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# Sliding contact fracture of dental ceramics: Principles and validation

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ABSTRACT

Ceramic prostheses are subject to sliding contact under normal and tangential loads. Accurate prediction of the onset of fracture at two contacting surfaces holds the key to greater long-term performance of these prostheses. In this study, building on stress analysis of Hertzian contact and considering fracture criteria for linear elastic materials, a constitutive fracture mechanics relation was developed to incorporate the critical fracture load with the contact geometry, coefficient of friction and material fracture toughness. Critical loads necessary to cause fracture under a sliding indenter were calculated from the constitutive equation, and compared with the loads predicted from elastic stress analysis in conjunction with measured critical load for frictionless normal contact—a semi-empirical approach. The major predictions of the models were calibrated with experimentally determined critical loads of current and future dental ceramics after contact with a rigid spherical slider. Experimental results conform with the trends predicted by the models.



## 1. Introduction

Ceramics possess many excellent characteristics, including high hardness, high melting point, excellent corrosion resistance and, potentially, low friction and low wear. In addition, ceramics can be derived from rocks and minerals, which make up about 25% of the Earth's crust compared with 1% for all metals [1]. Thus, ceramics have been perceived as the materials of the future, and have proved to be the current choice of material in a wide range of demanding applications. Some examples, among many others, are prosthetic devices for dental and medical applications, insulators for electronic applications, and mechanical seals and ball bearings for an array of engineering applications. However, in dental and medical prostheses, premature failure still remains a major concern and, in many cases, has been linked to excessive material loss and/or fracture [2–11].

The initiation of microcracks at two contacting surfaces of structural components is a phenomenon that bears on several problems of practical significance, such as a transition to rapid material loss (severe wear) and the onset of strength degradation (fracture). Therefore, there has been a large volume of literature concerning contact problems in brittle solids. The field of contact mechanics may have started in 1882 with a seminal publication by Hertz [12]. The original Hertz theory is restricted to frictionless contact between two elastic bodies. Over the past century, progress has been made to extend the Hertz theory to more realistic problems—frictional contact of two elastic solids in sliding or rolling contact [13–19]. A simple scheme—a blunt slider pressed against a flat surface—has been developed to elucidate the fracture behavior of brittle solids subjected to frictional contact [16,20]. While simple, such a scheme closely represents occlusal contacts between opposing dentitions [21–24], and is readily amenable to fracture mechanics analysis.

Most of the early studies on sliding contact tended to focus on the stress analysis of elastic fields [13–16,19]. Theory predicts that, for complete slip, the presence of a tangential force intensifies the stresses around the contact circle, and the maximum tensile stress occurs at the trailing edge of the indenter [19,25]. Thereby, the normal load needed to generate a fracture is projected to be significantly reduced under frictional sliding relative to frictionless normal loading [16,19]. However, such stress analysis can only predict where a crack is most likely to form, based on the location of maximum tensile stress. It does not specify when the cracks initiate. Prediction of critical fracture load remains a challenge.

Since the stresses in a brittle material beneath a blunt indenter remain elastic up to the point of fracture, linear elastic fracture mechanics may be applied to predict the fracture load. The first attempt to apply fracture mechanics to the Hertzian sliding contact problem was made in 1967 by Lawn [17]. Since then, several theoretical models have been developed to predict the critical load for crack initiation under sliding contact using fracture mechanics [25–29]. By relating the strain energy release rate to the stress intensity factor, it is possible to estimate the critical load for the

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onset of sliding fracture in elastic solids [28,29]. The central difficulty in such an approach is that the high stress gradients near the contact circle and the introduction of a small initial crack can further complicate the matter. It is, therefore, not surprising that the mathematical treatment is complex and is not amenable to accurate first-principles evaluation [25,30,31].

There have been a number of experimental studies on brittle fracture under sliding contact [17,20,25,32–37]. Most studies have focused on model brittle materials such as glass, alumina and zirconia. There have not been any systematic investigations into the sliding fracture resistance of dental ceramics.

In this study, based on the Hertzian stress field, assuming cracks form at the same tensile stress under normal loading as when sliding, and using the fracture mechanics approach of Lawn [31], the present authors have derived a simple constitutive relation to predict fracture of brittle materials under sliding. The constitutive equation has established a fracture mechanics relation between the fracture load and indenter radius, with the friction coefficient and material toughness the governing properties. The theory was then calibrated against experiment, where Hertzian indentation tests have been conducted on a variety of commercial and in-house developed dental ceramics under sliding and normal loads in water. It was found that this simple constitutive relation works very well in predicting the resistance to sliding contact fracture of ceramics with insignificant *R*-curve behavior and homogeneous microstructures.

