SOME TRENDS IN CONSTITUTIVE EQUATION MODEL DEVELOPMENT FOR HIGH-TEMPERATURE BEHAVIOR OF FAST-REACTOR STRUCTURAL ALLOYS*

C. E. PUGH, D. N. ROBINSON

*Engineering Technology Division,
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, U.S.A.*

SUMMARY

The temperature of many fast-reactor components is sufficiently high that creep behavior has to be taken into account in structural analyses and associated design assessment criteria. The thermal histograms and good heat transfer properties of reactor coolants impose short-time inelastic loadings, so that elastic-plastic behavior also has to be considered. With regards to the liquid-metal fast breeder reactor (LMFBR) efforts in the USA, the ASME Code Case 1592 considers these aspects in criteria for establishing acceptable limits for stresses and strains. However, inelastic (elastic-plastic and creep) analyses may be required to demonstrate that these criteria are satisfied. Vital to meaningful inelastic analyses is the mathematical model (constitutive equations) used to represent material behavior. The discussion here addresses some trends in constitutive equation development relative to the equations currently acceptable for inelastic analyses of LMFBR components. Possible differences in the mathematical structure of models are pointed out in terms of computational considerations.

Constitutive equations for interim use in LMFBR design work have been identified for three primary structural alloys; types 304 and 316 stainless steel and $2\frac{1}{4}$ Cr-1 Mo steel. The intent is to have a consistent basis for evaluation of component designs through the use of constitutive models that adequately predict known features of material behavior for broad classes (monotonic and cyclic) of loadings, are compatible with practicable analysis techniques, and require mechanical properties information that can be obtained from material test programs of manageable proportions. Those equations are continuously revised as more is learned about relevant material behavior and the applicability of improved theories is verified.

The current methods employ classical theories and treat total strains as the sum of elastic, plastic, creep, and thermal contributions. In the case of elastic-plastic behavior, a modified nonisothermal kinematic-hardening approach is used in which limited isotropic changes in the yield behavior are permitted during the accumulation of inelastic deformations. For creep, an equation-of-state approach based on strain hardening is employed. For the stainless steels, classical creep strain-hardening concepts are modified by auxiliary rules for cases involving stress reversals. These rules are further modified for $2\frac{1}{4}$ Cr-1 Mo steel to include a creep softening influence of reversed plastic strains. Although the premises on which these methods are based are not new, they have been measured against a sizable body of current experimental data and found to be reasonable. Before replacement techniques are adopted, superior capabilities have to be shown in this regard.

The discussion here on evolving models concentrates on time-dependent aspects of inelastic behavior. One can think of the prescription of a constitutive model as a process whereby (state) variables are identified which define the state of the material following an inelastic deformation history. The constitutive equations then consist of a *flow law* (expresses the inelastic strain rate in terms of stress and the state variables) along with a *growth law* (specifies how the state variables change during the loading and/or temperature history). In the case of some classical creep theories, such as time hardening and strain hardening, one state variable is employed, and the growth law reduces to a trivial adjunct to the flow law. However, this is not the case for some other candidate models, where the flow law and the growth law form a set of coupled equations. Several distinct theories are discussed briefly here in terms of their flow and growth laws.

To illustrate an example of a specific improvement that potentially needs to be made in current equations, the creep behavior of $2\frac{1}{4}$ Cr-1 Mo steel is considered. Apparent recovery of state occurs in this material when the loading history includes periods of unloading. This is to say, although very little creep-strain recovery occurs during such intervals of unloading, state recovery (or softening) does occur in that upon reloading to the same stress the material exhibits creep rates higher than just prior to the unloading. This increase in creep rate is not predicted by the strain-hardening theory of creep nor by any other theory that does not allow state recovery. The coupled flow and growth laws are given for one class of creep formulations that allows for such recovery.

* Work done at Oak Ridge National Laboratory, operated by Union Carbide Corporation for the Energy Research and Development Administration.