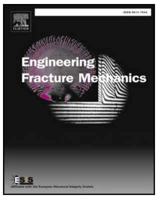
Engineering Fracture Mechanics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech



Determination of fracture strength and fracture energy of (metallo-) ceramics by a wedge loading methodology and corresponding cohesive zone-based finite element analysis

Ann-Sophie Farle[a], Jayaprakash Krishnasamy[b], Sergio Turteltaub[b], Cees Kwakernaak[a], Sybrand van der Zwaag[b], Willem G. Sloof[a,*]

[a] *Department of Materials Science and Engineering, Delft University of Technology, Mekelweg 2, 2628CD Delft, The Netherlands*
[b] *Faculty of Aerospace Engineering, Delft University of Technology, Kluyerweg 1, 2629HS Delft, The Netherlands*

ARTICLE INFO

Keywords:
Fracture strength
Fracture energy
Cohesive-zone modelling
Ceramics
Acoustic emission
Self-healing

ABSTRACT

A wedge loaded testing methodology to determine the fracture energy and strength of (semi-) brittle (metallo-)ceramics is presented. The methodology combines a tailored specimen geometry and a comprehensive finite element analysis based on cohesive zone modelling. The use of a simulation-based approach to extract both fracture strength and energy from experimental data avoids the inherent inaccuracies found in closed-form expressions that rely on a priori assumptions about the deformation field. Results from wedge splitting tests on Ti_3SiC_2 and Ti_2AlC (MAX phase) materials are used to illustrate the procedure. The simulation-based approach is further validated by comparing the fracture strength and fracture energies predicted by the proposed method and those indicated by a conventional four-point bending fracture toughness test (ASTM standard). The new protocol offers the possibility to measure not only the fracture properties of brittle material in its pristine state but also in the healed state.

1. Introduction

Testing procedures to accurately quantify the fracture strength and fracture energy of materials typically depend on a variety of factors such as the material's elastic characteristics (compliant or stiff) and its fracture response (ductile or brittle). The absolute values may also depend on loading rates, the measured primary response variables such as loads and displacements and the post-processing of the recorded data. Ease of sample preparation, insensitivity to non-defined parameters and repeatability of the results also plays a significant role in the design of a testing procedure.

For brittle materials, it is also known that the measured fracture properties depend on the ratio between the size of the critical flaw(s) and the zone where the stress concentrates in the sample (e.g., the measured fracture strength in a tensile test would typically be different from that in a bending test). Bending tests have been accepted as the simplest yet least precise test method to determine fracture strength and fracture energy of brittle materials [1,2]. Bending tests commonly require controlled pre-cracks, which are difficult to produce and measure in most (semi-) brittle materials [2,3]. Moreover, this test, assuming a machining induced pre-crack in the material, may overestimate the fracture toughness and is highly sensitive to machining induced surface imperfections [3]. The sensitivity to surface flaws furthermore creates the necessity for higher sampling sizes to compensate for measurement error. The wedge splitting test was established by Tschegg [4]. Wedge-loading to determine fracture properties in concrete and concrete like

---

[*] Corresponding author.
E-mail addresses: annsophiefarle@hotmail.com (A.-S. Farle), W.G.Sloof@tudelft.nl (W.G. Sloof).

https://doi.org/10.1016/j.engfracmech.2018.03.014
Received 23 November 2016; Received in revised form 11 February 2018; Accepted 13 March 2018

Nomenclature

(X)FEM	(eXtended) Finite element analysis
CZM	Cohesive Zone Modelling
Δ	Effective cohesive opening displacement
E	Young's modulus
EDM	Electric discharge machining
f	Coefficient of kinematic friction
G_c	Fracture energy
K	Cohesive stiffness
K_{1C}	Stress intensity factor in mode I
LEFM	Linear Elastic Fracture Mechanics
l_{fpz}	Cohesive zone length
MAX	$M_{n+1}AX_n$
SCB	Semi-circular bend test
T	Effective traction
ν	Poisson's ratio
WLS	Wedge loaded specimen
σ_c	Critical traction & effective fracture strength

materials has been performed by Bruhwiler et al. [5] but not yet modified and applied to the specific requirements of ceramic materials. In addition to the aforementioned difficulties, the quantification of crack-healing efficiency in self-healing materials requires methods to create stable cracks. Chevron-notched specimens can negate problems caused by pre-cracking attempts so in this sense this sample geometry is generally viewed as an improvement compared to samples without chevrons [2]. Furthermore, when setting the requirements for an optimally informative test method, it is clear that an ideal test should not only report the load-displacement data but also the actual crack length at every stage of the cracking process. For the determination of the crack length both optical [6] and acoustical methods [7] are available while in specific cases also X-ray tomographic methods [8] can be used.

