ON THE METHOD OF DAMAGE ASSESSMENT IN POROUS CERAMICS

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ABSTRACT

The paper proposes a new method of estimation of the current mechanical characteristics and of damage evolution in porous ceramics subjected to mechanical loading. The essence of the method is the modelling of material damage development both by micromechanical and phenomenological approach. The micromechanical approach requires determination of the initial material structure by SEM. The phenomenological approach needs experimental testing of the material under quasi-static compression with observation of the several repeated cycles of: loading, unloading and subsequent reloading, what enables detailed analysis of changes of the elastic material constants and further damage assessment. Micromechanical description of damage evolution in ceramics comprises the consideration of distributed pores and cracks inside the so called Representative Surface Element and application of averaging procedure in order to get the global material behaviour. In the phenomenological approach we introduce an internal parameter describing macroscopic material damage (the second order tensor) and specify criteria of cracks nucleation, their propagation and final failure of the material sample. Experimental part of the method covers microscopic (SEM) observation of the initial ceramic structure, compressive loading tests with unloading and reloading until the specimen failure, SEM observations of fracture surfaces in order to specify the way of cracking and determination of fracture toughness K_{Ic} by three point bending of notched beams. Tests are carried out on polycrystalline samples of Al_2O_3 and MgO with the porosity from 0 to 30%. They show that the real polycrystalline ceramics at the moment of fabrication have an initial structure consisting of grains, grain boundaries, primordial microflaws (cracks, pores) etc. During the loading and unloading process the material structure changes. In particular one can observe:

- microdefects nucleation,
- crack growth with varying direction of propagation (wing crack model),
- coupling of microcracks into macrocracks leading to the final material failure.

The process of compressive loading-unloading is the most often met case of loading in engineering practice, for example as a result of changeable pressure acting on the ceramic furnace lining in steel industry, ceramic layers of the pistons' crowns in combustion engines etc. Main advantages of the proposed method are:

- examination of brittle materials behaviour in the controlled deformation process,
- estimation of the global material stiffness tensor by deformation analysis during loading and unloading,
- current anisotropy assessment of the material by the elastic constants depending on damage evolution.

1 INTRODUCTION

Ceramic materials are nowadays widely used in many fields of technology. An important group of ceramics are porous materials, which may be considered as multiphase materials with a gas in pores as a second phase. They find an application in filtration, sound or heat insulation, furnace lining in steel fabrication and others (e.g. Davidge [1], Evans et al. [2], Pampuch [3]).

Considerable influence on mechanical strength of ceramic materials has their initial structure. It may be characterised by dimensions of grains, grain boundaries' properties, an existence of pores, cracks etc. The behaviour of ceramics under loading and unloading is strongly related to damage growth, what substantially influences global material mechanical characteristics. The necessity of better understanding of the nature of these processes results from the growing field of practical applications of ceramic materials in various branches of technology.

Up to nowthe initial characteristics of ceramic materials were considered as invariant, i.e. these materials were described as linear-elastic-brittle. Such approach is a large simplification, because mechanical properties of the real structural materials change during deformation.

The proposed method presented here is based on micromechanical modelling taking into account the real internal structure of porous ceramics. The examination of this process and it's theoretical description will allow a new way of determination of elastic features change of materials with specific initial structure. Moreover, understanding and modelling of damage growth mechanisms will become possible.

There are several items that make the method original:

- research of porous ceramics under variable compressive loading,
- theoretical description of material deformation process taking into account an anisotropy of microcracks propagation,
- introduction of phenomenological approach applying tensor damage parameter
- comparison of micromechanical and phenomenological description of material behaviour in order to give physical interpretation of macroscopic damage parameter.

The research of damage processes of ceramic materials pertains to the most up-to-date problems of polycrystalline material behaviour. So far there were mainly uniaxial testing of ceramics conducted. There is a lack of more accurate experimental data of ceramic materials under compression (e.g. Munz [4]). Furthermore, there were not considered the process of gradual degradation of elastic characteristics following the development of material deformation. The researchers were only determining final strength characteristics related to current material damage state.

Thus, understanding of the interdependence between structure parameters and global material respose is still unsatisfactory. Theoretical explanation of phenomena proceeding inside material during compressive loading is being described on the basis of wing-crack model. The idea of Moss and Gupta [5] was developed by Horii and Nemat-Nasser [6] and Nemat-Nasser and Obata [7], as well as Ashby and Hallam [8]. Comprehensive work on wing-cracks propagation in ceramics gave Sadowski [9], where internal structure parameters were considered. However, there were no porosity taken into account. The basic formulae giving the so called effective elastic constants, as Young modulus and Poisson ratio for porous materials with cracks gave Kachanov [10]. Sammis and Ashby [11] found, that pores may act as crack sources. Hardy and Green [12] stated, that mechanical characteristics (Young modulus, fracture toughness) of porous alumina (with porosity from 20 to 40 percent) depend on degree of densification and sintering. This makes microstructure analysis is very important and essential.

The influence of various parameters on the dependence of mechanical characteristics on porosity under tension discussed Rice [13, 14] in his works. On the other hand Lu et al. [15] on the basis of pure experimental data introduce theoretical models defining macromechanical features. Those are, however, purely experimental relations without physical microanalysis of damage growth in porous materials.

