An alternate method for determination of brittleness of ceramics and polymers

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Abstract. As opposed to a pendulum scratching test for the determination of brittleness parameter for ceramics and polymers, this paper proposes an alternate brittleness parameter based on indentation analysis. The important advantages are that (i) no elaborate experiments are needed, and (ii) the proposed brittleness parameter has physical implications. The proposed parameter is as effective as the pendulum test for categorizing the brittleness of ceramics and polymers.

Keywords. Brittleness; ceramics; polymers; indentation analysis; pendulum test.

Lamy and Berlie (1984) proposed a test method for measuring the brittleness values of ceramics and polymers. The method called for an elaborate set-up using a heavy pendulum swinging over the test pieces. A diamond stylus was attached to the pendulum. During the swinging motion of the pendulum, the stylus scratched the test pieces giving rise to grooves. According to Lamy and Berlie (1984), the groove has either ductile or brittle morphology. They define a transition groove depth as a measure of brittleness. Experimentally, this transition groove depth is shown to be equal to $32 (K_{Ic}/H)^{1.5}$, where K_{Ic} is mode I fracture toughness and H is hardness. The brittleness parameter B_{IB} , due to Lamy and Berlie is defined as $(1/32) (H/K_{Ic})^{1.5}$. Physically any ratio of H and K_{Ic} should grade materials according to brittleness. While K_{Ic} controls fracture, H dictates deformation. In general, one can think of materials with high K_{Ic} and low H . Materials belonging to this group should not fracture easily because of their ability to deform. Metals belong to this class of materials. On the other side of the spectrum, there are materials with low K_{Ic} and high H . These materials are brittle because they tend to fracture easily, being unable to deform substantially. Ceramics belong to this class. Polymers are somewhere intermediate between the two. Apart from the aforementioned physical picture, the quantity $(K_{Ic}/H)^{1.5}$ does not have any physical meaning. This can be checked by carrying out a dimensional analysis. Therefore, the brittleness parameter obtained after elaborate experimentation is at the best, an *ad hoc* parameter without any physical basis.

This paper proposes an alternate way of categorizing ceramics and polymers. The method proposed herein is based on indentation analysis. There are several advantages. First, the indentation technique is a very simple alternative to elaborate experimentation. Second, in the present method, as long as K_{Ic} and H values are known, simple calculations can replace actual experimentations. Third, the proposed brittleness parameter has a sound physical basis.

The key idea of this paper is to relate the brittleness parameter to threshold crack size in the context of an indentation experiment. Threshold crack size is the length of the crack when the material begins to fracture. During an indentation test, the

material undergoing evaluation deforms first, which is controlled by hardness. Fracture takes place at a later stage and is controlled by toughness. Therefore, as the material begins to fracture, both H and K_{Ic} have equally important roles to play. Our new brittleness parameter, on the one hand, is related to a function of H and K_{Ic} , and on the other can be correlated to the plastic zone size. From a simple dimensional analysis, it can be shown that the parameter has the dimensions of length. If the plastic zone size is bigger than the threshold crack size, obviously the material is going to deform and vice versa. Therefore, a brittleness parameter related to threshold crack size has a physical meaning.

Next, a simple relationship between the threshold crack size, hardness and toughness can be obtained by referring to the model proposed by Lawn and Evans (1977) for ceramic materials. The main assumption of the model is the presence of fortuitous flaws in the elastic/plastic boundary in the indentation field where the tensile stresses are the greatest. During unloading of the indenter, these flaws experience an increase in tensile stresses until one of them becomes critical. This initiation event must occur by overcoming some kind of energy barrier, typical to the material. Hence, the initiation process is a material property and independent of flaw statistics. The size of the threshold flaw as given by Lawn and Evans (1977) is equal to $44.2 \times (K_{Ic}/H)^2$. The brittleness parameter B_{LE} can then be defined as $(1/44.2)(H/K_{Ic})^2$. Since, the Lawn and Evans model is basically valid for ceramic materials, one has to perform some calculation in order to apply the Lawn–Evans formulations to polymers. This is so because in the case of polymers, yield stress values rather than hardness values are available in the literature. Therefore, Johnson's (1970) pressurized cavity approach is applied. This model treats the indentation field in terms of a pressurized cavity. The pertinent equations are given below.

