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Sliding fracture of soda-lime glass in liquid environments

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The critical load required to form a hertzian fracture in sliding is markedly influenced by the liquid environment in which sliding takes place. The presence of an active environment (water and phosphoric acid) reduces the critical load by 65 to 70%, while the presence of a less-active environment (liquid paraffin) reduces the friction and increases the critical load. It is shown that the critical load in some environments can be predicted in agreement with experimental results provided that the critical load in a certain environment is known.

1. Introduction

When a hard sphere slides over a flat surface of brittle material, above a certain load, a Hertzian crack appears at the rear of the ball. Because the tensile stress at the rear of the contact circle is enhanced due to kinetic friction between the ball and the flat surface, the critical load required to form the hertzian crack in sliding is much lower than the critical load in static loading. The initiation of such cracks in sliding has been analysed by Lawn [1]. His treatment is based on Griffith's energy balance criterion coupled with the inhomogeneous stress field given by Hamilton and Goodman [2]. He found that the relation between the critical load W_c and ball radius R may be expressed as $W_c \propto R^2$ for a coefficient of friction, $\mu > 0.02$. Gilroy and Hirst [3] have investigated the cracking of glass under a sliding steel ball. They found that the $W_c \propto R^2$ relationship was obeyed at $\mu = 0.5$ over a range of indenter radii. Powell and Tabor [4] found a $W_c \propto R$ relationship for a sliding fracture experiment of polycrystalline titanium carbide. A similar relationship was also found by Bethune [5] for a sliding fracture of glassy polymer. It has also been shown experimentally by several investigators [3–6] that the magnitude of the reduction in the critical load in sliding experiments was smaller than that predicted by Lawn's theory [1].

The environment in which sliding takes place can affect the frictional behaviour of a material and possibly its fracture properties. The work by Westwood and co-workers [7, 8] has established that, when sliding involves some appreciable degree of ploughing, surface active liquid environments can markedly affect and even control the frictional behaviour of MgO and soda-lime glass by influencing their near-surface flow properties. The effect was termed a chemomechanical effect [6, 7]. Soda and Sato [9] found that the lower critical load for a sliding Hertzian fracture of soda-lime glass was observed in a hydrophilic environment.

In this paper, the critical load for a sliding fracture of soda-lime glass was measured in various liquid environments. The results are discussed in relation to the fracture mechanics.

2. Experimental procedure

The apparatus used was a modified Bowden–Leben friction tester as shown schematically in Fig. 1. The soda-lime glass specimen (50 mm x 80 mm x 10 mm in size, Asahi Glass Co. JIS-R3202), thoroughly degreased and ultrasonically cleaned, was mounted on a carriage which could be slid at a constant speed of 0.28 cm sec^{-1}. The beam was rigidly fixed to one end of a phosphor bronze leaf spring on which strain gauges were mounted for measuring the frictional force. The other end of the spring was rigidly supported on a heavy stand. The slider was a spherical tungsten carbide ball (Toshiba Tungally Co., G2), which contained 5 to 6% cobalt as a binder, or a steel ball bearing. The

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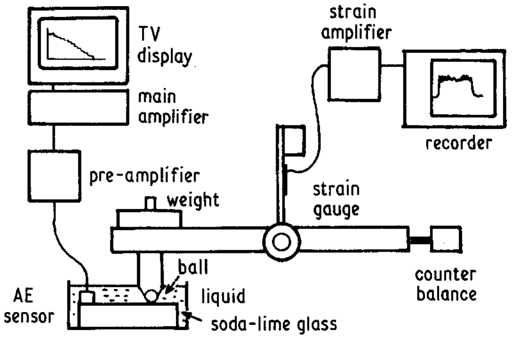


Figure 1 Schematic diagram of the experimental apparatus.

ball radii were between 0.76 and 3.6 mm. The glass plate (as-received) and the slider were immersed in the chosen liquid environment. The liquids were distilled water, phosphoric acid, cyclohexane, acetone, ethanol, n-butanol and liquid paraffin. These particular liquids were chosen because the data for the surface fracture energies of soda-lime glass in these liquids were already available [10]. The load was applied as a dead weight and was between 0.5 and 160 N. To determine the critical load for the Hertzian fracture, the acoustic emission (AE) technique (using an AET Co. machine model number 5000) was employed along with an optical microscope examination of the friction track.

