DAMAGE MODEL FOR BRITTLE REFRACTORY MATERIALS UNDER THERMAL SHOCK CONDITIONS

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Summary A brittle damage model based on multiscale considerations and homogenisation procedures is presented. Cell models are developed as RVE including different microstructural features. The material laws themselves are formulated on the continuum level. Local failure occurs if the damage variable reaches a critical value. For simple configuration of microstructure, the relation between stress, strain und temperature is derived from analytical considerations. In order to properly model the thermo-mechanical coupling, the temperature-dependence of material constants is taken into account. Fracture and damage mechanical approaches are combined using different techniques.

Introduction

Refractories are generally subjected to combined thermo-mechanical loading. The challenging aim in this research field is to develop refractory structures with materials properties matched for specific applications. Above all, the thermal shock resistance is the one mechanical property, which has to be improved. This requires an understanding of the influence of the microstructure.

Within the framework of continuum mechanics, it is possible to develop models at the macro level of the material and structural behaviour by introducing effective tensors which may contain a detailed representation of the microstructure and account for thermo mechanical equilibrium on the micro-level. In connection with numerical methods, stress, deformation and damage at thermo-mechanical loading can be determined for arbitrary structures and boundary value problems.

The aim of this study is to present a trans- and intercrystalline microcrack based damage model for brittle materials under thermo-mechanical dynamical loading conditions. To combine fracture- and damage-mechanical approaches, submodels containing a sharp crack tip are introduced in the FEM model at the ends of the damage zones. Within the submodels numerical and analytical approaches can be integrated, representing interactions between macro-cracks and microstructure. Results are presented in terms of numerical simulations e. g. of damage patterns or Hasselmandiagrams at different conditions.

Theoretical framework

To explain the homogenisation process, we consider a solid continuum with thermomechanical initial and boundary conditions given by stresses $\vec{t}$ and heat flux $\vec{q}$ (Neumann) or displacement $\vec{u}$ and temperature θ (Dirichlet). To incorporate local microstructural features, mesoscale cell models with linear elastic matrix properties are introduced generally containing voids, cracks or grain boundaries. The cell model with boundary ∂V describes a Representative Volume Element (RVE) [1] in the continuum. In the homogenization process generally we obtain effective elastic (C^*_{ijkl}) and thermal properties (λ^*_{ij} and α^*_{ij}) of an RVE. To derive average stress and strain tensors for the inhomogeneous field, we consider two subdomains with different properties, i.e. the defect or crack phase V_c inside the matrix material volume V_m.

The basic equation for an average macroscopic stress field in a simply connected domain V is given as

$$\langle\sigma_{ij}\rangle = \frac{1}{V}\int_V \sigma_{ij}(x_l)dV = \frac{1}{V}\int_V \left(x_{j,k}\sigma_{ik} + x_j\sigma_{ik,k}\right)dV = \frac{1}{V}\int_V (x_j\,\sigma_{ik})_{,k}dV \tag{1}$$

where $x_{j,k} = \delta_{jk}$ and $\sigma_{ik,k} = 0$ in the case of quasi static crack growth and without the action of body forces. Applying Gauss's theorem, stress is transformed to the surface. We get the average stress $\langle\sigma_{ij}\rangle$ with t_i as the traction vector and ∂V as the boundary of the RVE:

$$\langle\sigma_{ij}\rangle = \frac{1}{V}\int_{\partial V} x_j\sigma_{ik}n_k\,dA = \frac{1}{V}\int_{\partial V} x_j\,t_i\,dA \tag{2}$$

The equation of volume average macro-strain can accordingly be given as

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$$\langle \epsilon_{ij} \rangle = \frac{1}{2V} \int_V (u_{i,j} + u_{j,i}) dV = \frac{1}{2V} \int_{\partial V} (u_i n_j + u_j n_i) dA\,. \tag{3}$$

Applying the superposition principle and considering linear elastic behavior for the material matrix, the average strain is decomposed into a part due to the matrix and one due to the defect phase. In case of microcracks of zero stiffness inside the material matrix, Eq. (3) leads to the result

$$\langle \epsilon_{ij} \rangle = c_M \langle \epsilon_{ij} \rangle_M + \frac{1}{2V} \int_{S^+} (\Delta u_i n_j + \Delta u_j n_i) dA \;\; = c_M \, \langle \epsilon_{ij} \rangle_M + \langle \epsilon_{ij} \rangle_C \tag{4}$$

with $\langle \epsilon_{ij} \rangle_M$ as average strain in the surrounding matrix of volume $V_m = c_M V$ and the displacement jump at the crack interface. For a defect phase consisting of microcracks, the factor $c_M = 1$. The last term of Eq. (4) $\langle \epsilon_{ij} \rangle_C$ describes the average strain of the defect phase [2].

The criterion for microcrack evolution has been chosen in equivalence to a classical R-curve based Mode-I macro crack growth criterion [3]

$$K_I(\sigma, a) = K_R(\Delta a) \tag{5}$$

with K_I as Mode- I SIF depending on local stress and the crack length a and K_R depending on the crack propagation length Δa.

The essential thermal parameters of refractory materials which influence reliability and life time are thermal conductivity λ_{ij}, thermal expansion α_{ij} and specific heat c_H. Thermally induced stresses are calculated from Hooke's law introducing the temperature change $\Delta\theta$

$$\sigma_{ij} = C^*_{ijkl} \epsilon^{el}_{kl} = C^*_{ijkl} \left(\epsilon^{tot}_{ij} - \alpha_{ij} \Delta\theta \right) \tag{6}$$

where ϵ^{tot}_{ij} is the total strain and ϵ^{el}_{kl} denotes the elastic strain. In order to simulate thermal stress, the temperature distribution in the material is required. Therefore, the thermal field problem

$$\rho c_H \frac{\partial \theta}{\partial t} = \lambda_{ij} \frac{\partial^2 \theta}{\partial x_i \partial x_j} \tag{7}$$

is solved first, supplying a transient temperature field as loading quantity for the mechanical boundary value problem.

A thermal shock FE-simulation was made imposing an intermittent heat flux on the top surface of a plate. Each thermal shock was (0,5 s thermal loading) followed by a break of 2 s. The locally absorbed surface heat flux is 42 MW/m². Fig. 1 shows the damage patterns of thermal shock performance at different load cycles.

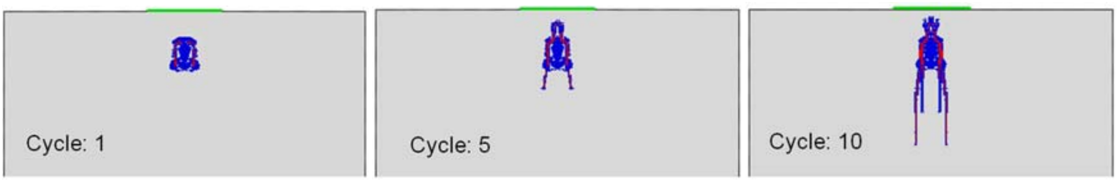

Fig. 1 Damage patterns at different thermal shock cycles (0,5 s heating + 2 s break), green: surface heat flux 42 MW/m², blue: pre-damage area, red: destroyed domains/ macrocrack

CONCLUSIONS

In this short paper it is shown, that within the framework of continuum mechanics, thermo mechanical damage models can be developed at the macro level of brittle refractory material by introducing effective tensors and temperature dependent parameters. Results show damage patterns under thermal shock conditions. In any case damage zones are initiated at locations with highest temperature and tensile stress gradients.

References

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