

Pores and cracking in ceramics

J. Wang, L.J. Vandeperre, R.J. Stearn and W.J. Clegg*

Department of Materials, University of Cambridge, Pembroke St, CB2 3QZ, UK

Experiments have been carried out in which the passage of a crack through simple, well-defined pore arrays has been studied, using poly(methyl methacrylate) as a model system. These show that the crack front bows as it passes between the pores. This causes an increase in the length of the crack front, which is associated with an increase in the applied force required for continued crack growth. At high pore volume fractions this increase in line length is limited as the bowing crack intersects a pore ahead of it in the crack plane. Using these observations it is shown that the estimated change in the length of the crack front with porosity is very similar to the experimentally observed variation in the fracture energy in different ceramic systems.

Key words: Porosity, cracking, fracture energy.

Introduction

The effect of porosity on variables such as the elastic modulus and thermal conductivity can be readily quantified [1]. However its effect on the fracture energy is not well understood with many different types of behaviour apparently being observed [2].

It is often suggested that the fracture energy should change with porosity in the same way as the elastic modulus on the basis that a material's surface energy is related to its elastic modulus [3, 4]. Whilst this may be correct for a homogeneous material, there is no reason to believe that the surface energy of the alumina in the porous structure should be modified by the presence of the pores. Rather one might expect that introducing porosity reduces the amount of material that can break and hence the energy that is dissipated. The fracture energy of a porous body, R_p , would therefore be expected to decrease linearly with the area fraction of pores on the crack plane, A , according to

$$\frac{R_p}{R_d} = (1 - A) \quad (1)$$

where R_d is the fracture energy of the dense material. Two types of porous structure may be considered. In the first, the body is made up of discrete pores surrounded by a matrix. This is the structure that might be made by adding particles of a fugitive phase to the powder compact and then removing them by heating. In that case, provided the crack cuts through the structure in some random plane then the area fraction of pores in the crack plane, A , is equal to the volume

fraction of pores in the body, P .

Porous materials are more usually made by sintering a powder compact so that it is not fully dense. Here fracture occurs by failure of the necks between the particles that are developing during sintering. The situation is more complex than before, but there are two limits. The first is where the body contains no pores, so that the fracture energy is equal to that of the dense material. The second is the unsintered powder compact, where the porosity can be obtained from the relative density of the powder compact and where the fracture energy is approximately (but not equal) to zero.

Calculations suggest that the variation between these two points should be non-linear [5] so that the variation in fracture energy is given by

$$\frac{R_p}{R_d} = \left(1 - \frac{P}{P_g}\right)^n \quad (2)$$

where P_g is the volume fraction of pores in the unsintered powder compact. The value of the exponent is normally unknown, although there is data obtained from partially sintered materials that are consistent with a value for n of 1 [4].

However it has been shown recently that the change of fracture energy with porosity reported above [4] is due predominantly to changes in the grain size of samples sintered at different temperatures (and hence associated also with different porosities) [6]. Once these effects are removed, the fracture energy appears to vary in a similar way to that observed in structures consisting of isolated pores in a matrix. That is the fracture energy remains approximately constant as the volume fraction of pores is increased up to a volume fraction of 0.2, after which the fracture energy falls more rapidly [6, 7].

*Corresponding author:
Tel : +44-1223-334470
Fax: +44-1223-762836
E-mail: wjc1000@cus.cam.ac.uk

That this behaviour is seen in different materials containing different pore structures suggests that these effects are due to the pores. The aim of this paper therefore is to investigate what happens as a crack passes between two pores and to relate this behaviour to the variation in fracture energy that is measured in porous ceramics.

Experimental Procedures

To see what happens as a crack passes between two pores, samples were made from P.M.M.A. In the first set of experiments, where the aim was to understand what happened as the crack passed between two pores, the pores were introduced by drilling two hemispherical holes in the side of the sample and in the same plane as the growing crack. This had to be done carefully and under cold water to avoid the introduction of internal stresses.

In later experiments the effect of introducing pores in the centre of the sample and ahead of the initial pores was studied. Here the pores were made by drilling holes whose axis was perpendicular to the crack plane.

The processes occurring during crack growth were studied in samples where the cracks were grown by wedging. A notch was then sawn into the plate, as shown, and the notch sharpened by gently tapping a razor blade into the base of the notch. The crack was then grown from this sharpened notch by pressing a wedge into the notch using a simple loading device, so that each insertion of the wedge gave rise to an increment of crack growth. This left a series of lines on the final fracture surface each line corresponding to the rest position of the crack after each increment of growth and recorded the shape of the crack front as it passed along the sample.

Quantitative measurements of the applied force required for cracking were obtained using a double cantilever beam sample tested at a constant displacement rate.