Aside from the physical testing requirements defined above, an important aspect of a testing methodology is the interpretation of the measured data. The quantities of interest, fracture strength and fracture (propagation) energy, are typically not measured directly but rather need to be derived from the measured response variables such as loads and actual crack dimensions. For fracture properties, the traditional approach has relied on using the theory of Linear Elastic Fracture Mechanics (LEFM), which, often in combination with analytical solutions for simple geometries or finite element simulations (FEM) for complex geometries, is used to derive closed-form expressions from which the fracture strength and/or the fracture toughness can be computed (i.e., a critical value of the stress intensity fracture at which a crack propagates) [9,10]. An alternative approach is to conduct finite element (FEM) numerical simulations of the fracture test using a Cohesive Zone Modelling (CZM) approach [11,12]. In combination with the experimental data, the simulations can be used to extract the fracture properties of the material taking into account the whole fracture process, namely nucleation and propagation of a crack. CZM combines ingredients found in stress-based and energy-based formulations for fracture mechanics. CZM has been implemented in conjunction with cohesive elements and, more recently, within the so-called eXtended Finite Element Method (XFEM). This methodology overcomes some intrinsic limitations of the (traditional) LEFM approach since it can model both nucleation and propagation of cracks. CZM, with either cohesive elements or XFEM, has been applied, for example, in [13] to predict the fracture behaviour of adhesive joints, in [14] for the analysis of delamination in fiber-reinforced polymer (FRP) beams, in [15] to simulate the crack propagation in wood, in [16] to predict the fatigue crack nucleation and propagation in quasi-brittle materials, in [17] to estimate the fracture toughness of free standing 8 wt.% Y_2O_3-ZrO_2 (8YSZ) coatings and in [18] to analyze a specimen geometry to enhance crack stability for brittle materials and to improve closed-form formulas by deriving the so-called geometrical factor for different specimen dimensions. Other relevant work includes [19], where simulations

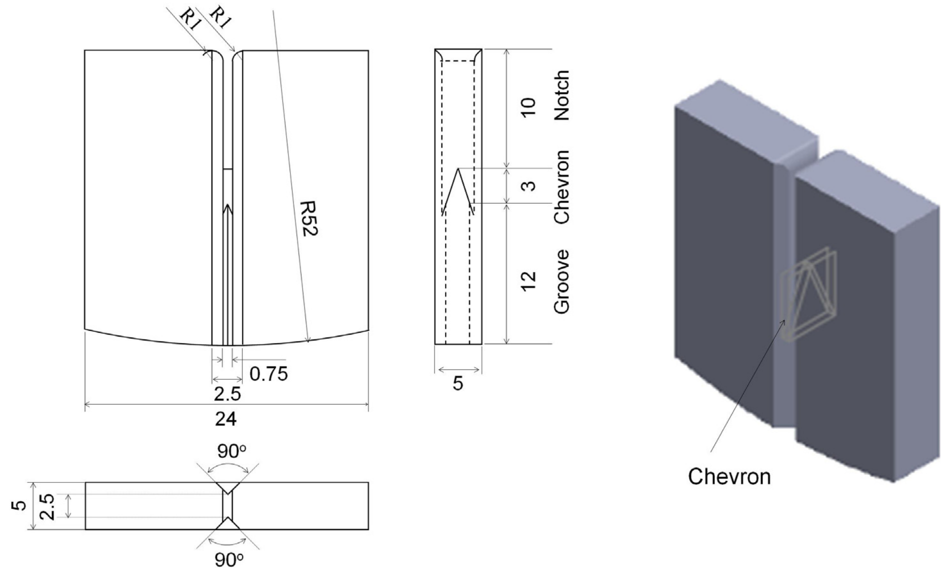


Fig. 1. Wedge splitting test specimen geometry with lengths in mm.