EDGE TOUGHNESS OF BRITTLE MATERIALS

M. HANGL*, R. DANZER*, R. PAAR†

Brittle chipping of edges often occurs when machining or using brittle materials, e.g. advanced ceramics. In industrial applications this is one of the most common reasons for the failure of ceramic components. E.A. Almond and N.J. McCormick [1] developed a method to investigate the behaviour of ceramic edges under mechanical loading. This method, whereby an indenter is used to load an edge near region in a sample until flaking occurs, can be used to characterize ceramic materials and to rank them with respect to their resistance against edge flaking. In this work the influence of the edge geometry on the measured edge toughness is investigated.

INTRODUCTION

Following the ideas of E. A. Almond and N. J. McCormick a sample is loaded with a Rockwell-C indenter (polycrystalline diamond) close to the edge until edge flaking occurs (Fig.1). This test is performed in varying distances from the edge and the peak load is recorded each time.

Plotting the load P, which is required to produce an edge flake, against the distance d between the centre of the indent and the edge reveals a linear relationship (Fig. 2). The slope of the linear regression through the data points in fixed experimental conditions (shape of indenter, geometry of the edge) is characteristic for a material.

In general the best fit line does not exactly meet the origin of the plot as one would expect. An explanation could be the uncertainty in measuring distance and load [1].

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* Christian Doppler Labor für Hochleistungskeramik, Institut für Struktur- und Funktionskeramik, A-8700 Leoben, Magnesitstrasse 2, Austria

† C.E.C., Joint Research Centre IAM, 1755 ZG Petten, The Netherlands

Additional reasons for this deviation are possibly internal stresses in the material and the finite contact zone between the indenter and the samples surface due to deformation of both [3]. For sharp edges the deviation is neglected in the following.

According to Fig. 2 the load (P) required to produce a flake at a sharp edge can be written as

$$P \approx M \cdot d$$

where d is the distance between the edge and the centre of the indent.

For given experimental conditions the slope M is a measure of the resistance of a material against flaking and is called *edge toughness* [1,2]. The standard testing conditions used were Rockwell-C indenters and rectangular sharp edges. This edge toughness value M depends only on the investigated material.

RESULTS

Relationship to Fracture Toughness

The edge toughness of several brittle material with varying fracture toughness was determined. In Fig. 3 results from this work and results from the work of Almond and McCormick are plotted together against the critical strain energy release rate (note the log-log scale). A square-root relationship between the edge toughness and the critical strain energy release rate ($M \propto G_c^{1/2}$) is observed. Because of the relation $G_c = K_c^2/E$, the edge toughness is proportional to both the critical stress intensity factor and the reciprocal of the square root of Young´s Modulus ($M \propto K_c$ and $M \propto E^{-1/2}$).

Edge Geometry

The edge geometry influences the load necessary to produce an edge flake. Almond and McCormick tested edges with different included angles. They showed that the influence of the edge angle α on the edge toughness M does not depend on the material [2]. They found an empirical correction factor $f(\alpha)$ which describes the ratio of edge toughness of arbitrary angled sharp edges to that of rectangular sharp edges (Fig. 4).

In our laboratory several tests were performed on specimens with chamfered edges. In Fig. 5 the results are compared with those of samples with rectangular sharp edges. The edge toughness is the same for both, but the measured flaking loads on the chamfered edge are much higher. A „Master-Curve" describes both data sets, if an effective distance is introduced (Fig. 6). It can be assumed that the removal of material by chamfering the edge changes the stress state under the indenter only slightly. The same can be said for the strain energy release rate of a crack underneath the indent. Therefore the effective distance d_{eff} is approximately given by completing the chamfered edge to a sharp edge.
A more general definition of the effective distance and the edge angle for arbitrarily shaped edges is given in Fig. 7. A section perpendicular to the edge through the centre of the flake is shown. The flake, which will form under load, is drawn in a broken line. The *effective angle* of an edge is defined as the angle which is included by two tangential planes. Plane 1 is in contact with the point of indentation. Plane 2 contacts the sample surface on which the crack ends. The *effective distance* is defined as the distance between the centre of the indent and the intercept of the two tangential planes.

In this way for any arbitrarily shaped edge an *effective distance* and an *effective included angle* can be defined. This concept can be used to design edges in such a way that flaking forces become higher than a selected value. This will be demonstrated in the following section.

APPLICATION OF THE CONCEPT ON THE DESIGN OF CERAMIC VALVES

Ceramic valves made of SSN (sintered silicon nitride) are used in prototype vehicles. If for any reason hard particles get between the valve seat ring and valve the situation is similar to that in the experiments discussed above.

