Grain Boundary Failure and Geometrical Models of Creep Damage

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Abstract. A geometrical model for the grain structure of a polycrystalline material forms the basis of a statistical model of creep damage. Damage is introduced into the grain boundary structure by failure of the grain boundary facets. Suitable relations such as creep potentials are used to relate damage parameters on a microscopic level to macroscopic quantities such as the creep strain rate and the creep life. Two examples with different materials are presented together with experimental and simulation results.

Keywords. Creep damage, creep potential, grain boundary failure, damage simulation, Stochastic Geometry, Dirichlet tessellation

1 Introduction

The paper intends to show how the scatter of the macroscopic creep damage can be related to the scatter of the microstructure of the material, which is an important task in the field of lifetime predictions based on micromechanical models of creep damage. The basic idea is to perform statistical simulations of creep damage on a microscopic level and to have then a parameter, which allows one to relate the microscopic damage to macroscopic quantities like the creep strain rate or the creep life. This parameter should also be related to experimental investigations of creep damage.

In the following, a specific class of creep damage is considered. Damage is assumed to be caused by the nucleation and growth of voids on grain boundaries.

In this case, the scatter in the microstructural area comes mainly from two sources. The first is the geometrical one, characterized by the scatter in grain size and orientation of the grain boundaries. The second source is damage-related and is characterized by the scatter of the input-variables for local damage evolution.

This leads to a simulation procedure consisting of two steps: In a first step, the grain boundary structure of the material, as it appears in metallo-
graphic sections, is simulated. In a second step, damage is introduced into the grain boundary structure.

The results of the simulation have then to be compared with experimental results in order to draw conclusions about the applicability of the selected models. Modifications and improvements of the models have to be made according to experiments.

It is shown how the simulation of the microstructure can be performed using methods of stochastic geometry, how the simulated microscopic damage can be incorporated in a macroscopic formulation and how simulated and experimental results fit together.

2 Creep damage by cavitating grain boundary facets

On a micromechanical scale, different mechanisms of creep damage can be identified [1]. An important creep damage mechanism is the formation and growth of voids on grain boundaries. In metals, voids nucleate mainly on grain boundaries which are oriented perpendicularly to the loading direction. Existing voids grow by stress directed diffusion of matter from the surface of the void into the grain boundary. The growth rate of the voids is proportional to the normal stress $\sigma_n$ acting on the grain boundary.

Two limiting cases of void growth can be distinguished. If the stress $\sigma_b$ acting on the grain boundary coincides with the remote applied stress $\sigma_n$, void growth is stress-controlled. This corresponds to a situation where we have 'isotropic damage' of the material with the amount of cavitation on each grain boundary being representative for the whole section of the material. For isolated cavitating facets, however, the surrounding grains, which have non-cavitated grain boundaries, may have a supporting influence on the cavitated grain boundary, which leads to a relaxation of the normal stress $\sigma_b$ that controls void growth. If the stress on the grain boundary relaxes completely ($\sigma_b \approx 0$) the cavitated facet acts as a microcrack [2]. The growth of voids is then mainly determined by the deformation of the adjacent grains and thus becomes strain-controlled. $\sigma_b \approx 0$ corresponds to a situation where the nucleation of voids on the grain boundary is identical with the formation of a microcrack. In an advanced stage of damage, the isolated microcracks begin to interact and coalesce. Final failure occurs by formation of a dominating crack.

This damage mode, which has been observed in creep experiments, will be considered in this paper.