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Interaction of cracks between two adjacent indents in glass

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Experimental observations of the interaction behaviour of cracks between two adjacent indents were made using an indentation technique in soda-lime glass. It was specifically demonstrated how one indent crack initiates and propagates in the vicinity of another indent crack. Several types of crack interactions were examined by changing the orientation and distance of one indent relative to the other. It was found that the residual stress field produced by elastic/plastic indentation has a significant influence on controlling the mode of crack interaction. The interaction of an indent crack with a free surface was also investigated for glass and ceramic specimens.

1. Introduction

The use of indentation flaws is now well established for studying mechanical properties of glass and ceramics. The specific attraction of indentation techniques lies in their simplicity as a means of introducing predetermined flaws into test specimens. Some important applications of these indentation techniques include: estimation of strength and fatigue response (with post-threshold [1, 2] and sub-threshold [3, 4] flaws); evaluation of fracture toughness [5, 6] and *R*-curve behaviour [7]; examination of indentation deformation [8–10] and elastic recovery [11, 12]; preparation of single-edge precracked beam (SEPB) fracture toughness specimens [13, 14]. These techniques are further extended to study the interfacial behaviour of the fibre/matrix composite system [15] as well as of the bonded dissimilar material system [16].

In the present work the indentation technique was applied to examine interaction behaviour of cracks between two adjacent indents in glass. Specifically, it was demonstrated how one indent crack initiates and propagates in the vicinity of the other indent crack. For this purpose, several types of crack interaction were examined by varying the orientation of one indent relative to another, both with and without residual contact stress around the indent. The interaction of a crack with a free surface was also studied for comparison purposes. The main attention of this paper is focused on experimental observations to provide a better understanding of the interactions by indentation-induced cracks.

2. Experimental procedure

The controlled surface flaws in this study were produced using a Vickers diamond indentor (Tukon, Page-Wilson Corporation, Bridgeport, CT) with a contact time of 15 s in air. The test specimens were soda-lime glass plates (Fisher Scientific Corporation, Medford, MA) and were annealed to remove any spurious residual stress prior to indentation. Three types of indent orientations applied in this study (Types I–III) are illustrated in Fig. 1. Two different conditions of crack interaction were imposed for each orientation. One condition was that a Vickers indent was placed in a glass plate and a second indent was then put nearby the first indent. The other condition was that a Vickers indent was put in a plate but the plate was annealed, and then a second indent was put nearby the first indent. For simplicity the former condition is termed "as-indented" and the latter is termed "annealed". The same indentation load was used to produce both the first and second indents. The annealing was done at 520 °C in air for approximately 24 h to remove residual contact stress due to indentation. In Type I experiment, the direction of cracks emanating from the corners of a second indent was measured as a function of distance between the two indents. Also, the size of the cracks emanating from the second indent was determined when possible. Indentation loads were varied from 9.8–68.6 N.

To examine the effect of crack interaction with a free surface, the indentation was placed near a free surface of a specimen with the indentation diagonal perpendicular and normal to the free surface (Fig. 1d). In addition to glass specimens, ceramic flexure bar specimens of SiC whisker-reinforced composite silicon nitride (30 vol % SiC whiskers) and similar monolithic silicon nitride, both fabricated by Norton Company, were also utilized for comparison. One side of each

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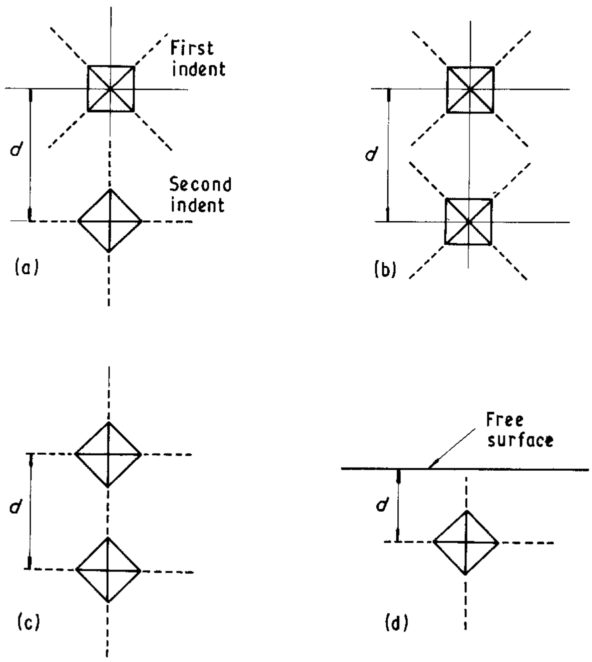

Figure 1 Schematic drawing of indentation geometries applied in this study: (a) Type I, (b) Type II, (c) Type III, and (d) Type IV orientations.

