Controlled Crack Growth with a Dual-Tip Indenter

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ABSTRACT: *A new indentation tip with two rectangular pads is proposed. These pads are loaded, located to the sides of any pre-existing crack, for example, as developed from a Vickers micro-indentation. From the controlled growth of these cracks it is possible to compute different Fracture Mechanics parameters such as the critical stress intensity factor of the material or the arrest stress intensity factor for brittle materials. An example of its application to common soda-lime glass is described.*

INTRODUCTION

It is possible to grow cracks, in brittle materials, by pressing two rigid blocks symmetrically located to the sides and parallel to a pre-exiting flaw. The load to which the crack starts to propagate provides information about the critical stress intensity factor for the material, and the final crack size about the arrest stress intensity factor, at the temperatures at which the experiments were carried out.

This method can also be used to characterise the interface between two materials, locating each pressing pad in a different material and both parallel to the interface between the materials. By miniaturisation it may be even possible to use this technique as a micro-mechanical toughness probe.

An indenter has been designed and made, based on this idea and its application in a very brittle material (soda-lime glass) will be shown in this contribution. The indenter is used to grow in a stable way some previous cracks generated by a Vickers diamond microindenter.

MATERIAL AND EXPERIMENTS

A very brittle, homogeneous and transparent material was chosen for the experiments: ordinary soda-lime glass, as used for windows.

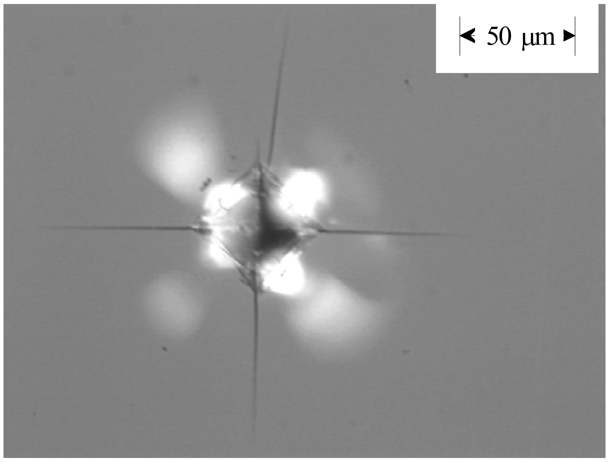

Figure 1: Microcracks produced by a Vickers' diamond microindenter with a load of 9.81 N, for 10 s, on an ordinary glass, 10.38 mm thick.

A transparent material has the additional advantage of allowing for the observation of the microcrack shapes and depths.

Tests were performed on flat window glass with a thickness t = 10.38 mm. Rectangular glass blocks of 108 × 36 mm were indented, by means of a Vickers microhardness tester (Leco, model M-400-G2). A diamond Vickers pyramid was used with an applied load of 9.81 N with a dwell time of 10 s. This load produces 4 cracks starting from the corners of the pyramid, as shown in Figure 1. The couples of opposing cracks are connected under the indentation, forming two semicircular surface cracks.

The hardness measurements, obtained from the size of the diagonals of the indentation, give an average value H_{V1} = 4.94 GPa (see Table 1).

The critical stress intensity factor for the glass can be estimated from the size of the cracks and using empirical equations proposed by many authors, see, for example, Ponton and Rawlings [1,2] reviews for semicircular and Palqvist crack geometry.

TABLE 1: VICKERS' INDENTATIONS ON ORDINARY GLASS,
WITH A LOAD OF 9.81 N FOR 10 S.

Test number	1st diag. (μm)	2nd diag. (μm)	H_{V1} (GPa)	1st crack (μm)	2nd crack (μm)
1	61.9	63.3	4.64	168.5	153.5
2	63.5	62.4	4.59	160.6	150.0
3	61.5	63.9	4.61	153.2	≈
4	61.7	60.9	4.84	133.5	≈
5	56.5	54.7	5.89	148.4	≈
6	59.3	59.8	5.13	158.0	≈
Mean	61		4.94	153	
St. Dev.	± 3		± 0.5	± 10	

For a semicircular crack geometry, the equation proposed by Anstis et al. [3] is universally accepted:

$$K_H = 0.0154\sqrt{\frac{E}{H_V}}\frac{P}{c^{3/2}} \tag{1}$$

where E is the modulus of elasticty (for glass, E = 69 GPa, after Ashby and Jones [4]), H_V is the Vickers hardness (H_V = 4.94 GPa, see Table 1), P is the applied load (P = 9.81 N) and c is the crack size produced after the indentation ($2c$ = 153 μm, in Table 1). Substituting these values in Eq. (1), the glass toughness is estimated as:

$$K_H = 0.0576\frac{P}{c^{3/2}} = 0.84\,\mathrm{MPa}\sqrt{\mathrm{m}} \tag{2}$$

This is a very reasonable estimation for the glass toughness, taking into account that the usual range reported is 0.8 - 1.7 MPa√m, see, for example, Cebon et al. [5].

