Engineering Fracture Mechanics 76 (2009) 2249–2259

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Uniaxial and biaxial fracture behaviour of refractory materials

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ARTICLE INFO

Article history:
Received 31 March 2009
Received in revised form 22 June 2009
Accepted 3 July 2009
Available online 16 July 2009

Keywords:
Refractory materials
Biaxial fracture properties
Wedge splitting test
Damage
Acoustic emission

ABSTRACT

Mechanical fracture properties of specimens taken from refractory materials of different brittleness are described using the wedge splitting method according to Tschegg in uniaxial and biaxial load cases. Notch-tensile strength, fracture energy and the characteristic length were determined. Fracture energy under a uniaxial load is more or less the same for all materials; if a load becomes biaxial, values fall to approx. 70% in materials with reduced brittleness and to 40% in brittle materials, compared to uniaxial values. The sensitivity against crack propagation (l_{ch}) changes insignificantly under both uniaxial and biaxial loading of brittle and brittleness-reduced materials.

1. Introduction

In the past, different test methods were applied to specify the mechanical fracturing properties of refractory materials under a uniaxial load. Fig. 1a shows a schematic representation of a mode I crack in a cube. The notched beam test [1,2], the compact tension method [1] and the wedge splitting method according to Tschegg [3] are examples of test equipment. The wedge splitting method according to Tschegg can be applied on refractory materials in order to determine fracture mechanical properties (e.g. the specific fracture energy or the notch-tensile strength) at elevated test temperatures (up to 1500 °C) [4,5].

In practice, exclusive uniaxial stresses (see Fig. 1a) are very rare. Most damage cases are caused by combined stress states, i.e. a combination of biaxial, triaxial and multiaxial loads. Fig. 1b shows the biaxial stress of a mode I crack. It was impossible to carry out the different kinds of multiaxial fracture tests with the beam in bending or the compact tension method. However, after refining the wedge splitting method according to Tschegg, it was possible to investigate mode I crack propagation under biaxial load [6,7] (see Fig. 1b).

Biaxial stress is likely to occur upon operation of refractory-lined steel ladles, e.g. upon filling a steel ladle, where the sudden temperature increase on the hot face causes tensile hoop stress at some distance to it. This stress can trigger a mode I crack and can be accompanied by compressive stresses in radial directions (Fig. 1b). Similar thermal stresses occur in many refractory-lined industrial kilns and can also be overlaid by additional mechanical stress. An example for that are rotary cement kilns in which oval kiln deformation under dead weight leads to an additional periodic mechanical stress of the refractory material (Fig. 1b).

As a consequence of the above-mentioned practical examples, the fracture mechanical values obtained under biaxial loads applied on three refractory materials of different brittleness had to be tested. A cube shaped specimen is used for

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0013-7944/$ - see front matter
doi:10.1016/j.engfracmech.2009.07.011

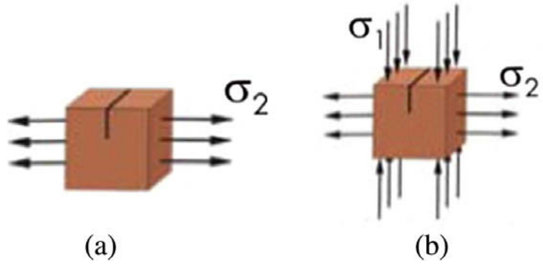

Fig. 1. Mode I crack under (a) uniaxial and (b) biaxial load.

the wedge splitting test according to Tschegg, and damage is analysed by acoustic emission. The fracture mechanical properties obtained have been analysed, compared with concrete [8] and discussed.

2. The wedge splitting method according to Tschegg

The wedge splitting test according to Tschegg [3,9] has been patented in 1986 and described several times. It has since been used by scientists all over the world for analyzing concrete, asphalt, wood, synthetic materials and refractory materials. In the following, a short description of this method is given.

Fig. 2 shows a simplified description of the wedge splitting test according to Tschegg for uniaxial load. Stable crack propagation can be achieved by displacement-controlled loading with a simple mechanical or hydraulic testing device. This procedure can be used for both quasi-brittle and brittle materials. Specimen shapes may be cubic, cylindrical disk or bar [9], as shown for a plate-shaped specimen in Fig. 2a. The direct guidance of the load (F_M), its short paths in the loading facilities and in the specimen (Fig. 2b, F_H, F_V), make the test equipment behave extremely rigidly which results in a low energy accumulation in the specimen and the testing machine. The decrease of the elastically stored strain energy as well as the favourable and relatively low ratio between the specimen volume and the fracture surface, contribute to stable crack propagation as required for determining the specific fracture energy.

The loading equipment consists of two load transmission pieces with movable rolls (see Fig. 2b) and a wedge (wedge angle e.g. 15°) placed in an appropriate groove of the specimen (see Fig. 2a). The ratio between the vertical and horizontal forces can be calculated by means of a simple formula. The forces are transmitted from the wedge to the test piece via rolls (ball bearing) with negligible friction [9].

The displacement (δ or COD for crack opening displacement) is measured in the line of action of the horizontal forces by electronic strain gauges fixed on both specimen sides and attached to a metal frame (see Fig. 3). The two gauges allow the average displacement to be determined and indicate uneven crack propagation [9]. In case a crack leaves the symmetry plane of the specimen (the so called ligament area) it will be eliminated. The cubic-shaped specimen has less weight compared to a bending bar [1,2] and is thus easier to handle. In [10], the fracture mechanical properties obtained from beam tests were compared to those from the wedge splitting method according to Tschegg when applied to concrete, and were found to yield the same results.

Fig. 4a and b, shows a schematic drawing of the test equipment under biaxial load [6,7]. There σ_1 is applied with several hydraulic cylinders and a stress σ_2 is applied using the wedge splitting method. Fig. 4a (left) shows how the biaxial test equipment is arranged. The specimen is positioned on the linear support and the wedge and the load transmission pieces are mounted. Fig. 4b shows the testing equipment as readily composed for the investigation. The two loading frames with

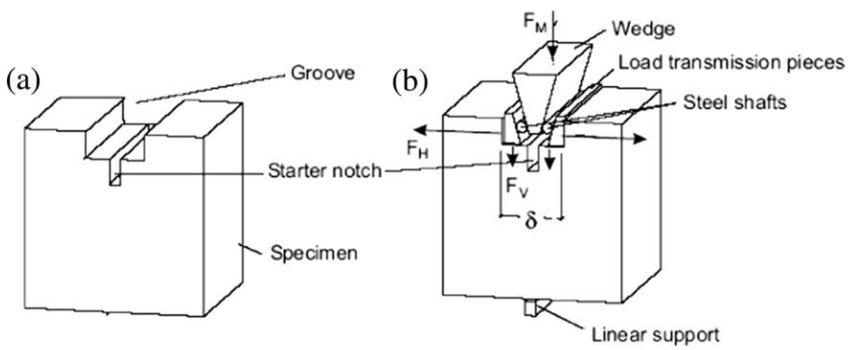

Fig. 2. Specimen shape (a) and principle (b) of wedge splitting test according to Tschegg under uniaxial load.