma_0),$$

where $d\varepsilon_{\text{int}}^{cr}$ - creep strain intensity increment; $\sigma_0 = (\sigma_r + \sigma_\theta + \sigma_z)/3$; σ_{int} - stress intensity. Creep strain intensity increment during time interval dt is determined in the following way:

(5) $$d\varepsilon_{\text{int}}^{cr} = A(\sigma_{\text{int}})^n e^{-\frac{Q}{T}} dt,$$

where A, n, Q - the creep constants; T - the absolute temperature.

Oxygen concentration have an influence on oxygen stabilized α-phase creep rate only and it can be taken into account in the following way Burton et al. (1979):

(6) $$\dot{\varepsilon}^{cr,\alpha}(C) = \dot{\varepsilon}^{cr,\alpha}(0) e^{-3.42C},$$

where $\dot{\varepsilon}^{cr,\alpha}(0)$ - creep rate of α-phase with oxygen concentration of as-received cladding; $\dot{\varepsilon}^{cr,\alpha}(C)$ creep rate of oxygen stabilized α-phase with oxygen concentration C; C - weight fraction of excess oxygen in percents.

Finally, if R, t, h - layer dimensions in unloaded state, then layer dimensions changes under loads (temperature, internal and external pressures) are given by:

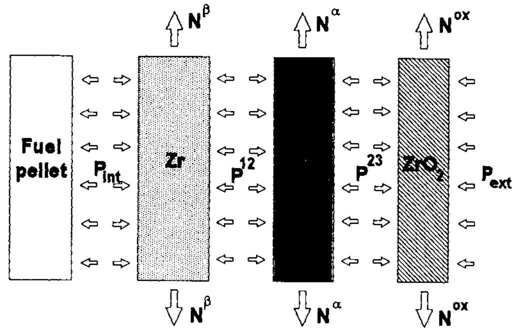

Fig.2 Calculation diagram of the oxidized fuel cladding

(7) $$R_{def} = R(1+\varepsilon_\theta), \quad t_{def} = t(1+\varepsilon_r), \quad h_{def} = h(1+\varepsilon_z),$$

(8) $$R_{\text{int},def} = R(1+\varepsilon_\theta) - \frac{1}{2}t(1+\varepsilon_r), \quad R_{ext,def} = R(1+\varepsilon_\theta) + \frac{1}{2}t(1+\varepsilon_r),$$

where R_{def} - the middle layer radius under load; t_{def} - the layer thickness under load; h_{def} - the layer height under load; $R_{\text{int},def}, R_{ext,def}$ - the internal and external layer radii under load, correspondingly. Consideration of the mutual layers displacements (calculation diagram is given in Fig.2) yields the following system of equations:

(9) $$\begin{gathered} R^\beta(1+\varepsilon_\theta^\beta) + \frac{1}{2}t^\beta(1+\varepsilon_r^\beta) = R^\alpha(1+\varepsilon_\theta^\alpha) - \frac{1}{2}t^\alpha(1+\varepsilon_r^\alpha); \\ R^\alpha(1+\varepsilon_\theta^\alpha) + \frac{1}{2}t^\alpha(1+\varepsilon_r^\alpha) = R^{ox}(1+\varepsilon_\theta^{ox}) - \frac{1}{2}t^{ox}(1+\varepsilon_r^{ox}); \\ h^\beta(1+\varepsilon_z^\beta) = h^\alpha(1+\varepsilon_z^\alpha); \\ h^\alpha(1+\varepsilon_z^\alpha) = h^{ox}(1+\varepsilon_z^{ox}), \end{gathered}$$

where indexes β, α, ox reference to the β-Zr layer, α-Zr(O) layer and oxide layer, correspondingly. After substitution of (1) - (8) in (9), the system of equation (9) can be written in 5 unknown: $N^\beta, N^\alpha, N^{ox}, P^{12} = P^\beta_{ext} = P^\alpha_{\text{int}}$ and $P^{23} = P^\alpha_{ext} = P^{ox}_{\text{int}}$.

