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Time-independent formulation for creep damage modeling in metals based on void and crack evolution

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ABSTRACT

An advanced creep modeling, based on dislocation mechanics and incorporating damage effects, is developed at continuum scale. In the proposed formulation, creep damage does not depend on time (time-independent damage formulation) but on the accumulated creep strain. Thus, the tertiary creep stage can be predicted as the evolution of the secondary stage in which the current stress is increased by damage effects, and possible other microstructural instability processes, in addition to geometry modifications. The proposed formulation extends the initial continuum damage mechanics approach proposed by Kachanov in order to have a more explicit correlation between material creep response, damage mechanics and material microstructure. The possibility to account for possible microstructure modifications that may occur as a result of solid-solution kinetics, by means of the identification of the evolution law of damage parameters is discussed. An example of the applicability of the proposed model to IMI834 titanium alloy is given.

1. Introduction

Increasing demand for higher operative temperatures and longer design life requires new materials and advanced design tools for more accurate life predictions based on shorter duration laboratory tests. In order to achieve this challenging task, material modeling needs to be extended to include the microstructural material scale where irreversible processes, such as deformation and damage, take place. To this purpose, much more information, such as grain size, grain boundary type, crystal orientation, dislocation density, nature of the deformation mechanism, number and type of phases, residual stresses, etc. are needed to characterize the material in its thermo-mechanical state.

At elevated temperatures, materials subjected to constant or very low loading rates undergo creep deformation that may lead the components to structural failure either by exceeding the maximum allowable design strain or by ductile crack initiation and propagation.

One of the major issues in creep modeling and design is the possibility to predict the accumulation of the inelastic strain with time, under constant stress and at a given temperature, based on experimental data obtained from short-duration creep tests. Unfortunately, the occurrence of the tertiary creep stage jeopardizes the possibility to simply extrapolate secondary (steady-state) creep-stage information to longer durations. Any *a priori* estimation of the transition strain or time at which tertiary creep might start is very difficult to be made since the occurrence of the tertiary creep can be driven by several mechanisms.

Rotherham [1] highlighted that although softening due to metallurgical causes may well occur and give rise to an increasing rate of creep, strain softening is not likely to be the general explanation of tertiary creep. Evidence of the fact that, in some class of metals, damage (in form of grain-boundary cracks) triggers the initiation of creep-stage III has been given since 1942 by Tapsell et al. [2] and supported by Hanson and Wheeler [3] who concluded that: “The onset of tertiary creep is accompanied by definitive metallographic features, which intensify steadily into definite cracks. At the same time a marked decrease in density can be observed. The decrease of density coinciding with the onset of tertiary creep can only be interpreted as the beginning of cracking”.

More recently, Dobeš [4] performed constant stress creep tests on Al–C–O alloys and concluded that, because the secondary phases in the investigated alloys are very stable, the increased creep rate found in the tertiary stage has to be attributed to the reduction of the effective cross-section of the test specimens caused by the formation of internal defects such as cavities or cracks, since the reduction of the cross-section due to the plastic deformation was compensated by the loading system used in the investigation.

According to Evans [5], tertiary creep is thought to be the result of the general long-range structure deterioration, and various damage mechanisms are possible. They would include, for example, changes in precipitate morphology, alteration in second-phase

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interfaces, changes in mobile dislocation density, grain boundary cavitation and cracking. More than one process can occur at a time. In agreement with this, Ohba et al. [6] found that, in 2.25Cr–1Mo steel, one of the main mechanisms causing tertiary or acceleration creep in the steel is the microstructure softening while microstructure observations did not give evidence of any formation of creep voids at grain boundaries or intergranular cracking, as could be understood from high values of total elongation and reduction of area.

Whilshire and Burt [7] indicated that several different processes can start tertiary acceleration, including grain-boundary cavity and crack development, neck formation and particle coarsening with precipitation-hardened alloys. According to these authors, more than one process can then affect the subsequent rates of strain accumulation, while the damage mechanisms initiating tertiary creep and causing failure can also differ.

Although the term damage is often used to implicitly indicate the formation of voids and cracks, in continuum damage mechanics (CDM) the damage notion is much more general since it accounts for the effects caused by all irreversible processes which reduce the material load carrying capability. Therefore, in creep, it can be used to account for all mechanisms responsible for the loss of material creep resistance and consequent increase of the creep rate. Kachanov [8] developed the theoretical framework of CDM in particular for creep. Successively, CDM has been extended to other failure mechanisms such as plastic deformation, fatigue (both LCH and HCF), and in few cases, brittle fracture driven by ductile cleavage [9–12]. CDM has been widely used in the literature to try to predict creep life of materials [13–17]. These formulations agree, in most of the cases, in the definition of the damage variable as the ratio of the damaged resisting section over the nominal one, while they differ in the definition of the damage evolution law. Robotnov [18], for instance, proposed that the evolution of the damage variable depends on the acting nominal stress. Lemaitre [10] proposed a damage evolution law in function of the creep time. In most of the cases, these evolution laws are derived without the support of the correlation with the physical mechanisms occurring in the material but only based on the results of macroscopic creep tests.

