Journal of the Mechanics and Physics of Solids 78 (2015) 123–140

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

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

Estimating the tensile strength of super hard brittle materials using truncated spheroidal specimens

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ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form
23 December 2014
Accepted 10 February 2015
Available online 12 February 2015

Keywords:
Brittle fracture
Diamond composites
Finite element modelling
Semi-analytical approach
Super hard materials
Tensile strength measurement

ABSTRACT

New approaches need to be introduced to measure the tensile capacity of super hard materials since the standard methods are not effective. To pursue this objective, a series of laboratory tests were constructed to replicate the fracture mechanism of diamond-based materials. Experiments indicate that under a certain compressive test condition, stresses normal to the axisymmetric line in truncated spheroidal specimens (bullet-shaped specimens) are in tension contributing to the tensile fracture of the material. From experimental and numerical studies, it is concluded that semi-prolate spheroidal specimens can be used to determine precisely the tensile strength of brittle stiff diamond-like composites.

1. Introduction

Tensile breakage in materials especially with a high ratio of compressive to tensile strength, indicating a large brittleness index, is perhaps one of the most common damage forms taking place in materials used in various engineering practices. The engineering literature is almost exclusively replete with direct and indirect testing methods to estimate this critical mechanical parameter or property of a given material. However, it is often inconvenient to adopt a direct tensile strength testing method, e.g. by pulling apart a target specimen in the so-called direct pulling test (DPT), owing to its difficulty in sample preparation and potential disturbance to the sample by generating unwanted stresses (e.g. bending) transmitted to the specimen (Erarslan, 2011). Indirect tests such as Brazilian tensile strength test (BTS) (Hondros, 1959; ASTM, 2008), ring test (Hobbs, 1965), flatten Brazilian disc (Wang et al., 2004) and semi-circular bending test (SCB) (Coviello et al., 2005) are typical testing methods and procedures which have drawn more attention. The indirect BTS, officially proposed by ISRM (1978), is perhaps the most popular example of indirect methods with its initial applications tracing back to rock and concrete testing. The method aims at generating an indirect uniform tensile stress region at the central vicinity of a thin disc sample by a far-field diametral compression. Despite being widely used for both soft and moderately hard and brittle materials (Hondros, 1959; ASTM, 2008), the application of BTS to super-hard diamond based samples has been criticised and

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Abbreviation: 2D, two-dimensional; 3D, three-dimensional; ASTM, American society for testing and materials; BTS, Brazilian tensile strength test method; COV, coefficient of variation; CSIRO, Commonwealth scientific industrial research organisation; DPT, direct pulling test; EDM, electric discharge machining process; FE, finite element numerical modelling; ISRM, international society for rock mechanics; LVDT, linear variable differential transformers; SCB, semi-circular bending test; SD, standard deviation; TSDC, thermally stable diamond composite; UCS, unconfined compressive strength

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http://dx.doi.org/10.1016/j.jmps.2015.02.011
0022-5096/

List of Symbols

E, υ	elastic Young's modulus and Poisson's ratio of the material
a	length (semi-major axis) of a truncated spheroidal sample
b	semi-width of a truncated spheroidal sample
c	half-distance between foci in a prolate spheroidal coordinate system
b', c'	normalised semi-minor and focal distance, respectively
F	force at failure applied to the flat end of a truncated spheroidal sample
F'	tip force distributed arbitrarily over the contact zone
ω	tip semi-contact angle in a prolate spheroidal coordinate system
α	tip semi-contact angle in a simplified prolate spheroidal coordinate system
π	the ratio of circle's perimeter over its diameter
x, y, z	Cartesian coordinates
A, B, C, D	different design profiles of tested samples
δ	semi-width of the separated wedge at the tip of a broken sample
u, ϕ, θ	prolate spheroidal coordinates
ξ, η, θ	simplified prolate spheroidal coordinates
σ_{xx}, σ_{yy}, σ_{xy}	components of stress tensor in Cartesian coordinates
$\sigma_{\xi\xi}$, $\sigma_{\eta\eta}$, $\tau_{\xi\eta}$, $\tau_{\xi\theta}$, $\tau_{\eta\theta}$	components of stress tensor in a simplified prolate spheroidal coordinate system
$p(\eta)$	an arbitrary tip pressure defined in a simplified prolate spheroidal coordinate system
h_1, h_2, h_3	metric coefficients (scale factors)
$P^{\square}_{\square}$	maximum uniform or Hertzian pressure
$H(\square)$	Hertzian pressure
R	radial distance
γ, β	constants dependent on Poisson's ratio

