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Modelling edge chipping in flint knapping, cutting tools and sharp teeth using a trapezoidal prism structure

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ABSTRACT

Edge chipping tests were performed on trapezoidal prisms made of soda-lime glass and two rock materials, and the evolution of damage observed in-situ. The indent distance H and specimen's wedge and surface inclination angles α and θ were systematically varied. The configuration used, distinguished by two free surfaces interacting with the chipping crack, yielded the type of chip morphology commonly found in such applications as flint knapping, material shaping tools and some dental teeth. The tests were complemented by a fracture mechanics analysis incorporating all system variables as well as load orientation angle ϕ. The analysis produced closed-form analytical expressions that predicted reasonably well the chip dimensions and chipping force. The results presented provide useful insight into such aspects as the mechanics behind rock shaping, fracture prevention in material shaping tools and bite force of some mammals and sharp-teeth fish based on inspection of chipped fossil teeth.

1. Introduction

Edge chipping is a basic phenomenon encountered in such diverse fields as flint knapping, a technique used for fashioning tools and blades in early civilizations (Whittaker, 1994; Brumm et al., 2006; Peresani, 2012), wear in cutting tools (Liu et al., 2002; Scieszka, 2005; Kuttolamadom, 2012; Kuttolamadom et al., 2012; de et al., 2006; Thamizhmani and Hasan, 2010; Yoshino et al., 2015), tribology (Petit et al., 2009). Chipping is also relevant in anthropological studies, where it has been suggested that chip scars found on fossil teeth may relate to bite force (Constantino et al., 2010) as well as food consumption and in turn human evolution (Schubert and Ungar, 2005; Scott and Winn, 2011; Becker and Chamberlain, 2012). Chipping occurs when a crack formed by a concentrated contact force is drawn into a free surface. The chip morphology and chipping force are dictated by numerous variables including stiffness, bluntness and orientation of the indenter as well as inclination of the chipped surface relative to the indented one. This work is primarily concerned with the formation of thin, elongate flakes, a few prominent examples of which are shown in Fig. 1: flint knapping (a), material cutting tools (b-c) and dental teeth (d-e).

Most edge chipping studies on rocks, ceramics, glass or dental materials deal with orthogonal blocks (Almond and McCormick, 1990; Morrell and Gant, 2001; Chai and Lawn, 2007a; Petit et al., 2009; Quinn et al., 2010; Gogotsi et al., 2010; Mohajerani and Spelt, 2010; Bao et al., 2011). As demonstrated in Fig. 2a, this configuration leads to a rather broad, elliptic-like scar which aspect ratio greatly differs from those assembled in Fig. 1. Several authors have attempted to produce the type of chip scars depicted in Fig. 1a using rock materials of various exterior platform angles and indent distances which were subjected to normal or oblique impact (Speth, 1975; Dibble and Pelcin, 1995; Pelcin, 1997a, 1997b; Davis, 1998; Nonaka et al., 2010; Magnani et al., 2014). While such works have yielded some simple empirical relationships for predicting flake mass, no fracture mechanics treatments for the chipping behavior in this class of problems seems to be available.

Observations of the fracture patterns in Fig. 1 reveal that the chipped scars are conclusively bounded by two surfaces, as opposed to the single one characterizing the commonly studied orthogonal block case, see Fig. 2a. This suggests that the elongate shape of a chip scar is due to an early encounter of indentation cracks with a free surface. Accordingly, this work employs the trapezoidal prism specimen shown in Fig. 3a, which is defined by two free surfaces having wedge angle α. This configuration may be viewed as a natural extension of the cylindrical rod case shown in Fig. 2b (chai, 2015). The evolution of damage due to Vickers indentation in specimens made of soda-lime glass and two rock

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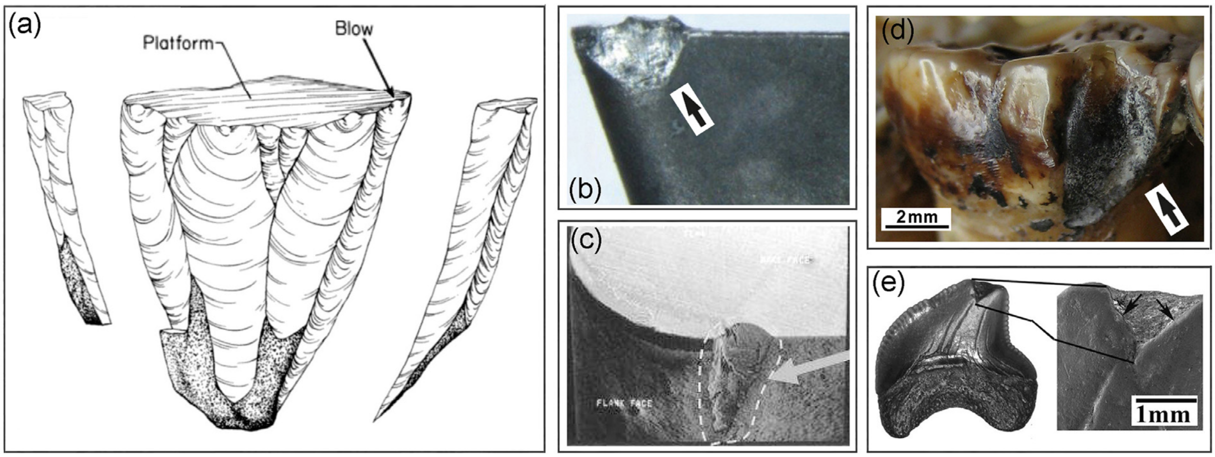