## 2. Contact mechanics

### 2.1. Elasticity model of stress analysis

The present study first considers the simpler case of a hard spherical indenter loaded normally on the flat face of an isotropic brittle solid. The stresses at any point throughout the solid were calculated by Huber [13] and discussed extensively by Johnson [18] and Lawn [38]. Here, the focus is on the distribution of the tensile stress component responsible for the formation of ring cracks. Following the analysis by Johnson [18] and Lawn [38], the maximum tensile stress $\sigma_m$ occurs at the contact circle in the specimen surface and is given by

$$\sigma_m = (1 - 2v)\frac{P}{2\pi a^2} \tag{1}$$

where $v$ is the Poisson's ratio of the specimen, $\boldsymbol{P}$ is the normal load, and $a$ is the contact radius.

Consider a rigid spherical indenter carrying a normal load $\boldsymbol{P}_n$, which slides over the flat surface of a brittle solid with a constant velocity. This sliding motion, or any tendency to slide, introduces a tangential force of friction $\boldsymbol{Q}$, acting on each surface, in a direction opposite to the motion. According to Amontons' law of friction [39], formulated in 1699, the frictional (tangential) force $\boldsymbol{Q}$ is linearly proportional to the applied normal load $\boldsymbol{P}_n$

$$Q = \mu \boldsymbol{P}_n \tag{2}$$

where $\mu$ is the coefficient of friction.

The question here is the effect of the tangential force $\boldsymbol{Q}$ on the contact stresses. Building on a method introduced by Green [40] for the stress analysis of a normally loaded half-space, Hamilton and Goodman [16] and later Hamilton [19], then Sackfield and Hills [41], derived explicit equations for calculating the stress field in the solid for the case of complete slip. In this configuration, the maximum radial tensile stress $\sigma_{sm}$ occurs at the trailing edge of the moving indenter and is enhanced dramatically relative to that under the normal load

$$\sigma_{sm} = \frac{3\boldsymbol{P}_n}{2\pi a^2}\left[\frac{1}{3}(1 - 2v) + \mu\pi\frac{(4 + v)}{8}\right] \tag{3}$$

where $\boldsymbol{P}_n$ is the applied normal load during the sliding action. The first term in brackets represents the stress due to the normal load, while the second term signifies the added stress due to the friction.

If cracks form at the same tensile stress under normal loading as when sliding, and since $a \propto P^{1/3}$ (i.e. the contact radius is proportional to the reciprocal cube of the applied load), the critical normal load $\boldsymbol{P}_n$ for the onset of fracture in sliding can be related to the critical load $\boldsymbol{P}$ for fracture under frictionless normal loading [20,34]

$$\boldsymbol{P}_n = (1 + k\mu)^{-3}\boldsymbol{P} \tag{4}$$

and

$$k = \frac{3\pi(4 + v)}{8(1 - 2v)} \tag{5}$$

In sliding, the cracks are no longer complete circles, but have the shape of a series of horseshoes, often referred to as herringbone cracks. Eqs. (4) and (5) connect quantitatively the normal and sliding contact between a sphere and a planar surface.

While the above stress analysis provides information on where the maximum tensile stress is, it only indicates where a crack could form. Therefore, if one uses Eq. (4) to predict the critical normal load $\boldsymbol{P}_n$ for the onset of fracture in sliding, the critical load $\boldsymbol{P}$ for fracture under frictionless normal loading must be obtained first. This can be done either experimentally or analytically. The latter requires knowledge of fracture mechanics, which is dealt with in the following section.

### 2.2. Fracture mechanics criterion for crack initiation

Introduction of Griffith–Irwin fracture mechanics into the Hertzian fracture problem was made by Frank and Lawn [42]. Two important aspects of the problem have been identified: crack initiation and crack propagation. Since the study is focused on the critical load for the onset of fracture, it concentrates on the criterion for crack initiation.

In the case of a solid loaded normally with a rigid spherical indenter of radius $r$. Surface ring cracks (the initial stage of cone cracks) tend to form in highly brittle solids, i.e. material with single-valued toughness ($K_{1C}$) and with insignificant crack growth resistance curves (*R*-curves). The critical load for the onset of surface ring cracks, under frictionless normal loading, is given by

$$\boldsymbol{P} = A\left(\frac{K_{1c}^2}{E^*}\right)r \tag{6}$$

where $A$ (=8.63 × $10^3$) is a dimensionless coefficient [31], and $E^*$ is the effective modulus

$$\frac{1}{E^*} = \frac{1 - v_i^2}{E_i} + \frac{1 - v^2}{E} \tag{7}$$

where $E$ and $v$ are the elastic modulus and Poisson's ratio of the brittle material; $E_i$ and $v_i$ are the elastic modulus and Poisson's ratio of the indenter.

Now a constitutive equation can be constructed to predict the critical normal load $\boldsymbol{P}_n$ for the onset of fracture in sliding. Combining Eqs. (4) and (6) gives

$$\boldsymbol{P}_n = A(1 + k\mu)^{-3}\left(\frac{K_{1c}^2}{E^*}\right)r \tag{8}$$

where $k$ and $E^*$ are defined in Eqs. (5) and (7), respectively.

Eq. (8) describes, in a very succinct way, the interrelation between three important aspects of the fracture process in sliding contacts: the fracture initiation load $\boldsymbol{P}_n$; the coefficient of friction $\mu$ at the sliding interface; and the materials, as evidenced in the