Afterwards, the dual tip indenter is used to grow one of the two cracks created by the Vickers' indentation. The indenter geometry, made of steel, is shown in Figure 2.

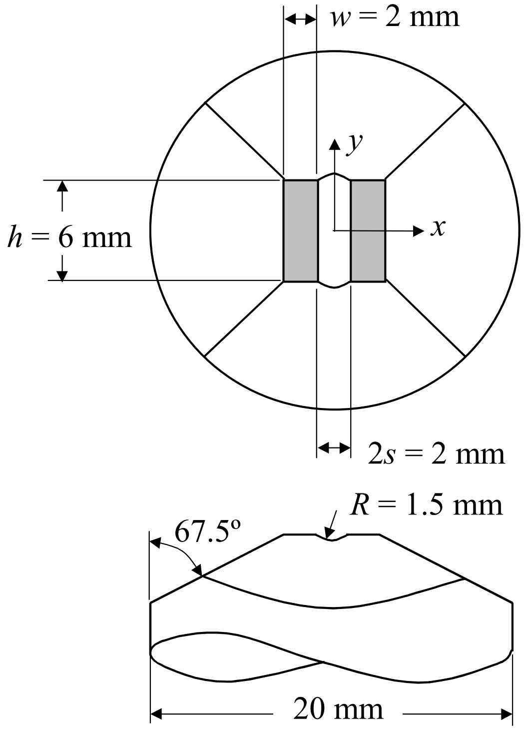

Figure 2: Geometry of the dual-tip indenter used in the experiments.

An electromechanical testing machine (Instron 4467,- with a load capacity of 30 kN) was used to apply the load on the dual-tip indenter. Pre-cracked glass samples were located between both pads and a 20 mm diameter backing steel plate. The indenter is guided by an axial roller bearing.

One of the cracks created by the Vickers indentation is located in the middle and parallel to the pads. That is named as the 1st crack. The displacement speed used was 0.2 mm/minute. The maximum load was kept for 15 s before unloading the samples.

STRESS FIELD

The stresses generated by the dual-tip indenter can be computed integrating the Boussinesq's solution for the point load, perpendicular to a semi-infinite homogeneous elastic solid, over both rectangular loaded regions (see, Saada

[6]). Figure 3 shows the results obtained for the normal stress (σ_{xx}) on the mid-plane between the pads, versus depth (z) and at different location (y) measured along the loading pad (see Fig. 2 for the definition of geometry).

These computations show that the dual-tip indenter generates a tensile stress field close to the surface and a compressive one at larger depths.

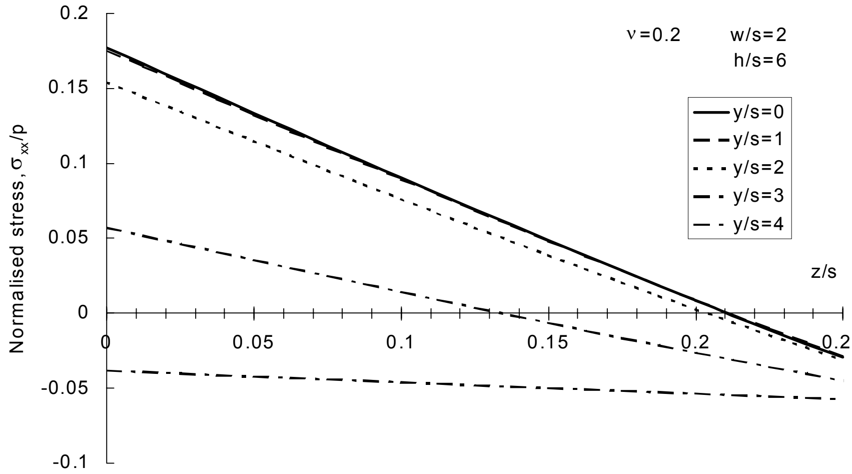

Figure 3: Normal stress at the mid-plane between the loading pads, for a Poisson ratio, $\nu = 0.2$ (typical value for glass, after Cebon et al. [5]). Because of symmetry there is no shear at the mid-plane between both pads.

The tensile stresses open the crack, previously generated by the Vickers micro-indentation. The maximum tension is located at the surface, at the centreline between both pads, its value is $\sigma_{\max} = 0.177\ p$, p being the pressure on the pads:

$$p = \frac{F}{2hw} \tag{3}$$

where F is the total load on the indenter.

