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ANISOTROPIC TRANSIENT DEFORMATION OF ZIRCALOY FUEL CLADDING AT HIGH TEMPERATURES

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SUMMARY

The accurate prediction of time dependent fuel cladding anisotropic deformation depends primarily on the characterization of the material and secondarily on the analytical analysis procedures that are used.

The characterization of Zircaloy at elevated temperatures begins with using testing techniques which employ high heating rates and transient deformation, loading and measurement procedures. The objective is to provide a material condition that is representative of the material during the actual event or temperature excursion to be predicted. Transient deformation tests using uniaxial and biaxial stress conditions have been performed over a range of high temperatures which provide a basis for the analytical analysis. The materials data is characterized by a series of cubic spline discretized surfaces for each test temperature.

The three dimensional cubic spline surface analyses for uniaxial and biaxial tests provide a means of developing anisotropy coefficients which are dependent upon stress levels, strain, temperature, and time. The constitutive relationships needed for a finite element incremental analysis are composed of not just one equation but a series of Hermite bicubic coefficients which describe the individual surfaces.

The concept of characterizing the effective stress in terms of anisotropy coefficients is shown in the following equation for an incremental change in time dependent strain:

$$F_k = A_1(\varepsilon_{ij}, \sigma_{ij})_k (\sigma_{11}-\sigma_{22})^2 + A_2(\varepsilon_{ij}, \sigma_{ij})_k (\sigma_{22}-\sigma_{33})^2 + \\ + A(\varepsilon_{ij}, \sigma_{ij})_k (\sigma_{33}-\sigma_{11})^2 .$$

For this equation all values are computed on an incremental basis.

The cubic spline surfaces which are in turn characterized with a Hermite bicubic interpolation, describe the stress, time, strain relationship as a function of temperature for the diametral and axial strains for both uniaxial and biaxial material tests. The simultaneous solutions in terms of applied stress allows the evaluation of the anisotropy coefficients A_1, A_2, A_3.

These procedures have been incorporated with an axisymmetric finite element code (DILATE) to predict the deformation that occurs during a low speed ramp loading test condition. Experimental ramp tests have also been performed which demonstrate the validity of the procedure.

The finite element code employs a constant strain triangle axisymmetric element as the basis for the analysis. It uses the formulation for effective stress shown in the previous equation. In addition the coefficients shown are used in modifications to the Prandtl-Reuss equation for the incremental inelastic strain. Large strain deformation is approximated by creating a new stiffness matrix at the end of each time step. The inelastic strains are computed using a strain hardening procedure. The code is capable of following any combination of axial and pressure loading conditions as well as thermal gradients.

Advanced experimental measurement techniques, coupled with a discretized cubic spline surface analysis used for constitutive law development makes it possible to accurately predict anisotropic transient behavior using a finite element analysis.