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Understanding the tensile strength of ceramics in the presence of small critical flaws

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ABSTRACT

The effect of small critical flaws on the strength of polycrystalline ceramic materials is analyzed with the help of an initiation criterion combining both a stress and an energy conditions. If the size of the defect is smaller than the characteristic material length, numerical predictions reveal that the defect (either sharp or blunt) has no effect on the strength. This result is in a good agreement with experimental results obtained from the strength measurements of ceramic materials with controlled flaws. Combining two fracture tests after introducing flaws with controlled sizes enables to identify the fracture parameters of the ceramic material.

1. Introduction

The use of ceramic materials has been usually motivated by their outstanding structural properties such as oxidation and corrosion resistance, high temperature stability, hardness and wear resistance. Some examples are high temperature resistant parts for metallurgical processes, wear-resistant plates for paper machines, or bio-inert implants in medicine. Technical ceramics are also required in advanced systems due to their unique functional properties, e.g. extreme non-linear dependence of electrical resistance with temperature (used in thermistors), electric field (used in varistors), and a high piezo-electric coefficient (used in sensors and actuators).

A fundamental issue affecting the functionality, lifetime and mechanical reliability of such components and systems is the initiation and uncontrolled propagation of cracks in the brittle ceramic parts. Contrary to metals or polymers, crack propagation in ceramics is usually catastrophic due to the lack of plastic deformation upon tensile loading. Ceramics are said to have low tolerance to damage, due to their low resistance to the propagation of cracks (low fracture toughness). Another limitation for applications demanding high reliability is the inherent scatter in strength caused by the different size, type and location of critical flaws in the ceramic (e.g. pores, inhomogeneities, surface defects, contact cracks), introduced during processing, machining or in service. As a result, ceramic parts hold an inherent probability to failure upon loading, their strength being characterized by a distribution function described in most cases by the Weibull theory [1].

The tensile strength of ceramics is very sensitive to the presence of flaws, which usually act as crack initiators [2]. Common critical flaws are spherical pores generated during the ceramic processing [3,4] or sharp defects introduced by surface machining [5].

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Nomenclature

Parameters

a_0	flaw length
A	dimensionless incremental energy release rate
B	specimen half-length
d	size of intrinsic defects controlling the strength
E	Young's modulus
g	average grain size
G^c	fracture energy
G_{inc}	incremental energy release rate
h	specimen width
k	geometric parameter
k_{xx}	dimensionless opening normal stress
K_I^c	fracture toughness
ℓ	crack length
ℓ^*	crack length at initiation
L^c	characteristic length
W	potential energy
y	coordinate (direction perpendicular to the applied loading)
α	scaling factor
λ	singularity exponent at the tip of a V-notch
ν	Poisson's ratio
σ	applied traction stress
σ_{xx}	opening normal stress
σ^c	tensile strength
σ^*	applied traction stress at initiation
ω	V-notch half opening angle

Superscripts

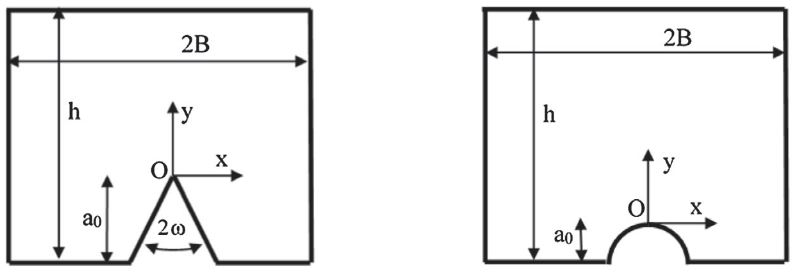
c	critical values
$*$	values at initiation

Acronyms

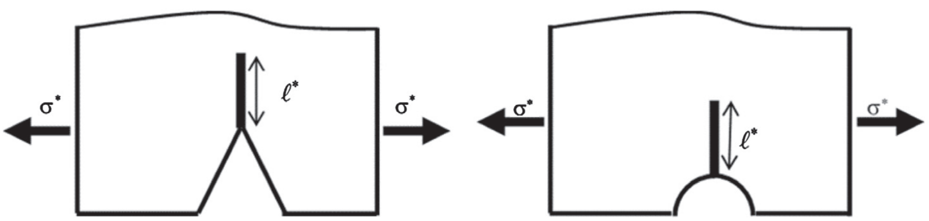
CC	coupled criterion

The relation between such extrinsic flaws and the ceramic strength is usually assessed by estimating an "equivalent crack length" at failure [6], also called Griffith crack length which is the basis of a linear elastic fracture mechanics analysis. For instance, in the case of a blunt defect like a rounded pore, the equivalent crack length is postulated to be a small radial crack in the vicinity around the pore [7]. In case of a sharp defect like a notch, it is assumed that an array of micro-cracks along the notch wedge develops during loading, thus triggering the fracture of the brittle material [8,9]. The latter is indeed the hypothesis for measuring fracture toughness in ceramics using the Single Edge V-Notched Beam testing protocol [10].

Despite the advances in fracture mechanics, prediction of crack initiation in ceramics and the role of microstructural features in governing the fracture is still a matter of research. In this paper, we aim to analyze the effect of small flaws on the strength of polycrystalline ceramic materials. For this purpose, a coupled (stress-energy) criterion (CC) within the framework of finite fracture mechanics is employed. It requires strength and fracture toughness values to describe the initiation of a crack near a stress concentrator. An advantage of this approach is that the critical stress can be easily determined without requiring any assumption



a) Specimen with a sharp or a blunt flaw



b) Crack initiation in the vicinity of the sharp or the blunt flaw

Fig. 1. Geometry of a specimen with a surface flaw and crack initiation under tensile loading in the vicinity of the surface flaw.