3. Results

3.1. Surface damage

As the load was increased, surface damage began to appear. After sliding, the damage was checked under the optical microscope with transmitted polarized light. The dark-field image clearly revealed the subsurface feature of the cracks. Fig. 2 shows typical dark-field images of the track at 108 and 142 N loads in ethanol. As can be seen in Fig. 2, the Hertzian crack (hc) is not generally a smooth cresent and it sometimes spread downwards. Each partial Hertzian crack (hc) is linked at its ends to straight cracks (sc) nearly parallel to the sliding direction. At higher loads, the number of Hertzian cracks per unit sliding distance increases and the damage is more extensive.

After being checked under the microscope, the glass surface was coated with gold and the surface features examined by scanning electron microscopy (SEM). Fig. 3a and b shows some typical SEM views of the track at 39 N with a 1 mm radius WC ball in liquid paraffin and at 59 N with a 2.5 mm radius WC ball in water, respectively. In liquid paraffin (less active environment) the track is rather smooth; fine scratch traces (s) are visible, whereas in distilled water the friction track exhibits more frequent and extensive Hertzian cracks and scratch grooves (sg) than the former. Outside the contact area, the traces of the hertzian cracks are not cresent-shaped but their appearance is more like that of a "tulip"; such extended cracks (ec) were not observed in the less active environment. These facts perhaps suggest the reduction of fracture stress near the sub-surface layer in an active environment, which results in greater ease of crack propagation even outward from the contact region. Fig. 4a shows the same track as in Fig. 3b but at a higher magnification. It illustrates clearly that a scratch groove (sg) consists of continuous rows of jagged pits or flaws. Such friction-induced flaws are more clearly seen in Fig. 4b and c in cyclohexane and phosphoric acid, than in water. The tracks exhibit highly laminated layers and/or delaminated fragments as well as pits from which cracks start along a line of maximum tensile stress

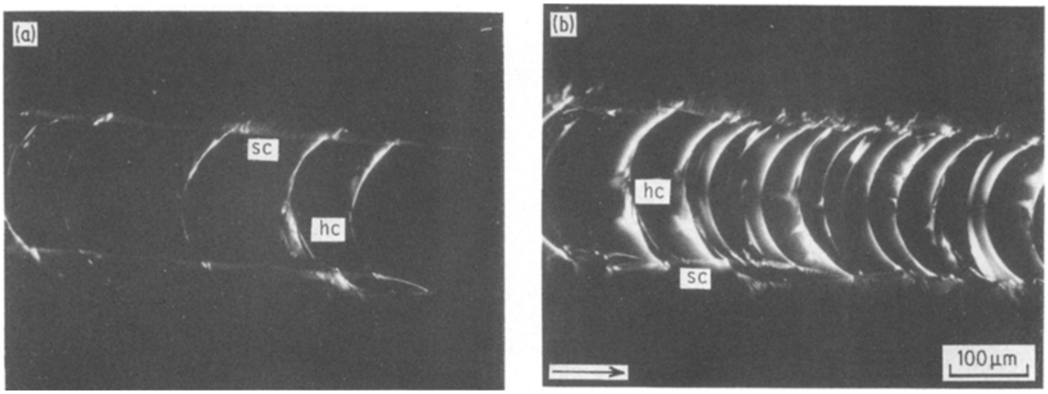


Figure 2 Optical micrographs of a friction track produced by a 2.5 mm WC ball on soda-lime glass in ethanol, dark-field image: (a) 108 N and (b) 142 N. Arrow indicates sliding direction.