Results and Discussion

Growth of a crack between two pores

The way in which the crack grows through just two pores can be seen in Fig. 1. Once the crack has started to grow, it is observed to accelerate once it is almost touching the pores, taking up a position mid-way between the two pores, see Fig. 1(a). As the crack moves beyond this point, it starts to bow, as shown in Fig. 1(b). As the crack bows further the crack gradually moves around the pore, eventually completely enveloping it, at which point the crack intersects the pore at the sample surface. Further loading enables the crack to break free of the pores giving rise to a burst of crack growth. This is consistent with observations on fracture surfaces of various materials containing pores, including sodium chloride [8], magnesium oxide [9] and inorganic glasses [10, 11], as well as the observation of tails seen on the far side of pores [12], presumably caused by the crack spreading around the pore on slightly different planes. It is therefore clear that the crack must grow around the pore rather than through it, as might perhaps be expected.

To see whether this interaction between the pore and the crack is likely to be of a sufficient magnitude to influence the fracture energy, measurements were made of the applied force required to grow the crack through the pores. The results are shown in Fig. 2. Initially the sample simply loads up elastically and no crack growth occurs. When the applied force (or moment) becomes sufficient, the crack propagates at a constant applied force, until the crack almost reaches the perimeter of the pores when there is a load drop as the crack moves rapidly in toward the pores. The applied load then remains constant for a short time, until the crack begins to bow, whereupon the load begins to increase. This continues until the applied force is greater than that required to grow the crack in a pore free region of the material. That this is not due simply to drift in the measuring apparatus can be seen in Fig. 2, because once the crack escapes from the pores the applied force required for crack growth becomes equal again to the value required before the crack reached the pores.

These experiments clearly demonstrate that the pores can inhibit the propagation of cracks and that this interaction is associated with an increase in length of the crack front, suggesting that the crack front may be

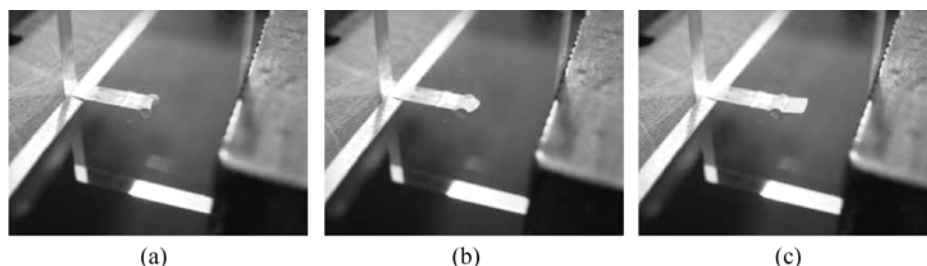


Fig. 1. A crack front grows through a set of pores, (a) upon approaching the pores, the crack is drawn into the material between the pores. (b) This is followed by bowing of the crack in the centre between the pores. (c) Only after the crack front has extended by a significant amount by bowing, is the crack front seen to advance again in the dense material ahead.

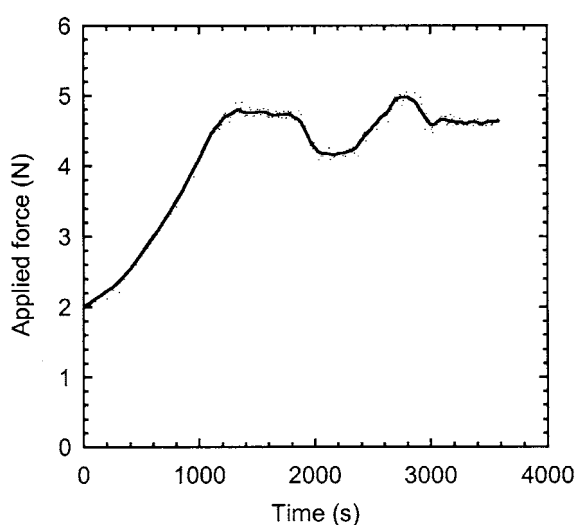


Fig. 2. The variation in the applied force required to grow a crack through the body above. Note that the applied force decreases as the pores are drawn toward the crack and then increases above that required for growth in the pore free region of material as the crack bows between the pores.

considered to have a line tension, as suggested previously by Lange [9] and by Lawn [13], although there has been no attempt to estimate the effect of porosity on the fracture energy using this approach.

To do this the increase in line length as the crack moves between the pores and a criterion for the breakaway of the crack from the pores must be known. The former was determined from measurements of the traces of the crack fronts on the crack plane. These showed that the crack fronts could be described as segments of ellipses.

The next step is to understand how the shape of the ellipse changes as the crack moves forward. From photographs of the final fracture surfaces which showed the it is found that the ellipse develops by every point along the front of the ellipse at a given time

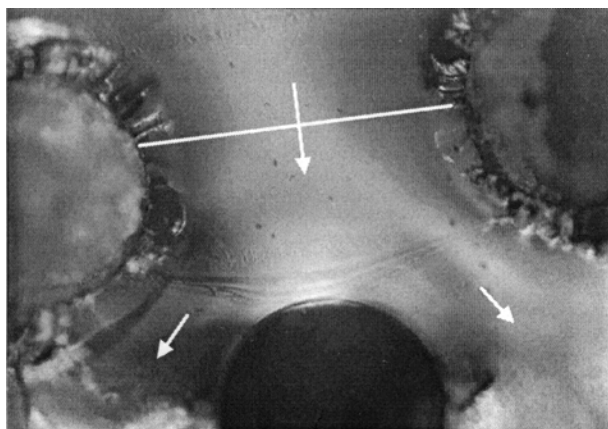


Fig. 3. At a high volume fraction of porosity, the crack front intersects with the pore ahead of the crack tip, allowing crack growth to continue while less material is broken. Note the small steps on the fracture surface indicating the bowing of the crack.

moving forward by an equal amount in a direction perpendicular to the ellipse. This means that the mid-point between the particles moves directly forward, whilst the end-point moves by an equal amount in a direction parallel to the initial crack front. Intermediate points move in directions corresponding to their position along the line.