Proper analysis of brittle fracture in compression must base on full understanding of cracking mechanisms and finding universal fracture criterion. In order to apply porous materials with success we must understand their mechanical qualities in relation to their microstructures. Thus, it is necessary to elaborate more sophisticated experimental techniques and improve theoretical models towards their better compatibility with the real materials.

2 MODEL DESCRIPTION

An idea of theoretical description of internal structure changes in polycrystalline porous ceramics was proposed by authors of this paper in several articles (e.g. Sadowski [16 – 19], Samborski [20]). We propose to use for the purpose of the ceramics behaviour description the following models:

- micromechanical, based on averaging procedures of existing defect arbitrary distributed inside material,
- phenomenological, in which the changes of structure are described by internal parameters.

Macroscopic constitutive equation describing all defects propagation inside ceramic material is the following:

$$\varepsilon_{ij} = S_{ijkl}\left(p, \omega_{nm}, \tilde{p}\right)\, \sigma_{kl} \tag{1}$$

where: ε_{ij}, σ_{kl} are deformation and stress tensors, respectively. S_{ijkl} is the compliance tensor of rank four, dependent on the following internal parameters: porosity p, damage tensor of rank two ω_{nm} and plastic effects $\tilde{p}$.

As it is known, deformation in ceramics is very small. Therefore, in modelling we make an assumption of the global deformation tensor (ε_{ij}) decomposition in several parts: purely elastic $\varepsilon_{ij}^{\mathrm{e}}$, as the material matrix response, $\varepsilon_{ij}^{\mathrm{po}}$ connected with pore existence, $\varepsilon_{ij}^{\mathrm{cr}}$ describing crack growth and $\varepsilon_{ij}^{\mathrm{pl}}$ describing plastic effects. Thus, we may write:

$$\varepsilon_{ij} = \varepsilon_{ij}^{\mathrm{e}} + \varepsilon_{ij}^{\mathrm{po}} + \varepsilon_{ij}^{\mathrm{pl}} + \varepsilon_{ij}^{\mathrm{cr}} \tag{2}$$

In general case of loading of the material damage development induces anisotropic behaviour of the ceramics. For the purpose of this effect description we introduce tensor damage parameter of the following form:

$$\omega_{ij} = \phi_1\delta_{ij} + \phi_2\sigma_{ij} + \phi_3\sigma_{im}\sigma_{mj} \tag{3}$$

where ϕ_1, ϕ_2, ϕ_3 are scalar functions of the stress tensor σ_{ij}. The last two terms of the above-written equation make it possible to describe anisotropy.

Formulation of the particular forms of the constitutive equations for analysed porous ceramics is currently the aim of our research.

3 EXPERIMENTAL PROCEDURE

Experimental aspect of the method covers uniaxial compression tests of samples made of Al_2O_3 and MgO with various porosity, what enables an estimation of the global material response to applied load (compliance tensor among others). Detailed microscopic analysis of internal material structure before compression tests and after failure provide with essential data for micromechanical modelling.

There are three types of tests:

- uniaxial compression of cylindrical specimens subjected to loading-unloading and subsequent reloading (see Fig. 1). The analysis of the permanent deformation after each unloading cycle enables estimation of damage level and current material anisotropy caused by cracking;
- three-point bending of notched beams in order to get critical value of the stress intensity factor (K_{Ic});

- microscopic observations of material structure changes concerning: initial porosity estimation, grain diameter and grain boundary texture as well as fracture surface observation leading to determination of the way of cracking (through grains or across boundaries).

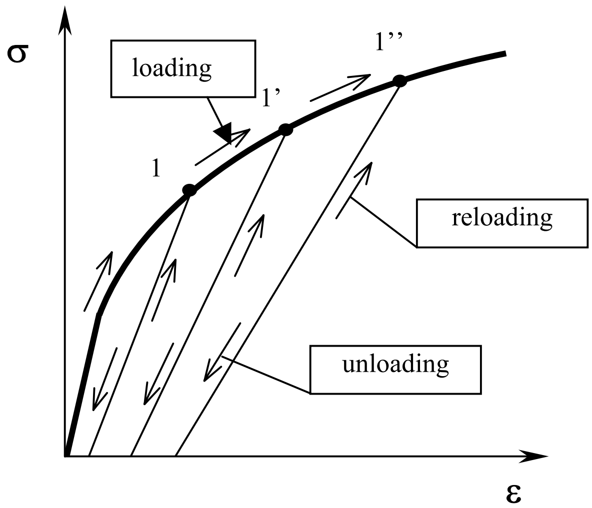

Figure 1: A scheme of the cycling loading-unloading process of porous polycrystalline ceramics.

In the experiments we use the following equipment:

- universal testing machine *Zwick Z100*,
- Wheatstone bridge *Esam Traveller*,
- Scanning Electron Microscope,
- optical microscope *OPTECH Biostar*,
- digital camera *Nikon Coolpix 990*,
- image analysis software *AnalySIS 3.0*.

4 REMARKS

The modern method of the description of the material behaviour with internal structure requires both experimental and theoretical approaches. The proposed method will enable description of damage evolution process during variable loading of the material taking into account most essential phenomena developing inside the material. The consistency of experimental macroscopic test with theoretical approach makes the proposed method applicable for description of other engineering materials having internal structure.

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