Mechanics of Materials 42 (2010) 1064–1080

Contents lists available at ScienceDirect

Mechanics of Materials

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

Edge chipping of borosilicate glass by blunt indentation

A. Mohajerani, J.K. Spelt *

Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, ON, Canada M5S 3G8

ARTICLE INFO

Article history:
Received 26 January 2010
Received in revised form 23 September 2010

Keywords:
Edge chipping
Glass
Hertzian crack
Indentation
Blunt indenter

ABSTRACT

The edge chipping of borosilicate glass by smooth steel and ceramic spherical indenters was investigated experimentally. Indentation near an edge typically formed Hertzian cracks beneath the indentation plane which then grew to asymmetric cone cracks intersecting the side wall. Although these early stages of crack propagation always followed the same general pattern, the ultimate failure of the edge could involve splitting parallel to the side wall, flaking, fragmentation, or crushing the edge. The nature of the failure depended on the constraint of the indenter, the indenter material, and the indentation distance from the edge. These patterns of edge chipping are quite different from those observed with sharp indenters. The results have application in manufacturing processes aimed at producing rounded edges in brittle materials or in situations where edge chipping is to be avoided.

1. Introduction

The fracture of sharp, brittle edges by concentrated loading near an edge is a common phenomenon which has been exploited in making stone tools (Almond and McCormick, 1986), in manufacturing (Mohajerani and Spelt, 2009), and as a convenient method of characterizing fracture toughness (Almond and McCormick, 1986; Gogotsi et al., 2007; McCormick, 1992; McCormick and Almond, 1990). Edge chipping is also a failure mechanism in applications involving hard, wear resistant materials such as drilling tools (Scieszka, 2001), cutting tools (De Melo et al., 2006), and engine valves (Hangl et al., 1996). It is also the fundamental mechanism in manufacturing processes such as vibratory finishing which is used to produce rounded edges on brittle materials (Mohajerani and Spelt, 2009).

A significant body of work has dealt with edge chipping by sharp indenters such as in the Vickers and Knoop hardness tests, or in Rockwell indentation where the indenter tip is slightly rounded (0.2 mm radius). Almond and McCormick (1986) examined the chipping of various brittle materials loaded with a conical diamond indenter of tip radius 0.2 mm, and observed that chips had a constant shape, regardless of the test material and the indentation distance from the edge, *d*. Several investigators have examined the critical force, *F*, required for chip removal, and reported a linear correlation between *d* and *F* (Chai and Lawn, 2007; Gogotsi et al., 2007; Gogotsi and Mudrik, 2009; Hangl et al., 1996; Morrell and Gant, 2001). The ratio of *F* to *d* is termed the edge toughness, having units of N/m as does the critical strain energy release rate of fracture. The examination of several brittle materials has revealed a universal correlation between the edge toughness and the fracture toughness or critical strain energy release rate (Gogotsi and Mudrik, 2009; Gogotsi et al., 2007; McCormick and Almond, 1990; Morrell and Gant, 2001), providing a useful means of characterizing the fracture toughness of brittle materials.

Chai and Lawn (2007) observed that median cracks from the tip of a Vickers indenter grew along the indentation force direction, forming a penny shaped crack, which veered to the side wall of the edge at a critical load, removing a chip.

Previous work on edge chipping by blunt indentation is much more limited, but has indicated that the phenomenon is quite different from that of sharp indentation. For example, a recent study of edge chipping of diamond by

* Corresponding author. Tel.: +1 416 978 5435; fax: +1 416 978 7753.
E-mail address: spelt@mie.utoronto.ca (J.K. Spelt).

0167-6636/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechmat.2010.10.002

spherical indenters (Zaayman et al., 2009) found that cracks were not penny shaped and that they did not grow in the direction of the applied force. Rather, such cracks were Hertzian and initiated by ring cracks around the indentation zone. They grew to a conical shape, and while their lateral expansion was stopped by intersecting the edge side wall, their downward growth continued in a curved path until they again intersected the side wall, thereby removing a chip. These differences from sharp indentation were attributed to the high hardness of diamond, which prevents the formation of a plastic zone at the point of contact that promotes the formation of median cracks (Zaayman et al., 2009). McCormick and Almond (1990) developed a model to predict crack initiation by blunt indentation of an edge by assuming that the indentation force plastically deforms the contact zone and modeling the surrounding elastic stress field as a semi-infinite body with a pressurized hole. They predicted that cracks initiate at points of maximum tensile stress, D or B and C in Fig. 1, depending on the size of the contact patch and the indentation distance from the edge. This prediction was consistent with the observations of Morrell and Gant (2001), from the indentation of tool steel edges (produced using powder metallurgy) using a Rockwell indenter. They observed that cracks that initiated from points B and C in Fig. 1, extended to the edge and formed side cracks, and cracks that initiated from point D in Fig. 1, extended to the contact patch, forming normal cracks.