The fifth equation can be obtained from the consideration of the force balance for the plugged cylinder:

(10) $$N^\beta + N^\alpha + N^{ox} = N^\Sigma$$

where N^Σ - total axial force, due to internal and external pressures, per circumference unit length:

(11) $$N^\Sigma = \frac{P_{\text{int}}(R^{clad}_{\text{int}})^2 - P_{ext}(R^{clad}_{ext})^2}{R^{clad}_{\text{int}} + R^{clad}_{ext}},$$

where $R^{clad}_{\text{int}}, R^{clad}_{ext}$ - the internal and external cladding radii under load; P_{int}, P_{ext} - the internal and external cladding pressures.

The considered approach gives solution for the case when the gap between fuel pellet and mesh wall exists. Therefore it is necessary to check the gap existence. If the internal

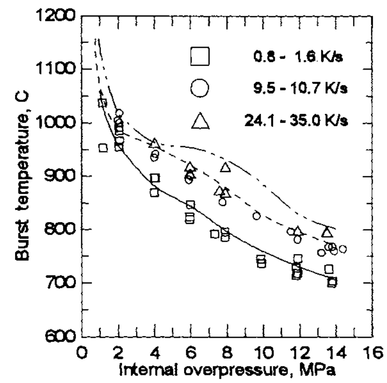

Fig. 3. Model predicted and experimental burst temperature versus internal overpressure for REBEKA experiment.

radius of the clad (with account of possible material relocation) is less than external fuel pellet radius, then the internal pressure calculated for cladding as a function of gap volume and temperature is not valid. In this case the obtained solution is not correct and additional equation should be writen to detrmine unknown internal pressure. If fuel pellet is considered as a rigid body and internal cladding layers (besides β-Zr, α-Zr(O) and external oxide layer,) are considered as incompressible liquid than an additional equation can be written in the following way:

(12) $$R^{\beta}(1+\varepsilon_{\theta}^{\beta})-\frac{1}{2}t^{\beta}(1+\varepsilon_{r}^{\beta})=R^{pellet}\sqrt{1+\frac{V_{tot}}{\pi H(R^{pellet})^{2}}},$$

where R^{pellet} - the external fuel pellet radius; H - the deformed cladding height; V_{tot} - the total volume of the internal layers. The total axial force N^{Σ} is assumed to be equal to zero.

The system of equationsis solved numericaly. Solution time step depens on creep strain intensity increment for β-Zr and α-Zr(O) layers. If creep strain intensity increment exceeds the limit value (0.005 was used in simulations) solution time step is reduced. After system solution new cladding dimensions and stress-strain state can be calculated. The cladding is assumed to fail by ballooning if the average circumferential strains exceeds the ultimate failure strain. The oxide layer is assumed to crack and has no deformation strength if the tensile circumferential stress in ZrO_2 shell exceeds the ultimate oxide strength. Rupture by flowering of the oxidized cladding at high temperature, (> 1600 K, i.e., the temperature at which the deformation strength of β-Zr and α-Zr(O) layer is insignificant) is assumed to occur when the sum of circumferential stress in ZrO_2 shell is caused by internal and external pressures and circumferential and radial temperature variations exceeds the ultimate oxide strength. Stress caused by oxide temperature variations can be calculated in the following way, Yamshchikov and Boldyrev (1993):

(13) $$\sigma_{\theta,\max}=\frac{1}{2}(\alpha^{T,ox}\Delta T_{r})E^{ox}+\frac{1}{4}(\alpha^{T,ox}\Delta T_{\theta})E^{ox}\frac{t^{ox}}{R^{ox}}(1-\frac{t^{ox}}{6R^{ox}}),$$