$$\frac{H}{\sigma_y} = \frac{2}{3} [1 + \ln(\beta)^3], \quad (1)$$

$$\frac{E}{\sigma_y} = 3(1 - \nu)\beta^3 - 2(1 - 2\nu), \quad (2)$$

$$\frac{E}{H} = \frac{9(1 - \nu)\beta^3 - 6(1 - \nu)}{2[1 + \ln(\beta)^3]}, \quad (3)$$

where σ_y is the yield stress, ν the Poisson's ratio, E the Young's modulus and β a quantity related to the plastic zone volume and indentation volume. From (2), the

Table 1. Physical properties of ceramics.

Material	H^* (GPa)	K_{Ic}^* (MPa m ^{1/2})
Silicon (single crystal)	9.0 (Lankford 1979)	0.75 (Jaccodine 1963)
Alumina (polycrystalline)	12.0 (Anstis <i>et al</i> 1981)	4.0 (Anstis <i>et al</i> 1981)
Soda-lime silica glass	5.6 (Anstis <i>et al</i> 1981)	0.75 (Anstis <i>et al</i> 1981)

*References in parentheses.

Table 2. Physical properties of polymers.

Material (References)	σ_y (MPa)	K_{Ic} (MPa m)	E (GPa)	β
Epoxide resin (cured with different amounts of TETA) (Yamini and Young 1980)	86	0.9	3.0	2.57
	110	0.6	4.2	2.64
PMMA (Felback and Atkins 1984)	70	1.1	2.8	2.68
Polystyrene (high impact) (Parvin and Williams 1976)	35	4.0	3.9	3.75

Table 3. Relative brittleness of ceramics and polymers.

Material	B_{LB} ($10^3 \text{ m}^{-3/4}$)	B_{LE} (10^3 m^{-1})
Si (Single crystal)	1299	3258
Soda lime (Silica glass)	637	1259
Alumina (polycrystalline)	1.60	203
Epoxide resin (cured with different amounts of TETA)	10.16	5.06
	3.44	1.20
PMMA	2.10	0.62
Poly styrene (High Impact)	0.15	0.02

value of β can be obtained using σ_y , E and ν . The value of β can then be substituted in (1) to obtain the desired hardness. We assume ν to be 0.3.

In the present paper, we have considered all the ceramic and polymer materials considered by Lamy and Berlie (1984). Table 1 gives relevant hardness and toughness data for the ceramic materials. Table 2 contains all the relevant data for the polymers. Table 3 shows the two brittleness parameters.

It is seen from table 3 that the new brittleness parameter B_{LE} classifies the materials in a way similar to that by B_{LB} . However, in the present case one ascribes a definite physical meaning for the aforesaid parameter. All the ceramic materials listed are more brittle than any of the polymers. Of the materials listed in table 3, Si is the most brittle while polystyrene is the least brittle. In terms of the threshold crack length Si has the smallest threshold length and polystyrene has the largest. These values are in accordance with the knowledge about these materials. For example, in the case of Si, no dislocation activity has been observed at room temperature. Therefore, the plastic zone size, if it exists at all, should then be smaller. In the case of polystyrene, crack tip blunting occurs by crazing of the material. Studies in polymers show that lengths of crazed zones are of the order of several hundred microns (McDonald *et al* 1981).

In conclusion, we propose an alternate brittleness parameter for ceramics and polymers as opposed to the pendulum test proposed by Lamy and Berlie (1984). The analysis is based on the indentation method. This parameter categorises the brittleness of ceramics and polymers quite well and has a more relevant physical explanation. Also, elaborate experimentation can be avoided.

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