CAFE model for creep damage induced by nonstationary creep deformation

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In polycrystalline materials in creep conditions under long-term loading two processes of opposite nature are developing. First is connected with hardening of material, the second one with softening of it. Both of them are results of changes in material structure. In the process of hardening the dislocation slips are inhibited by dislocation pile-ups or hard particles contained in material. The strain rate is going to slow down. Simultaneously the second phenomenon of material softening occurs. It is mainly connected with vacancy diffusion. Initially it allows the dislocations to climb over the obstacles, leading to stationary rate of creep deformation. The same process of vacancy diffusion is responsible for development of voids yielding degradation of material structure and finally to form macroscopic defects.

Macroscopically observed strains rate also reflects these changes in leading mechanism(s) of deformation. It allows to divide the whole period of creep life to three stages: the primary, secondary and tertiary creep. In the primary period the strain rate is decreasing, in the second one the strain rate is constant and in third period it is increasing. The whole process can be described using Continuum Damage Mechanics (CDM) equations (e.g. [1]). These equations are based on macroscopically defined state variables which are used to define so called ‘constitutive equations’ with parameters define by data fitting.

The constitutive equations define material response but do not provide information on their causes. Here the microscopic models come to play its role (see for example [2] for review of creep cavitation models). They are mainly concentrated on explanation of single microscopy mechanism; sometimes they describe the interaction among some of them. But it is difficult to describe the whole process using such models due to complexity of the structure they are operating on.

The solution for this problem is multiscale modelling. As not the whole structure can be modelled using microscopic model, it has to be applied to so called Representative Volume Element (RVE). The size of this element must be relevant to the scale of microscopic process in which the model is to be applied. If there are important differences in material structure or other circumstances in neighbouring parts of analysed structure the adequate number of models operating on their own RVE’s are needed. The neighbouring elements communicate on the higher level of analysis using variables proper for such scale of observation. In special cases the intermediate levels of modelling have to be introduced (see [3] for example of three levels model).

Multiscale modelling offers also the possibility to combine the simplified models of some mechanisms with precise description of mechanism under interest. It can be used to evaluate the influence of single microscopic mechanism on the behaviour of a whole structure. Such a model is presented in current paper. The mechanism under interest is diffusion growth of voids. It is modelled using Cellular Automata (CA) network described in previous author’s papers [4, 5]. As the voids are developing mainly on grain boundaries the CA model operates on the structure of grains and grain boundaries (see Figure 1). CA in connection with Finite Element (FE) builds the multiscale CAFE
Automata with different grain structure are running in every Gauss point of FE mesh. The FE code implements the macroscopic equations of CDM in form proposed by Chrzanowski [6]:

\[
\dot{\varepsilon} = B (\frac{\sigma}{1 - \omega})^n, 
\]

where \( B \), \( \alpha \), \( n \) are material constants, \( \varepsilon \) is strain, \( \sigma \) is stress, \( \omega \) damage parameter. This equation allows for modelling all three stages of creep. Parameters \( B \) and \( n \) are responsible for creep rate, whereas \( \alpha \) controls hardening process. The coupling of strain rate with damage parameter models the acceleration in tertiary creep. Damage parameter is also used for connection between two levels of current model. It is evaluated by CA model taking into account the largest microcrack developed in RVE. In return the current strain in every Gauss point is used to evaluate the actual dimensions of RVE.

**Figure 1:** Example of grain structure used in CA modelling.

The implementation of hardening process in FE part of CAFE simulation allows to obtain real shape of creep curve including all three stages of creep deformation (see Figure 2).

**Figure 2:** Example of creep curves obtain by CAFE model with and without hardening for copper in 823 K under 33.3 MPa stress.

**References**

[1] Mustata R., Hayhurst D.R., *Creep constitutive equations for a 0.5Cr 0.5 Mo 0.25V ferritic steel in the temperature range 565 C–675 C*, Int. J. Pressure Vessels and Piping, 82, 363-372, 2005


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