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Viscoelastic modelling of Zircaloy cladding in-pile transient creep

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ABSTRACT

In fuel behaviour modelling accurate description of the cladding stress response is important for both operational and safety considerations. The cladding creep determines in part the width of the gas gap, the duration to pellet-cladding contact and the stresses to the cladding due to the pellet expansion. Conventionally the strain hardening rule has been used to describe the creep response to transient loads in engineering applications. However, it has been well documented that the strain hardening rule does not describe well results of tests with load drops or reversals.

In our earlier work we have developed a model for primary creep which can be used to simulate the in- and out-of-pile creep tests. Since then several creep experiments have entered into public domain. In this paper we develop the model formulation based on the theory of viscoelasticity, and show that this model can reproduce the new experimental results. We also show that the creep strain recovery encountered in experimental measurements can be explained by viscoelastic behaviour.

1. Introduction

The cladding tube of nuclear fuel rod protects the urania pellets from the corrosive environment as well as contains the radioactive fission products. Early on during the rod reactor life the cladding creeps inwards due to pressure differential between the reactor system pressure and the rod fill gas. The inward creep of the cladding and swelling of the fuel pellet eventually lead to closing of the gas gap and mechanical interaction between pellets and cladding wall. And with very high burnup there is the possibility of high rod internal pressure exceeding the system pressure, potentially causing the cladding creep outwards faster than the pellets swell and re-opening the gas gap. All these affect the fuel performance and some have potential to cause fuel failures. It is therefore very important to properly understand and describe the various phenomena affecting the fuel rod. While numerous studies have been done on the creep properties of various cladding materials [1–13], the creep response to transient stresses is investigated only in a small subset of the work [1,2,5,8,10,12]. However it should be noted that the transient response governs the cladding behaviour during situations where most damage can happen, i.e. transients.

Conventionally fuel cladding deformation is assumed to have elastic and viscoplastic components. Viscoplastic creep is described by having three regions: the primary (or transient) region, the secondary steady state region and the third leading to failure. The correlations are matched to experiments with a single stress increase, and the change of stress encountered in fuel behaviour analysis is handled by hardening laws. The creep in metals is assumed to follow either a time or a strain hardening law, and the latter is believed to hold for Zirconium alloys in usual operating conditions [2].

Various creep correlations have been formulated over the years that take both thermal and irradiation creep into account. It is well known that the hardening laws used to take the transient conditions into account are simplifications and do not apply universally. Stress reversal and stress reduction are special situations where the hardening law fails and requires additional assumptions to model the observed behaviour [1,2,5]. These situations have been successfully described with complex formulations of cladding material thermodynamic states [14,15] and by assuming additional deformation terms such as reversible anelastic deformation [1,16]. Also anisotropy of the cladding tubes can be described with high precision with advanced methods [7,17].

While these formulations appear to provide correct prediction of the cladding creep behaviour they are not commonly implemented in fuel behaviour codes due to their complexity and computational limitations [18]. Fuel behaviour analysis is commonly performed with integral codes utilizing separate models to describe various phenomena, and the number of required simulations may rise to hundreds of thousands of fuel rod simulations depending on the application [19]. For this purpose, a simple and more practical approach is needed. Previously we have shown that the cladding behaviour during stress reversal and reduction can be roughly modelled using simple internal variable approach [20].

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In this paper we develop the primary creep model further starting from Standard Linear Solid model which is commonly used in studies of viscoelasticity of a wide range of materials and as such provides a solid theoretical foundation for the model. We compare the primary creep model to experimental data that has recently entered the public domain. The model with primary creep based on viscoelastic behaviour is derived in Section 2. Halden experiments IFA-699 and IFA-696 are used to assess the validity of the model in Section 3 and the results are discussed in Section 4. Conclusions are given in Section 5.

2. Creep model

2.1. Viscoelastic model

In studies of viscoelastic properties of solids, a common method of describing models is via so-called mechanical analogs [21]. These combine springs representing the elastic component of the material to dashpots representing the viscous components. The springs' displacement is $\epsilon_{\text{spring}} = \sigma/\kappa_i$, where κ_i is the elastic modulus of spring i and σ is the external stress affecting the given component, while the dashpots' rate of displacement is of $\dot{\epsilon}_{\text{dashpot}} = \sigma/\eta_i$, where η_i is the viscosity of the dashpot i. Other components are also possible in order to describe more complex interactions.

A mechanical analog of our creep model is shown in Fig. 1. There is a separate node describing the secondary thermal and irradiation creep in series to a Standard Linear Solid (SLS) model. Secondary creep is nonlinear [4,7,6,22] yet it interacts with rest of the system similarly to dashpot as it is decoupled from the elastic and primary creep deformations in creep experiments. Therefore the dashpot symbol D is used as a stand-in for a more complex function describing the secondary creep. SLS consists of two parallel arms, a spring and a serial combination of a spring and a dashpot. The SLS is the simplest mechanical analog capable of qualitatively describing material behaviour during both imposed stress (so-called creep tests) and imposed elongation (stress relaxation test) [21].

