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Finite element analysis of the fatigue crack growth rate in transformation toughening ceramics

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Abstract

The fatigue crack growth rate in the zirconia tetragonal polycrystal is analyzed through the finite element method. In order to achieve this purpose, a continuum based constitutive law for materials subjected to phase transformations has been suitably implemented into a commercial finite element code. The fatigue crack growth in a notched beam, subjected to a cyclic four points bending load, has been investigated through a sensitivity analyses with respect to the two most relevant constitutive parameters: one accounting for the amount of the transformation strain and one accounting for the activation energy threshold. The fatigue crack growth rate typical of transforming materials is characterized by two distinct stages: at the beginning of the crack propagation process, the crack growth rate exhibits a negative dependency on the applied stress intensity factor; thereafter, a linear positive dependency is observed. This two stage process is well caught by the finite element model presented in this paper. Moreover, the response of the computational analyses has shown that the strength of the transformation process is determinant for the crack growth process to be arrested.

Keywords: Transformation toughening; Fatigue; Zirconia; Stress intensity factor; Finite element method

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1. Introduction

Strength and fatigue life of the ceramic materials are extremely sensitive to pre-existing flaws which develop during the manufacturing process. These flaws act as initial defects determining stress concentration and potential crack growth. This is owed to the brittle nature of ceramics that makes the issue of fracture toughness of major concern in designing reliable ceramic components to be used in structural applications. Nowadays, advanced ceramics offer new possibilities in designing structural components thanks to their toughening mechanisms, based on the phase transformations phenomena, which delay the crack propagation. The transformation toughening mechanisms are peculiar features of partially stabilized zirconia (PSZ), tetragonal zirconia polycrystal (TZP) and zirconia toughened alumina (ZTA), and can be different according to the chemical composition of the material.

Pure zirconia is an oxide (ZrO_2) which cannot be obtained at room temperature without being damaged by distributed microcracks due to phase transformations occurring during the cooling process. For this reason pure zirconia is not used as a structural material. A stabilization of the cubic phase during the cooling process, by means of doping with calcia (CaO), magnesia (MgO), yttria (Y_2O_3) or ceria (CeO_2) can provide a material which does not exhibit damage or smeared cracks at room temperature. The material considered in this paper is an yttria doped tetragonal zirconia polycrystal (TZP). From the chemical microstructural point of view, this material is constituted of tetragonal crystals (t-ZrO_2) only. The peculiar mechanical property of the zirconia-based ceramics, and particularly of the TZP, is the phase transformation induced by the stress state. The tetragonal phase can spontaneously undergo to phase transformation at room temperature to a more stable monoclinic phase if a sufficient amount of mechanical energy (stress state) is provided to the system. The phase transformation is accompanied by an irreversible transformation strain state. The amount of this transformation strain depends on the lattice parameters misfit between the parent and the generated phases and on several other parameters like crystal orientations.

It is well known that the fracture toughness of zirconia-based ceramics can be greatly enhanced by exploiting the stress-induced phase transformations in the zirconia particles or zirconia grains (Evans and Heuer, 1980; Munz and Fett, 1998; Hannink et al., 2000; Rauchs et al., 2001, 2002; Kelly and Rose, 2002). This phenomenon produces the so-called *frontal toughening mechanism* or *extrinsic shielding mechanism* which originates from the development of permanent or transformation strains, such as those produced by the martensitic-type phase transformations, in the crack wake (Ritchie, 1999).

When the crack propagates, the crack's tip travels and the stress concentration migrates as well. This promotes new phase transformations in the zone ahead of the crack tip; whereas in the wake of the crack the particles or grains previously transformed stay in their new transformed state. An area of material subjected to permanent strains (transformation strains) is therefore created along