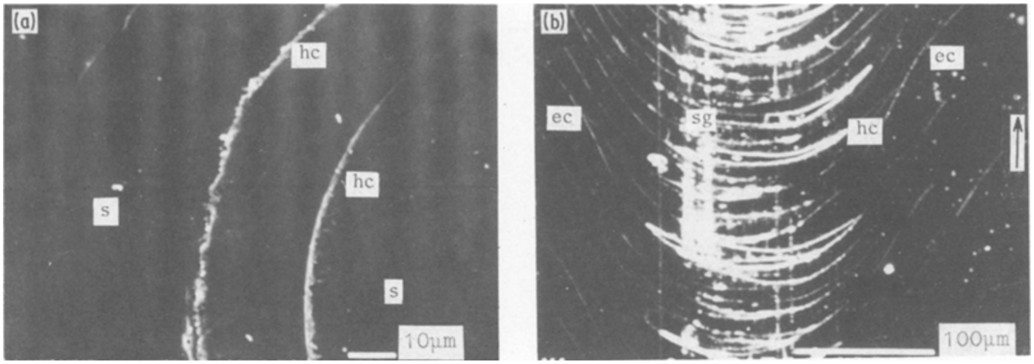


Figure 3 SEM pictures of friction track produced by: (a) a 1 mm WC ball at 39 N in liquid paraffin and (b) a 2.5 mm WC ball at 59 N in water. Arrow indicates sliding direction.

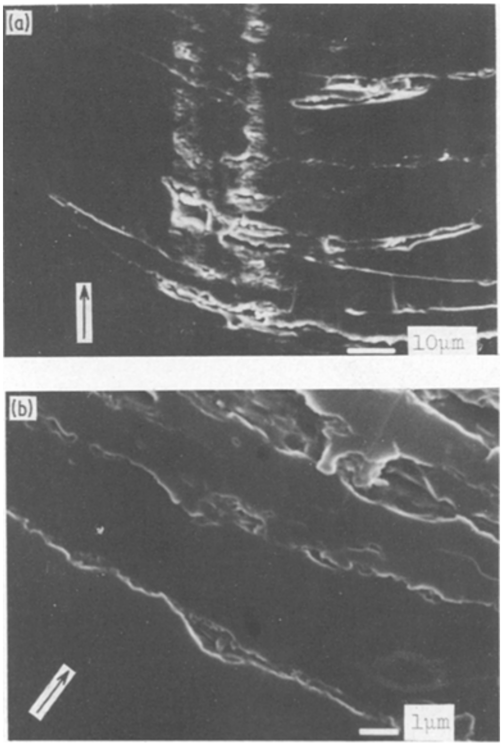
behind a slider. Obviously such pits or flaws formed during sliding act as a strength-reducing flaw.

3.2. Coefficient of friction

The coefficient of friction, μ, is sensitive to the condition of the surface. After thorough degreasing and ultrasonic cleaning the value of μ of the soda-lime glass against the WC ball in the air was 0.41 ± 0.06. The averaged value of μ in various liquid environments are shown in Fig. 5 as a function of the applied load. The full point in each plot indicates the critical load for the Hertzian fracture. Although considerable scatter and variation were found, the value of μ is almost independent of the applied load.

3.3. Critical load in various liquid environments

At low loads, no appreciable amount of AE was detected. As the load increases beyond the critical load, the total AE, e_T, per unit sliding distance, L, (e_T/L) increased rapidly, as shown in Fig. 6. The number of Hertzian cracks per unit sliding distance was measured from the optical micrograph; the results are also included in Fig. 6; they correlate well with each other. Fig. 7 shows e_T/L plotted against the applied load with a WC ball of 2.5 mm radius in various liquid environments. Above the critical load, the value of e_T/L increases with the load because the cracks become larger and their number increases. In water and phosphoric acid which are active reagents of soda-lime glass, the