Fig. 1. typical images of slender, wedge-like chipping flakes: (a) flakes produced by flint knapping (Whittaker, 1994), (b) chipping in carbide/Ti-6Al-4B tool material (Kuttolamadom, 2012; Kuttolamadom et al., 2012), (c) chipping in cemented carbide tool (de et al., 2006), (d) chipping in a pongo pygmaeus tooth (Constantino et al., 2010), (e) chipping in Squalicorax kaupi tooth (Becker and Chamberlain, 2012). Arrows point to the flakes.

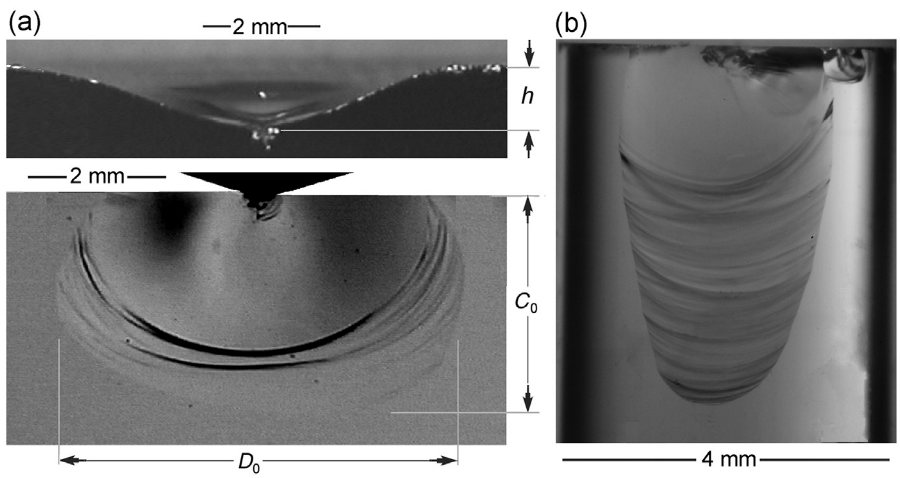

Fig. 2. Chip images in glass from surface-normal Vickers contact: (a) orthogonal soda-lime glass block; upper frame – top view of a specimen indented at h = 1.05 mm, lower frame – front view, h = 0.63 mm (Chai and Lawn, 2007a). (b) 4 mm radius cylindrical borosilicate glass rod indented on the flat surface (Chai, 2015); the elongate shape of the chip results from an early encounter of the median-radial crack with the cylindrical surface.

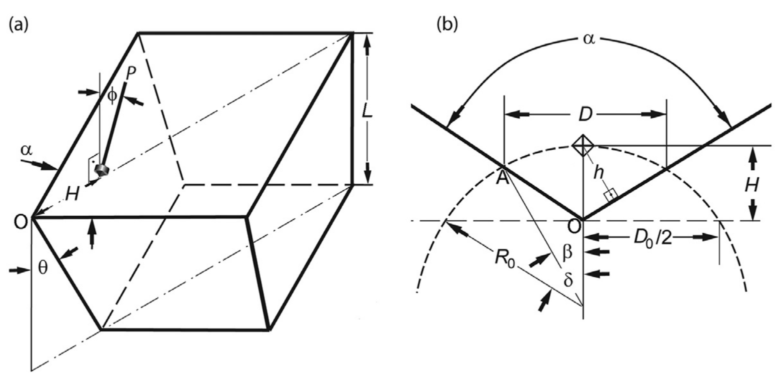

Fig. 3. (a) the trapezoidal-prism test specimen used, produced by cutting and polishing blocks of soda-lime glass or rocks; α, θ and ϕ represent wedge angle, inclination of outer surface relative to indented surface and orientation of loading line relative to indented surface, in that order. (b) the wedge model used to obtain chip dimension D; the heavy solid and dashed lines define the material boundary and assumed shape of the chip, respectively. The specimens are loaded by a Vickers tool at the indicated site.

materials were observed in-situ. The experimental apparatus is detailed in Section 2 while the test results and a companion fracture analysis are given in Sections 3 and 4, respectively. Section 5 discusses the results in the context of more general edge chipping systems.

2. Materials and method

In addition to soda-lime glass, a standard brittle and transparent material, two types of rocks extensively used in ancient times for making sharp tools and jewelry pieces were tested: ignimbrite, a mixture of volcanic ash composed of glass shards and crystal