The objective of the present study was to make experimental observations of the mechanisms of edge chipping in borosilicate glass by blunt indentation, as a function of the indentation distance from the edge.

2. Hertzian contact near an edge

Hetenyi (1960) studied the stress state of an elastic quarter-plane, loaded by a concentrated line force, F, located a distance d from an edge, and showed that the proximity of the load to the edge generates a maximum tensile stress of 0.314 F/d on the indented surface a distance 1.443d from the edge (Fig. 2). Therefore, in such a concentrated loading of an elastic edge, cracks would be expected to initiate from the point of maximum tensile stress, inward of the indentation point; however, in practice such cracks may not appear, because of local plastic deformation.

This work was followed by numerous refinements to investigate the effect of edge proximity in Hertzian contacts (Hanson and Keer, 1989, 1990, 1991, 1995; Hanson et al., 1994; Keer et al., 1983, 1984). Hanson and Keer (1995) studied the frictionless contact of elastic and rigid spheres with an incompressible edge. Non-dimensional contact centerline pressure distributions for a rigid sphere and an elastic sphere (both $4/\pi$ in diameter) at a penetration depth of $\pi/8$, for different indentation distances from an edge, are shown in Fig. 3. The non-dimensional pressure, $\bar{p}$, is defined as $\bar{p} = \frac{p}{\mu}$, where p is the contact pressure and μ is the shear modulus of the indented body. At large indentation distances from the edge (e.g. $d = 5$ in Fig. 3), where the effect of the edge on the contact stresses is negligible, $\bar{p}$ at a point x away from the edge, within the contact patch, can be obtained according to the Hertzian solution

$$\bar{p} = \bar{p}_{\max}\sqrt{1 - \left(\frac{x-d}{a}\right)^2} \tag{1}$$

predicting an elliptical pressure distribution on the contact patch, with the center of ellipse coinciding the centerline of the sphere. At shorter indentation distances from the edge, where the effect of the edge on contact stresses is not negligible, rigid and elastic spheres retain a Hertzian contact pressure distribution, but the center of contact (middle of each pressure curve) shifts progressively inward from the center of the indenting sphere (located at d;

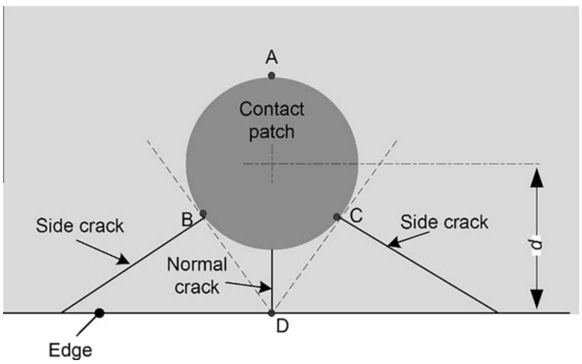

Fig. 1. The location of crack initiation on a surface indented by a sphere at distance d from the edge. The dashed lines extend from point D and are tangent to the contact patch margin.

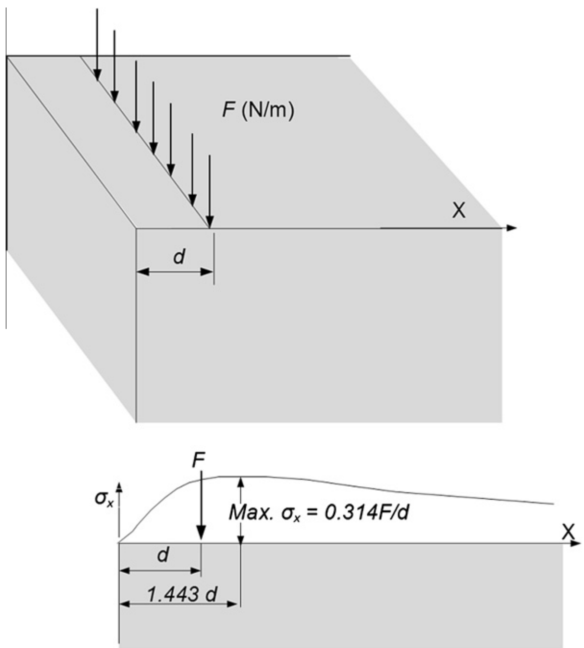

Fig. 2. Surface stress distribution predicted in (Hetenyi, 1960) due to the indentation of a concentrated line load near the edge of an elastic quarter-plane.