To quantify the flaking loads, edge toughness test were performed on the valves. The principle experimental set-up is shown in Fig. 8a. Half of the tray rests on the sample holder while the valve stem is clamped. Fig. 8b shows the typical geometry of a valve seat. The load was applied perpendicular to a tangential plane on the curved valve seat. Regarding the path of the crack that forms the edge flake and remembering the concept of arbitrarily shaped edges the valve seat can be seen as a chamfered edge with an included angle of 45°. Due to the fact that the distance d is relatively small in relation to the radius of the valve tray the curvature of the valve seat is neglected. It is important to know that there is a limited region (the overlapping of valve seat and valve seat ring) within the effective edge distance where a load can be applied in service conditions.

The results from the valve (•) and measurements on rectangular specimens (■) are shown in Fig. 9. These data have been transformed to values for a 45° edge (□) by using the results of Fig. 4. The transformed data fit perfectly to the data of the valve, taking into account the different effective distances.

It was shown that the flaking load of an edge of a specified material under constant geometrical conditions depends only on the effective distance of the indent from the edge. Although the region on the valve seat where the concentrated load is applied can not be influenced, the effective distance from the edge (d_{eff}) can easily be increased by increasing the thickness (t) of the valve tray (Fig. 8c).
This leads to a significant increase in the effective edge distances and, as a consequence, in the flaking loads (Fig. 10). For the two valve geometries, which are discussed above, the range of flaking loads can be increased from 500 - 1000 N to 1500 - 2000 N. Under the assumption that the load on the valve caused by the gas pressure is smaller than these values the valve is safe against edge flaking. Another possibility to increase the valve reliability is to optimise the angle between valve seat and valve tray in order to increase the flaking loads.

SUMMERY AND CONCLUSIONS

The flaking load is proportional to the distance of the centre of the indent from the edge. The slope of the best fit line (*edge toughness*) is a parameter which characterizes the resistance of a material against edge flaking. The influence of edge geometry on edge toughness is discussed. For chamfered or arbitrarily shaped edges a concept is proposed to calculate the flaking load using an effective distance from the edge and an effective edge angle. It is shown, how this concept can be used to quantify the resistance of a material against edge flaking and to improve edge design in order to avoid edge flaking.

References:

1. Almond, E.A. and McCormick, N.J. (1986) Constant geometry edge-flaking of brittle materials, *Nature* **321,** 53-55
2. Almond, E.A. and McCormick, N.J. (1990) Edge flaking of brittle materials, *J. of Hard Materials* **1,** 154-156
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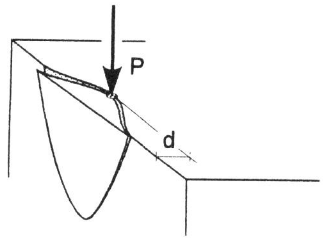

Fig. 1: Formation of an edge flake under load P applied at a distance d from the edge

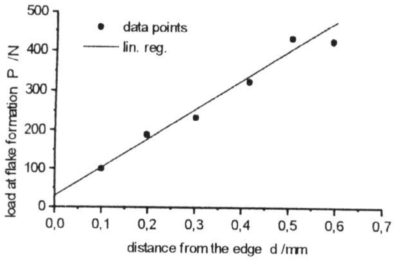

Fig. 2: Indentation load required to produce a flake (Si_3N_4).

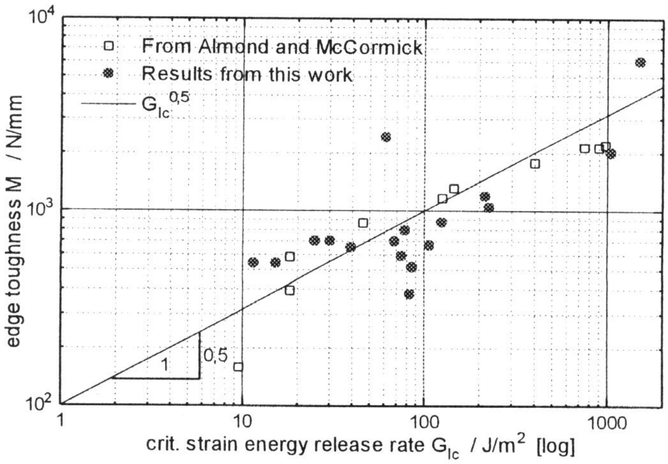

Fig. 3: Relationship between edge toughness M and the critical strain energy release rate G_{Ic} for several brittle materials; • : own measurements; □ : measurement of Almond and McCormick [2].