The bowing of the crack front arises from the conditions that the crack front is increasing in length, whilst the velocity at every point along the crack front remains equal. It is not due to some drag force imposed by the pores, as has been suggested elsewhere [9, 11].

To calculate the maximum increase in length of the crack front that is required if the crack is to bow between two pores requires that there is some criterion for the breakaway of the crack from the pore. Observations suggested that this occurred when the crack had spread completely around the pore. Sometimes breakaway was observed at an earlier stage, but this was always associated with the initiation of defects on the far side of the pore surface. It is worth noting that the increase in the maximum length of the crack front is not dependent on the absolute spacing as might be expected from a pinning model, but only on the volume fraction of pores.

As the volume fraction of pores increases, the possibility arises that the bowing crack front can intersect another pore in the crack plane, before it has reached the breakaway point, as shown in Fig. 3. Once this occurs then the maximum length of crack front occurs at the point just before the bowed crack intersects the pore ahead of it. If the porosity is assumed to consist of

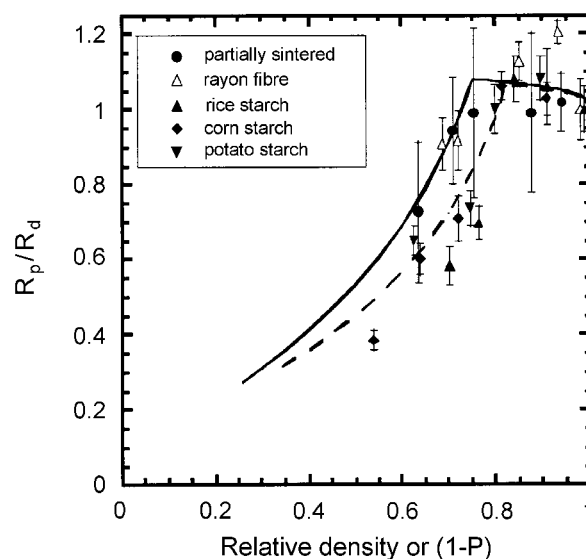


Fig. 4. The variation in the maximum crack length of the crack front estimated for face centred and body centred cubic arrays of pores, shown as the solid and dashed lines respectively, with changes in the relative density, or $(1-P)$, and compared with experimental data in a range of alumina materials with porosities of different sizes and types. The data is taken from ref [7].

a face cubic centred distribution of pores in the matrix, and it is also assumed that cracks grow in the plane with the densest packing of pores, that is a $\{111\}$ plane, the closest distance between the line connecting the centre of two pores and a pore ahead of it, d_{crit} , is given by:

$$d_{\text{crit}} = \left(\sqrt[3]{\frac{3}{2}} - \sqrt[3]{\frac{3P}{2\pi}} \right) \frac{a}{2} \quad (2)$$

where a is the length of an edge of the unit cell, P is the volume fraction of porosity. Similar expressions can be obtained for different arrangements of pores, such as body centred cubic arrays. Again the maximum length of the bowed crack front varies with the volume fraction of the pores rather than their absolute spacing.

Combining this with the crack front shape, allows the maximum increase in the length of the crack front to be estimated at the point when the crack front intersects with the boundary of the pore ahead of its tip. The result is plotted in Fig. 4 together with the experimentally observed variation in the fracture energy with porosity for produced using different inclusions and by partial sintering. It is seen that the agreement is surprisingly good, suggesting that the variation in the fracture energy with porosity is associated with the maximum increases in length of the crack front that occurs as the crack bows between the pores. In particular it can be seen that the measured fracture energy is independent of the size of the pores, which is approximately 3 mm in the case of those materials containing rice starch, 10 mm in those made with corn starch and approximately 40 mm in those made using potato starch [7]. It is the volume fraction of porosity that influences the fracture energy, as predicted.

Conclusions

Experiments in which cracks are grown at pairs of pores in poly (methyl methacrylate) show that the crack front bows as it passes between the pores. It is shown that this bowing arises not because of any drag force exerted by the pore on the crack front, but because the crack front is expanding, whilst at the same time the velocity of every point along the crack front is remaining constant. At low volume fractions of pores the crack front breaks away when the crack has

travelled completely around the pore. At higher volume fractions however the crack can intersect other pores ahead of them in the crack plane before the crack has reached this breakaway point. The maximum length of crack front is therefore reached just before the crack intersects the pore. Using these ideas, estimates have been made of the increase in line length that would be expected and give good agreement with the changes in fracture energy with porosity that are observed in ceramic systems.

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