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A laser irradiation disc test for fracture testing of refractory fine ceramics

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Abstract

The critical stress intensity factor, tensile strength and crack stability were analysed for a zirconia refractory by parameter identification based on a laser irradiation test and a finite element simulation. Furthermore, the results for the specific fracture energy were determined for different assumed cohesive behaviours. The tests were carried out on notched discs that were irradiated at their centres. During the tests, temperatures are recorded by a thermo vision camera and the crack propagation by an acoustic emission recorder. Acoustic emission allowed for the determination of the onset of crack initiation (time t_1) and unstable crack propagation (time t_2). A finite element model representing the geometry of the sample was built to determine the fracture mechanical parameters from t_1 and t_2. This method is believed to be favourable for rather brittle refractory ceramics, whereas for less brittle materials, a wedge splitting procedure according to Tschegg is considered more favourable.

Keywords: Fracture testing; FE simulation; Fracture energy; Zirconia refractory; Laser irradiation

1. Introduction

In this paper, a newly developed method for the determination of tensile strength f_t, based on the assumption of different cohesive behaviours, the crack stability and the specific fracture energy G_F of fine ceramic refractory specimens are presented. Usually, a wedge splitting test is applied for the measurement of the fracture energy of refractory materials.[1] This procedure has several advantages compared to other fracture mechanical tests. It allows for stable crack propagation even for relatively large specimens of ordinary ceramic refractories, as demonstrated in greater detail in Ref. 2. The method is therefore suitable for materials with a relatively large maximum grain size (e.g., 5 mm), which requires huge specimen dimensions (e.g., 100 mm edge length). In addition, some fine ceramic refractories are applied in metallurgy, e.g. zirconia nozzles for steel casting. These materials are more brittle than ordinary ceramic refractory materials. On the one hand, this brittle behaviour impedes stable crack propagation, but on the other hand, due to the low maximum grain size, by far smaller specimens maybe applied. Such smaller specimens reduce the elastically stored strain energy and supports crack stability. Therefore, one possibility for the fracture testing of brittle fine ceramics refractories is to apply a miniaturised wedge splitting test. However, especially for small specimens, it appears to be desirable to avoid the effort for mechanical load transmission especially for elevated temperatures. To this end, a thermomechanical testing method for fine ceramics refractory materials based on a notched disc irradiated by a laser at its centre was developed. In this method, the elastic energy in the sample, i.e., the crack driving force can be controlled by the laser power.

Several studies concerning the use of irradiated discs for the determination of thermal shock resistance can be found. For example, Sato et al.[3–5] and Liu et al.[6] tested carbon anodes by a so-called arc discharge technique. Stress intensity factors K_{IC} and crack mouth opening displacement CMOD have been evaluated as well as thermal shock resistance parameters. The CMOD is the distance between the crack faces in the root of the notch. Schneider et al.[7] investigated the thermal shock resistance (K_{IC} and fracture toughness) of Si_3N_4 by tungsten halogen lamp irradiation. For notched discs, analytical solutions for K_{IC} also exist and can be evaluated as demonstrated in Refs. 8–10. In the presented work, K_{IC} values and results for the tensile

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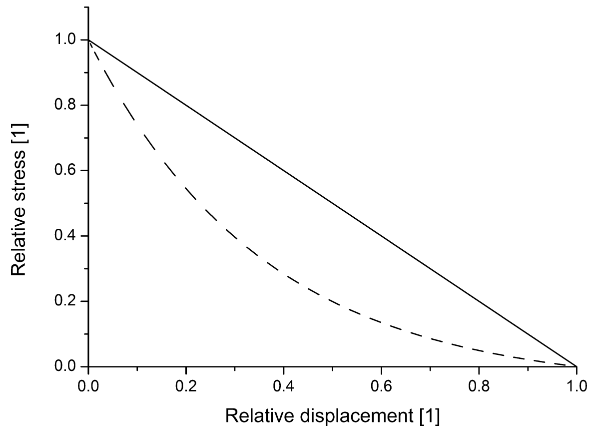

Fig. 1. Relative stress σ/f_t as a function of relative crack opening x/x_{ult} for exponential and linear cohesive behaviour.