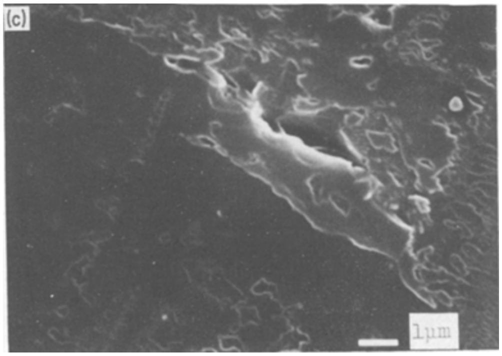


Figure 4 (a) The same track as in Fig. 3b but at a higher magnification, (b) the track in cyclohexane at 29.4 N load and (c) the track in phosphoric acid at a load of 19.6 N. Arrows indicate sliding direction. The radius of the WC ball is 2.5 mm.

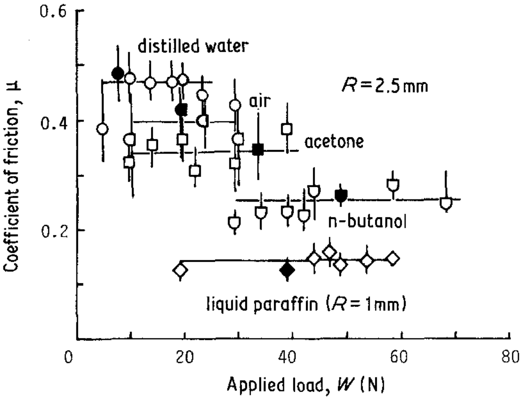


Figure 5 Coefficient of friction plotted against applied load in sliding of a WC ball; full point indicates the critical load for the Hertzian fracture in each environment.

critical load W_c is about 65 to 70% lower than that in air, while in acetone, ethanol and n-butanol, W_c is slightly higher than that in air. Because liquid paraffin is a less active reagent on soda-lime glass and acts as a lubricant reducing the friction, the Hertzian fracture did not occur with a WC ball of 2.5 mm radius up to a load of 160 N (the maximum load of the apparatus). The data in liquid paraffin with a WC ball of 1 mm radius is, therefore, included in Fig. 7.

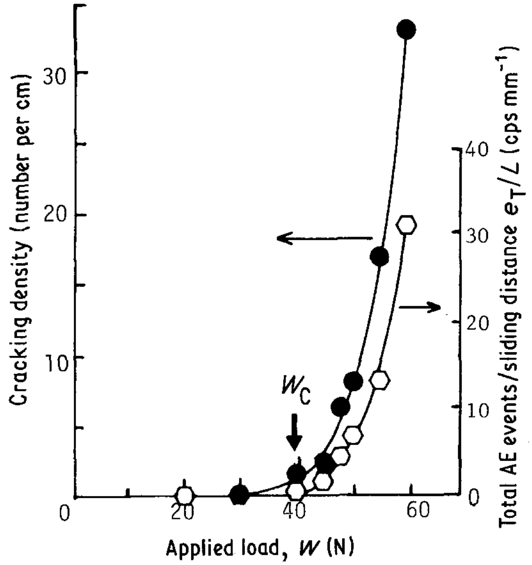


Figure 6 Total AE per unit sliding distance and cracking density plotted against applied load in liquid paraffin using a WC ball of radius 1 mm. Arrows indicate the critical load for the Hertzian fracture.

3.4. Effect of slider radius

The relation between the critical load and slider radius was estimated in air for WC and steel balls with radii between 0.76 and 3.6 mm. The result showed that the critical load was nearly proportional to the square of the ball radius, which was in qualitative accordance with the previous results [1, 3].

4. Discussion

The experiments have highlighted again that the liquid environment in which sliding takes place may affect markedly the critical load for the Hertzian fracture, as reported by some investigators [3, 5, 9].