proved not to be generally reliable (Serati, 2014). The main key barriers standing in the way of implementing the available recommendations to super hard materials are: (i) a large volume of material required to prepare a specimen, (ii) the material itself being too hard to cut, shape and polish in the laboratory to comply with the standard sample preparation codes and specifications, and (iii) the trimming and polishing processes required to make a standard sample, even at a much smaller scale, is time consuming and too expensive. The electric discharge machining (EDM) method is an example commonly used for shaping and polishing small diamond based Brazilian disc specimens (Serati, 2014). Inaccuracy, cost ineffectiveness and amount of time consumed for standard sample preparation for testing of super hard brittle materials need to be eliminated by introducing an alternative tensile strength measurement approach. This study aims to construct such a solution methodology from non-standardlaboratory tests for which standard tests are not applicable. To pursue the objectives, experimental measurements and finite element (FE) numerical modelling were used to understand the response of a selected ceramic-based silicon carbide (SiC) diamond composite under various load combinations. A series of laboratory tests was further carried out to replicate the fracture mechanism of the selected material comprising other synthetic materials (glass ceramic and graphite). For the purpose of numerical modelling, the geometry of the problem was represented in a prolate spheroidal coordinate system in which the corresponding contact tractions were analytically introduced by Hertzian and uniform pressure distributions. From the experimental and calibrated numerical studies, it is concluded that semi-prolate spheroidal specimens may be used, i.e. bullet profile specimens, to precisely determine the tensile bearing capacity of a super stiff brittle material of interest.

2. Preliminary observations

A thermally stable diamond composite (TSDC) material was selected as a super stiff brittle representative due to its ongoing successful applications in modern excavation industries, and a vast body of available experimental data at The Commonwealth Scientific & Industrial Research Organisation (CSIRO) rock mechanics laboratories (Boland and Li, 2010; Alehossein et al., 2009; Serati, 2014; Li and Boland, 2005). TSDC inserts, bonded to the pick bodies when used in hard rock cutting activities, are most commonly manufactured in a batch in truncated spheroidal shapes of various size, normally ranging from 8 mm to 25 mm in diameter. On request, the manufacturer may also produce a batch of small discs for laboratory testing purposes. To study the behaviour of the selected super strong brittle material, extensive laboratory tests with TSDC specimens with different geometry subjected to stresses with various boundary conditions were conducted at CSIRO. It was observed that under compressive loads, almost all spheroidal TSDC specimens behaved as perfectly brittle until failure with tensile breakage as the dominant rupture mechanism (Fig. 1). A single straight plane of fracture resulting from indirect (induced) tensile stress divided almost all the specimens into two halves. Fig. 1(c) represents a schematic description of the compression test conducted with TSDC specimens, in which a is the length of the sample along the axisymmetric line, b is the semi-width of the sample, F is the force at failure applied to the flat end, and F' is the tip contact force distributed arbitrarily over the semi-contact angle ω. The observed failure is very similar to the one in a standard BTS in which a compressed specimen fails in tension due to the resultant tensile stress concentrated at the disc centre. The similarity of the rupture with tested specimens in Fig. 1 to BTS results, in terms of the mechanism and the plane of fracture, strengthened the hypothesis that the failure force can be related to the tensile property of the material. However, for the