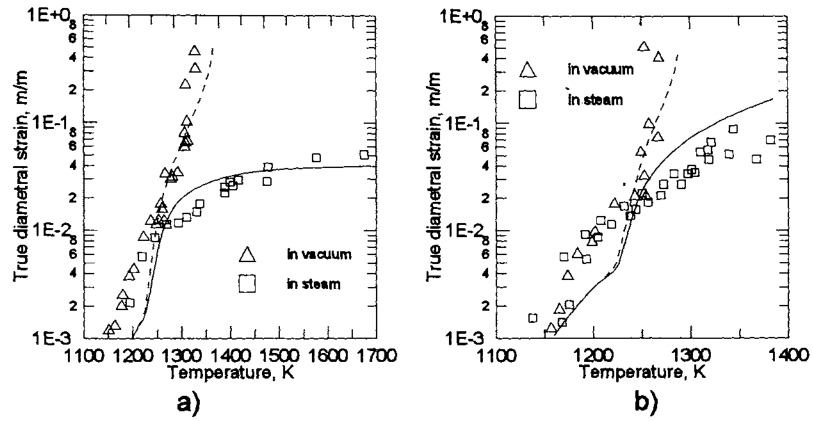

Fig. 4. Model predicted and experimental diametral strain data for Sagat's experiments: a) - internal pressure 0.34 MPa; b) - internal pressure 0.48 MPa.

where $\sigma_{\theta,max}$ - the maximum tensile circumferential stress; $\alpha^{T,ox}, E^{ox}$ - oxide thermal expansion coefficient and Young's modules at the average oxide layer temperature; ΔT_r - temperature difference between internal and external oxide shell surfaces; ΔT_θ - circumferential temperature difference.

2 RESULTS

The results are represented as comparison of the data predicted by proposed model and the data obtained in experiments Erbacher et al. (1982) and Sagat et al. (1984). To calculate oxidation of fuel cladding the model developed by Voltchek (1993) was used.

2.1 Rebeka experiment

Test preparation: The cladding tubes were made of Zircaloy-4 with 10.75 mm outside diameter and 9.30 mm inside diameter.

Test performance: The internal overpressure and the heating rate were kept constant during the deformation process. A heated shroud surrounded the test rod to minimize temperature differences on cladding circumference. Single-rod transient burst test in steam were performed with the following parameters: internal overpressure - 10- to 140 bar, heating rate - 1 to 30 K/s. Initial temperature - 573 K.

Experimental results: Fig.3 is a plot of burst temperature versus internal overpressure with heating rate as a parameter. With the same heating rate, a higher internal overpressure results in a lower burst temperature. The diagram reveals a distinct influence of the heating rate on the burst temperature: increasing of heating rate lead to increasing burst temperature.

Simulation results: The burst temperatures predicted by fuel cladding deformation behavior model are presented in Fig.3.

2.2 Sagat et al. experiments

Test preparation: The specimens were prepared from Zircaloy-4 cladding 15.25 mm in diameter, 0.45 mm wall thickness, and 489 mm long.

Test performance: Prior to each test, steam was admitted into the test chamber at a flow of about 2 g/s to provide an oxidizing environment on the specimen outside diameter. The apparatus was allowed to stabilize for about 600 s and after then the specimen was internally pressurized with the helium to the test pressure and then the temperature ramped using Joule heating (heating by specimen own resistance) until a predetermined strain was achieved or until the burst occurred. The measured diametral strain were obtained at a heating rate of 5 K/s and at different internal pressures ranging from 0.34 to 1.38 MPa for vacuum and steam environment.

Experimental results: The results show that at internal pressures greater than or equal to 0.69 MPa (hoop stress of 11.3 MPa) there was little difference between the vacuum and steam data as negligible oxidation occurred during the short test period. The effect of steam oxidation became important at lower pressures where the ramp temperatures exceeded 1300 K, reducing the strain rate of specimens tested in steam. The diametral strains obtained at internal pressures 0.34 and 0.48 MPa in steam are plotted versus temperature in Fig.4a and Fig.4b together with similar data obtained on specimens tested in vacuum.

Simulation results: The diametral strain data predicted by fuel cladding deformation behavior model are presented in Fig.4a and Fig.4b.

3 CONCLUSION

Comparison of model predicted data and experiments results shows that proposed approach for description of deformation behavior of oxidized zirconium fuel cladding can be applied to simulate cladding deformation behavior under sever accident scenario conditions.

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