strength and fracture energy have been evaluated from finite-element simulations carried out with the commercial software package ABAQUS. The results have been applied to evaluate thermal stress resistance parameters according to Kingery[11] and Hasselman[12] but also to gain input parameters for simulations based on the fictitious crack model (FCM) according to Hillerborg.[13] This model is often applied for the simulation of the thermomechanical behaviour of refractory materials.[14] Such materials behave linear elastically before the tensile strength is reached. Hillerborg assumes that the stress equals the tensile strength f_t at the crack tip. The failure criterion for crack opening under tensile loading is based on the maximum principle stress criterion according to Rankine.[15] Based on this criterion, failure is initiated if the first principle stress equals the tensile strength. The FCM describes the post-peak behaviour by cohesive forces between the crack faces. The physical justification is the energy consumption for crack propagation due to friction between the crack faces. The relationship between stress and crack opening may, for example, be defined by linear (Eq. (1)) or exponential (Eq. (2)) cohesive behaviour (Fig. 1),

$$\sigma = f_t \cdot \left[1 - \frac{x}{x_{ult}}\right] \tag{1}$$

$$\sigma = f_t \cdot \left[1 - \left(\frac{1 - e^{(-\varphi\cdot(x/x_{ult}))}}{1 - e^{-\varphi}}\right)\right] \tag{2}$$

where σ is the stress transferred between the crack faces, f_t the tensile strength x the crack opening displacement, x_{ult} the ultimate crack opening and φ a non-dimensional material parameter defining the cohesive behaviour. For $x > x_{ult}$, no stresses are transferred between the crack faces. Typical values for f_t and x_{ult} are 60 MPa and 8×10^{-3} mm, respectively. In addition to f_t and softening behaviour the cohesive behaviour can also be defined by f_t and the inclination ξ as a function of the crack opening (Eq. (3)).

$$\xi(x) = \frac{\partial\sigma(x)}{\partial x} \tag{3}$$

Frequently, thermal shock parameters are used to quantify the thermal shock resistance of ceramic materials. According to the theories of Kingery[11] and Hasselman[12] two routes appear to be possible in order to improve thermal shock behaviour. On the one hand crack initiation could be prevented at all; on the other hand the crack propagation could be hindered. For both cases parameters were developed for the characterisation of thermal shock resistance. For each case it depends on the application which route may be the more promising.

The thermal shock parameter R (Eq. (4)) according to Kingery is related to crack initiation:

$$R = \frac{f_t}{\alpha E}(1 - \nu) \tag{4}$$

R is the temperature difference between the minimum and the integral mean temperature in an infinite plane plate causing crack initiation, α is the coefficient of linear thermal expansion, E the Young's modulus and ν the Poisson ratio. As a measure of resistance to crack propagation Hasselman proposed the following relation based on the ratio of elastic strain energy to work of fracture[12]:

$$R'''' = \frac{\gamma \cdot E}{f_t^2} \tag{5}$$

Here, γ is the specific fracture surface energy. Because γ refers to the double of the nominal crack surface area and the specific fracture energy G_f to the single crack surface area, the following relation is valid:

$$\gamma = \frac{G_f}{2} \tag{6}$$

The so-called characteristic length,[13]

$$l_{ch} = \frac{G_f \cdot E}{f_t{}^2} \tag{7}$$

is – through Eq. (6) – closely related to R'''':

$$l_{ch} = 2R'''' \tag{8}$$

Both R'''' and l_{ch} are calculated from the relation between work of fracture and elastic energy in the moment of crack initiation. High values for l_{ch} indicate low brittleness, stable crack propagation and higher resistance against crack propagation. Additionally Hasselman described R_{st} as the thermal stress crack stability which is a measure of the resistance to quasistatic crack growth for long, pre-existing cracks:

$$R_{st} = \sqrt{\frac{\gamma}{\alpha^2 E}} \tag{9}$$

2. Test design

Thermomechanical loading was performed by the laser irradiation of 1 mm thick discs with a diameter of 50 mm and a 10 mm notch in the radial direction. The diameter of the laser spot was 6 mm (Fig. 2). This irradiation generates higher temperatures in the centre of the discs compared to those at the outer rim. The thermal expansion at the centre of the disc is constrained by the cooler edge, causing tensile circumferential stresses at the edge and compressive stresses in all directions