The depth of this tensile stress field is very shallow. For the geometry used in the experiments (Figure 2), and a Poisson ratio $\nu = 0.2$ (common value for soda-lime glass), tension turns into compression at a depth of 210 μm. This feature allows to propagate a crack in a controlled way, mostly along the surface, without jeopardising the integrity of the solid.

RESULTS

An applied load of 10 kN on the dual-tip indenter does not produce an appreciable crack extension (of the previous Vickers' microcrack obtained with 9.81 N). For a load of 16.42 kN, another sample exploded in fragments.

For 11 kN, the crack parallel to the loading paths grows, but the perpendicular one does not, as shown in Figure 4. The cracks, shown in Figure 1, were already shown in Figure 1. Now they are shown after the application of the dual-tip indenter, with an applied pressure p = 458.3 MPa (assuming that the pressure is uniformly distributed on the loading pads).

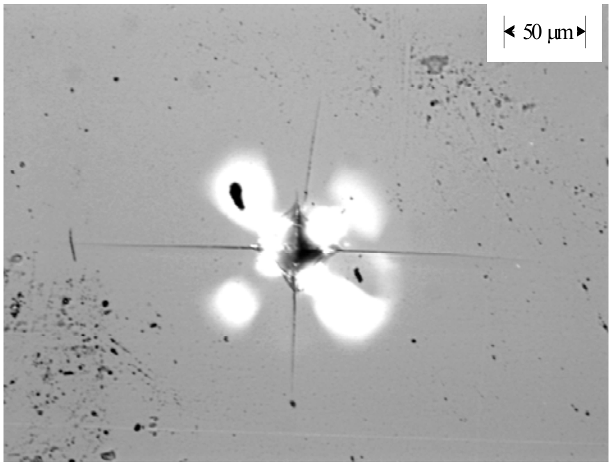

Figure 4: Cracks, previously shown in Figure 1, after being loaded with 11 kN, using the dual-tip indenter. The rectangular pads were located along the top and bottom ends of the micrograph.

DISCUSSION

The stress intensity factors along the crack front can be calculated using the equations proposed by Newman and Raju [7] for semi-elliptical surface cracks and using the superposition principle.

The elastic superposition principle allows for moving the loads from the boundaries of the solids to loads distributed on the crack surfaces. Now if the stresses transmitted through, where the crack actually extends, are kept, the values for the stress intensity factors are also kept (see, Martín-Meizoso and Martínez-Esnaola [8]).

Note that, because of symmetry, there is no shear at the mid-plane between the loading pads, so there will be no modes II and III, and the problem reduces to pure mode I, for all the points along the crack front of any-shaped crack, located on the midplane between the pads.

Assuming the cracks to be small in comparison with the loading pads, we can retain the top straight line in Figure 3 and compute the tension and bending that will result in a similar stress field. According to the nomenclature used by Newman and Raju [7]:

$$\begin{aligned} S_{\text{tension}} &= -1{,}850.4\ \text{MPa} \\ S_{\text{bending}} &= 1{,}931.5\ \text{MPa} \end{aligned} \tag{4}$$

For an initial crack, as generated by the Vickers' micro-indentation ($2c$ = 158 µm and assuming a semicircular surface crack: $a = c$), for a total load on the pads of 11 kN, the applied stress intensity factor at the crack intersections with the surface is 0.85 $\text{MPa}\sqrt{\text{m}}$, which is slightly larger than the previous estimation from the Vickers cracks (0.84 $\text{MPa}\sqrt{\text{m}}$, see Eq. (2)). So the cracks should grow along the surface, as they do. On the other hand, the applied stress intensity factor at the deepest point along the crack front is estimated as 0.63 $\text{MPa}\sqrt{\text{m}}$. So the critical stress intensity factor for an ordinary glass is not reached, and the crack should not grow in depth.

Figure 4 shows actually how the cracks have extended along the surface until reaching a final size of 305 µm. It is possible to use again the equations proposed by Newman and Raju [7] now on the resulting semi-ellipse ($2c$ = 305 µm and unchanged depth: a = 79 µm) to compute the arrest stress intensity factor at the surface: K_{Ia} = 0.83 $\text{MPa}\sqrt{\text{m}}$. Note that both stress intensity factors (critical and arrest) are very close, as expected for brittle materials.

It is also possible to compute the load required to trigger the first crack extension: 10.35 kN. It becomes clear why no crack extension was observed with a 10 kN load.

CONCLUSIONS

A dual-tip indenter allows growing surface cracks, in brittle materials, in a well-controlled way.

This technique can be extended to fatigue crack propagation experiments and can also be applied -at miniaturised size- as a toughness microprobe. It can also be extended to brittle interfaces.

Toughness measurements are accurate and repetitive: all the measurements obtained in these experiments, for the common soda lime glass, are in the range 0.84 ± 0.01 MPa√m.

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