Lawn [1] has extended the theory of Hertzian fracture due to Frank and Lawn [11] who verified the $W_c \propto R$ relationship; i.e. Auerbach's empirical law. He concluded that under sliding, W_c is not proportional to R but R^2 for $\mu > 0.02$; i.e.

$$\frac{W_c}{R^2} = \frac{\beta k^2 \gamma^{3/2}}{E^2(1-\nu^2)^{3/2}(1+A\mu)^3 I_f^3 c_f^{3/2}}, \qquad (1)$$

where

$$k = \frac{9}{16}\left[(1-\nu^2)+(1-\nu'^2)\frac{E}{E'}\right],$$

$$A = \frac{3(4+\nu)}{8(1-2\nu)}$$

and $\beta = 256\sqrt{(2\pi^3)}/9$, but more generally it should be replaced by another dimensionless factor to allow for the difference between the hertzian crack geometry and fracture model used [12]. E and E' are Young's moduli of the flat surface and the slider, ν and ν' are the Poisson ratios of the specimen and slider, γ is the fracture surface energy, c_f is the typical flaw size of the flat and I_f depends on both the Poisson ratio and on the location of the Hertzian crack with respect to the contact circle [12]. Lawn [1] also estimated the effect of a tangential force in reducing the normal load to produce the fracture. Later experiments [3–6], however, showed that Lawn's prediction overestimated this effect. Recently Warren [12] pointed out that the interpretations of Frank and Lawn [11] and Lawn [1] have an important weakness, namely that, in contrast to their assumption, Hertzian ring cracks are usually observed to form away from the circle of contact. This effect alters the estimation of I_f in Equation 1.

Lawn's theory is based on the energy balance

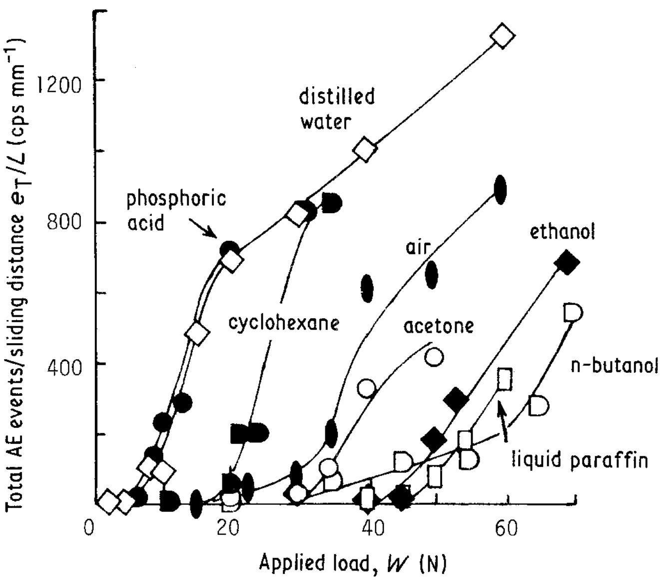


Figure 7 Total AE per unit sliding distance plotted against applied load in various liquid environments using a WC ball of radius 2.5 mm except in liquid paraffin when a 1 mm radius ball was used.

approach; the alternative investigation based on flaw statistics is also possible [13–15]. Although both approaches have been subjected to objections, it is noted that a similar equation to Equation 1 can be derived based on a flaw statistical approach along the lines given by Langitan and Lawn [16] (cf. Equation 13a of [16]), taking into account that the tensile stress is enhanced by a factor $(1 + A\mu)$ due to kinetic friction. In this approach, however, the chance of finding a particularly dangerous flaw increases with the indenter size; so that W_c increases less rapidly than R^2 in qualitative accordance with Auerbach's law. It is probable, however, that in the case of sliding, such flaws are generated during sliding over a sliding distance as seen in Fig. 4 and then c_f may become rather insensitive to the indenter size in contrast to the static loading, and again W_c is proportional to R^2. Critical comparison of the two approaches have been made by some investigators [16–18].