Recently, Bonora et al. [19] proposed, for the first time, the possibility that creep damage depends only on the inelastic deformation level reached during creep and not on the time. In this work, the conceptual framework of the CDM approach given in Bonora et al. [19] has been revised and extended. An example of the applicability of the proposed model is given through the application to IMI834 titanium.

2. Creep damage modeling

2.1. Background

The conceptual framework for the proposed approach to creep damage in metals and alloys is summarized in Fig. 1. Creep deformation occurs in the material subjected to constant load (or stress) when the temperature is sufficiently high (usually >0.3–0.4T_m, where T_m is melting temperature). The rate at which creep strain accumulates depends on both temperature and stress and it is associated to specific dislocation mechanisms (diffusional creep types or dislocation climb). During creep, different damage mechanisms may occur such as changes in precipitate morphology, alteration in second-phase interfaces, changes in mobile dislocation density, continuous secondary-phase precipitation, grain-boundary cavitation and cracking. For these latter two mechanisms, damage starts to occur in the material when the displacement field associated with a given macroscopic (average) creep strain level, is no longer accommodated by the microstructure. At this point, creep damage initiates along grain boundaries as microvoids or micro-cracks (ductile or quasi-brittle) by grain-boundary sliding and decohesion and at the secondary-phase precipitates or precipitation-coarsened dispersion in solid solutions, Fig. 2.

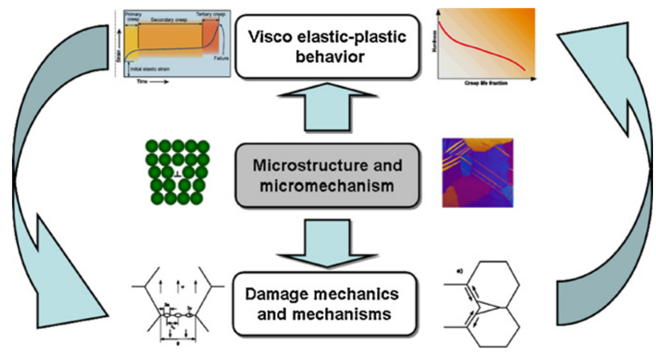

Fig. 1. Conceptual framework for creep damage modeling.

As a consequence of the damage development, the creep rate increases with the appearance of the creep stage III. The occurrence of necking, due to strain localization, results in a local increase of the stress which causes a further increase of the creep rate. The development of damage in the material meso/micro structure causes the degradation of material properties at the macroscopic length scale, such as hardness and Young's modulus, while at the microscale it affects the dislocations mechanics which governs the macroscopic material viscoplastic response.

2.2. Creep constitutive modeling

At high temperatures materials show rate-dependent plasticity. Above 0.3T_m for pure metals and 0.4T_m for alloys, the dependence of the flows stress on strain-rate becomes stronger. Relative to steady-state creep, several mechanisms control the accumulation of the inelastic strain according to the temperature and the stress levels. At elevated temperatures and low stress, as well as lower temperature but higher stress, creep occurs by diffusion. Several diffusion creep mechanisms have been recognized: lattice diffusion or Nabarro-Herring creep (high temperatures low stress), grain boundary diffusion or Coble creep, and core diffusion (low temperature higher stress). For these mechanisms the creep rate is directly proportional to the applied stress. At high temperature and sufficiently elevated stress, creep occurs by dislocation glide or glide-plus-climb. In this regime, called power-law creep, the creep rate is proportional to the applied stress to the power of n

$$\dot{\varepsilon} = A\sigma^n \quad (1)$$

Detailed modeling of each of these mechanisms, based on dislocation mechanics, has been proposed [20–23] while a detailed review of power-law creep is given in Refs. [24–27]. The coefficient

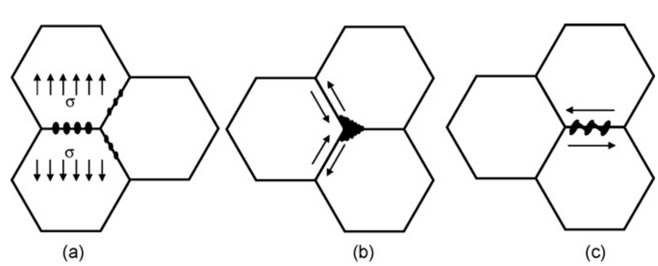

Fig. 2. Sketch of creep damage mechanisms: (a) void nucleation and growth leading to grain-boundary decohesion under normal stress; (b) ductile crack-growth initiation at triple points due to grain-boundary sliding; (c) creep crack resulting from void sheeting along grain boundary under shear stress.