Conventionally the stress response of the cladding is separated into elastic response ϵ_{el} and creep, which in turn has both primary (ϵ_p) and secondary (ϵ_s) components:

$$\epsilon = \epsilon_{el} + \epsilon_p + \epsilon_s. \tag{1}$$

SLS part of the model shown in Fig. 1 simulates the elastic and primary creep components of Eq. (1) and replaces the need for strain hardening rule. It should be evident from Fig. 1 that the elastic response and primary creep are intrinsically linked in this formulation and the secondary creep is separate, in contrast to most formulations [4,7,6] which consider primary and secondary creep linked and elastic response separate from the creep.

The solution to SLS is well known [21]. The general relationship is given by

$$\sigma(t) + \frac{\eta_C}{\kappa_B}\frac{d\sigma(t)}{dt} = \kappa_A\left(\epsilon(t) + \eta_C\frac{\kappa_A+\kappa_B}{\kappa_A\kappa_B}\frac{d\epsilon(t)}{dt}\right), \tag{2}$$

where either the strain ϵ or stress σ can be solved when the other is given as well as the initial condition is known.

In the context of fuel behaviour modelling we are interested in solving the strain as a function of piece-wise constant stress that can be implemented into the time-stepping scheme of the fuel performance code. For simplicity, we assume that the stress in the beginning is zero, $\sigma(t_0) \equiv \sigma_0 = 0$, and the strain correspondingly $\epsilon_0 \equiv \epsilon(t_0) = 0$. Further, we assume that the stress changes occur instantaneously at times t_i so that for $t_i \leqslant t < t_{i+1}$ the stress is constant $\sigma(t) = \sigma(t_i) \equiv \sigma_i$. Then the stress can be written as

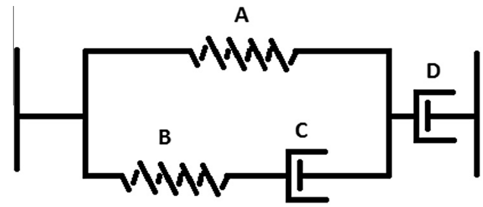

Fig. 1. Mechanical analog for the Standard Linear Solid model (nodes A, B and C) in series with a node D representing secondary creep contribution.

$$\sigma(t) = \sum_{i=1}^{N}\Delta\sigma_i\Theta(t-t_i), \tag{3}$$

where $\Delta\sigma_i = \sigma_i - \sigma_{i-1}$, Θ is the Heaviside step function and the sum is taken over all the N stress changes.

The solution of the SLS model is derived in Appendix A. The resulting strain including the elastic, primary creep and secondary creep contributions is of the form

$$\epsilon(t) = \frac{\sigma(t)}{\kappa} + C\sum_{i=1}^{N}\Delta\sigma_i\left(1-e^{-\frac{t-t_i}{\tau}}\right)\Theta(t-t_i) + \int_{t_0}^{t} f(\sigma(\xi))d\xi, \tag{4}$$

with the constants given by

$$\kappa = \kappa_A + \kappa_B, \tag{5}$$

$$C = \frac{\kappa_B}{\kappa_A(\kappa_A+\kappa_B)}, \tag{6}$$

$$\tau = \eta_C\frac{\kappa_A+\kappa_B}{\kappa_A\kappa_B}. \tag{7}$$

The first term in Eq. (4) corresponds to the elastic strain, the second to primary creep and the last one to secondary creep (both thermal and irradiation induced).

2.2. Implementation of model for primary creep

The primary creep term,

$$\epsilon_p(t) = C\sum_{i=1}^{N}\Delta\sigma_i\left(1-e^{-\frac{t-t_i}{\tau}}\right)\Theta(t-t_i), \tag{8}$$

involves a sum over the whole stress history with exponentially decaying contributions from all the previous stress changes. In such a non-Markovian form the model is difficult to implement into a fuel performance code. However, it is possible to write the model in a form where the future evolution of the system depends only on the present state of the system. This can be done by introducing an additional variable describing the internal state of the system where the memory effects can be embedded.

We describe the internal state of the cladding with a single time-dependent stress-like variable $\sigma_{\text{int}}(t)$. The time evolution $\sigma_{\text{int}}(t)$ describes the relaxation of the internal state of the system towards the steady state determined by the applied stress $\sigma(t)$. The scale of $\sigma_{\text{int}}(t)$ is chosen so that for an initial state with zero primary creep rate and the applied stress equal to σ_0, $\sigma_{\text{int}}(t_0) = \sigma_0$. As the applied stress is changed to σ_1, the variable $\sigma_{\text{int}}(t)$ starts to evolve in time, approaching the new steady state value $\sigma_{\text{int}}(t\to\infty) = \sigma_1$, which is reached when the primary creep has fully saturated. For several stepwise changes as in Eq. (3), the model takes the form (see Appendix A and Ref. [20])

$$\epsilon_p(t+\Delta t) = \epsilon_p(t) + C[\sigma(t) - \sigma_{\text{int}}(t)]\left(1-e^{-\frac{\Delta t}{\tau}}\right), \tag{9}$$

$$\sigma_{\text{int}}(t+\Delta t) = \sigma(t) - [\sigma(t) - \sigma_{\text{int}}(t)]e^{-\frac{\Delta t}{\tau}}. \tag{10}$$