It is of interest to check the dependence of the fracture surface energy and the coefficient of friction on the critical load in Equation 1. Therefore, taking the value of W_c in a certain environment as the reference value, the relative ease of the hertzian fracture in another invironment was estimated; i.e. from Equation 1,

$$\frac{W_c}{W_c^*} = \left(\frac{\gamma}{\gamma^*}\right)^{3/2} \left[\frac{1 + A\mu^*}{1 + A\mu}\right]^3 \left(\frac{R}{R^*}\right)^2, \quad (2)$$

provided that material combinations are unchanged in sliding; so that I_f and c_f in Equation 1 can be eliminated. The asterisk in Equation 2 indicates the reference value. The value of γ of soda-lime glass in a liquid environment was measured by Culf [10] based on Roesler's equation. Recently Field [19] pointed out that her values should be multiplied by 0.8 because of the use of a better Roesler constant. As an estimation example of Equation 2, W_c in air is chosen as the reference value; i.e. $W_c = 19.6$ N, $\mu = 0.41$, $\gamma = 3.2$ J m^{-2} in air and $R = 2.5$ mm. Provided that the measured value of μ in distilled water is 0.5 and γ is 2.32 J m^{-2}, the value of W_c in distilled water is

$$\frac{W_c(\text{water})}{19.6(\text{N})} = \left[\frac{2.32(\text{J m}^{-2})}{3.2(\text{J m}^{-2})}\right]^{3/2} \times \left[\frac{1 + 10.0 \times 0.41}{1 + 10.0 \times 0.50}\right]^3 .$$

Then W_c(water) is 7.43 N which is comparable with the experimental value of 6.9 N. Similar comparisons are made for W_c in another environment, taking W_c in air again as the reference value; the results are shown in Fig. 8. The agreement between Equation 2 and the experimental results are generally within a reasonable limit, although in cyclohexane and phosphoric acid the difference between them is about a factor of 3. This may occur in part because the reduction of fracture stress near the sub-surface (due to the chemomechanical effect) results in the formation of pits which act as a strength-reducing flaw; this leads to relative ease of crack formation.

In this connection, it is of interest to apply such calculation for the experimental results by

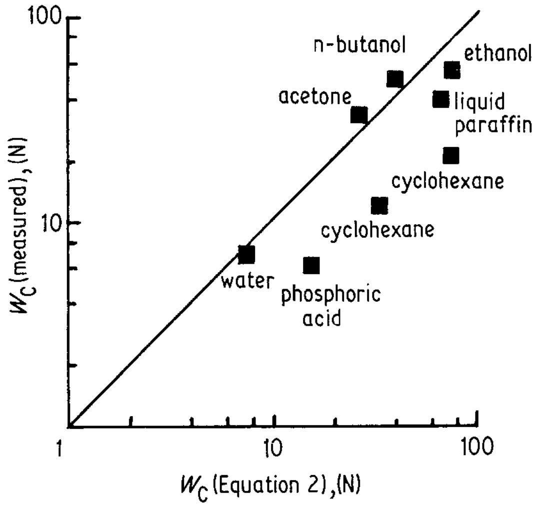


Figure 8 Comparison of W_c between Equation 2 and the experimental value.

Gilroy and Hirst [3], who measured W_c of soda-lime glass in air. The curve-fitting of their data gives the result: $W_c/R^2 = 1.9 \times 10^5\ \mathrm{N\,m^{-2}}$ for $\mu = 0.5$, $1.6 \times 10^6\ \mathrm{N\,m^{-2}}$ for $\mu = 0.3$, and $2.4 \times 10^6\ \mathrm{N\,m^{-2}}$ for $\mu = 0.15$. Taking W_c/R^2 for $\mu = 0.5$ as the reference value, Equation 2 gives the values of W_c/R^2 as $0.63 \times 10^6\ \mathrm{N\,m^{-2}}$ for $\mu = 0.3$ and $3.4 \times 10^6\ \mathrm{N\,m^{-2}}$ for $\mu = 0.15$, which are comparable with their corresponding experimental values.

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