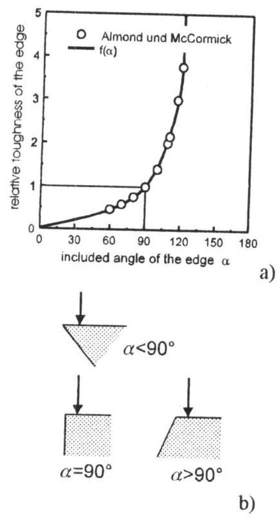

Fig. 4: a) Ratio of edge toughness values for sharp edges with varying angles (after [2]). b) Definition of the edge angle.

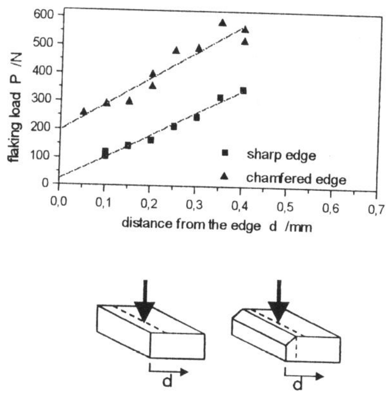

Fig. 5: Flaking load versus distance from the edge for a sharp and a chamfered edge; these tests were performed on rectangular silicon nitride samples.

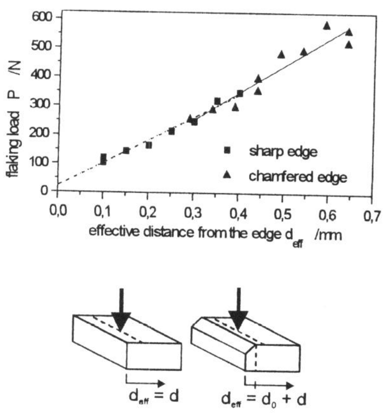

Fig. 6: Same measurements as in Fig. 5, but plotted versus the effective edge distance.

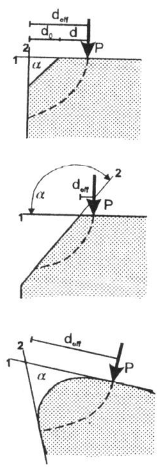

Fig. 7: Definition of effective edge distance and angle (section perpendicular through the edge): a) chamfered edge with large flake, b) the same with small flake, c) the same for arbitrarily shaped edge.

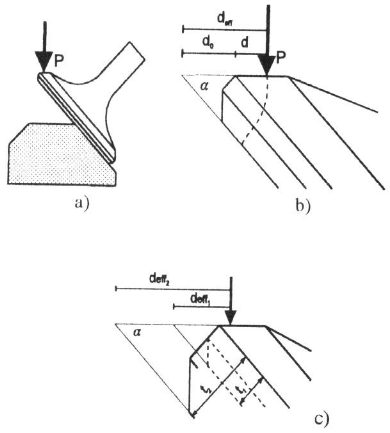

Fig. 8: a) Principle experimental set-up and b) definition of effective edge distance and angle; c) changing the thickness of the valve tray

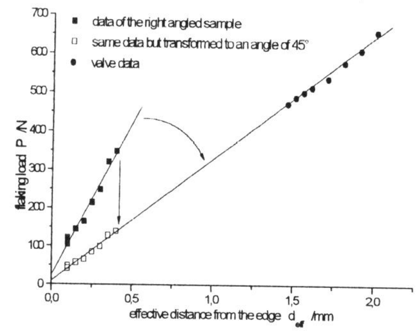

Fig.9: Valve test results compared with measurements on rectangular specimens.

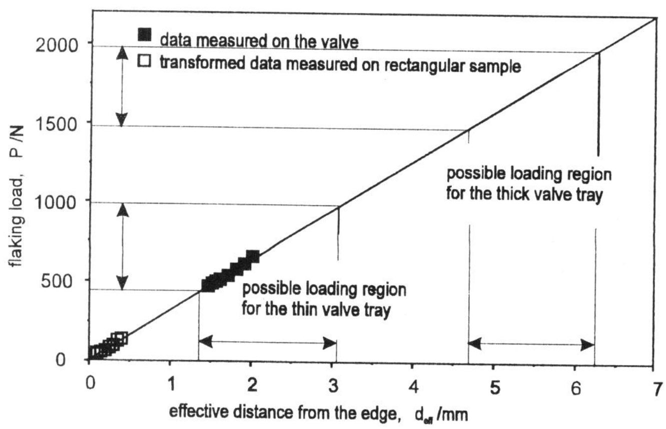

Fig. 10: Example for avoiding edge flaking: increasing the thickness of the valve tray increases the effective edge distances and the flaking loads. Marked are areas of loading points and flaking loads for valves with different geometries.