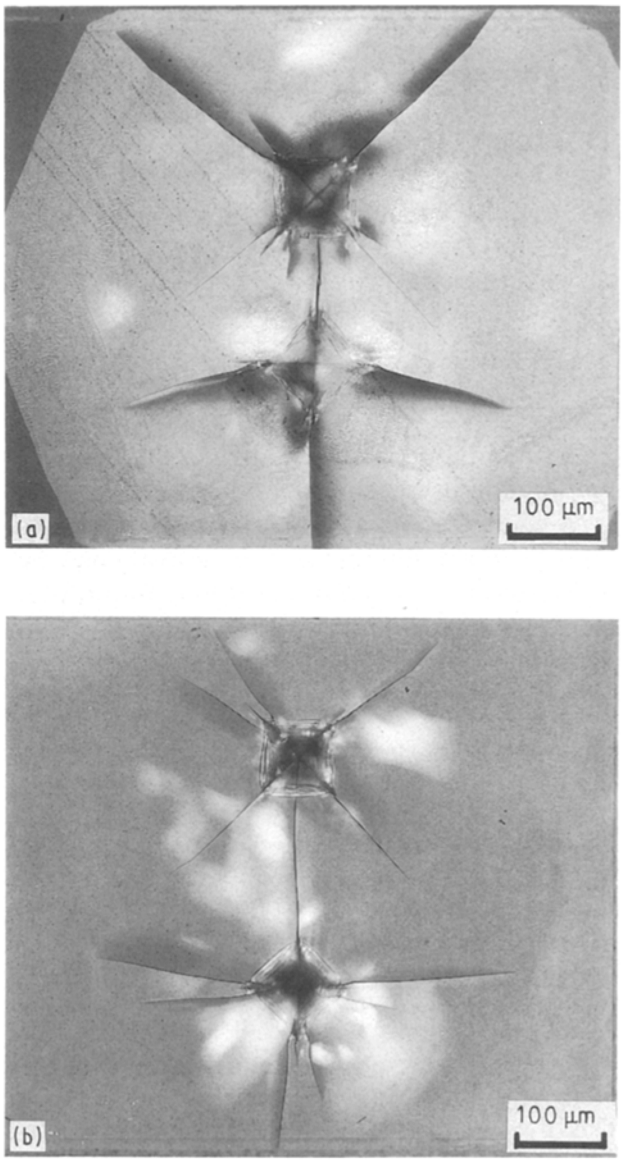

Figure 2 Crack interaction in Type I orientation in soda-lime glass with an indentation load of $P = 29.4$ N: (a) "as-indented", and (b) "annealed" conditions.

ceramic specimen was polished using 3 µm diamond polishing compound for indentation. This type of crack interaction has been studied previously in glass by Lardner *et al.* [16].

3. Results and discussion
3.1. Crack characteristics

Typical results of crack interaction for Type I orientation are shown in Fig. 2, where all indents were made in the glass specimens using an indentation load of $P = 29.4$ N. Note that when the second indent was placed near the first "as-indented" cracks (that is, "as-indented" condition), the crack emanating from the horizontal impression diagonal at the second indent deviated downward from the tip of the nearby first indent crack (Fig. 2a). On the other hand, when the second indent was placed near the first indent that had been annealed to remove residual contact stress (that is, "annealed" condition), the crack emanating from the second indent corners deviated toward the tip of the nearby first indent crack (Fig. 2b). In other words, for the "as-indented" condition, the nearby cracks between the first and second indents are "repulsive"; whereas, for the "annealed" condition, the crack interaction between the two indents is "attractive". Fig. 2 also shows that the size of the deflected crack for the "as-indented" condition is smaller than that for the "annealed" condition. These results indicate that the residual stress field around indent, produced by the elastic/plastic mismatches due to indentation, plays a significant role in controlling the mode of crack interactions.

Results of crack interaction for Type II orientation are shown in Fig. 3. Here, an indentation load of $P = 49$ N was used. Fig. 3a is for the "as-indented" condition, and shows a "repulsive" interaction between the two nearby cracks, causing the crack at the second indent deviating away from the crack tip of the first indent. For the "annealed" condition the interaction was opposite: cracks emanating from the second impression corners propagated toward the nearby crack tips of the first indent, resulting in "attractive" interaction (Fig. 3b). It can be seen from the comparison of Fig. 3a and b that the crack size in the attractive interaction is greater than that in the repulsive interaction. Here again, like the interaction in Type I orientation, the residual stress field around indents has a significant effect on the mode of crack interactions as well as the size of the crack propagated.

Fig. 4 shows the crack interaction in Type III orientation obtained with an indentation load of $P = 49$ N. The interaction between the two adjacent cracks is in a "repulsive" mode for the "as-indented" condition, as shown in Fig. 4a. For the "annealed" condition it is somewhat unclear whether the interaction is attractive or insensitive (Fig. 4b). However,

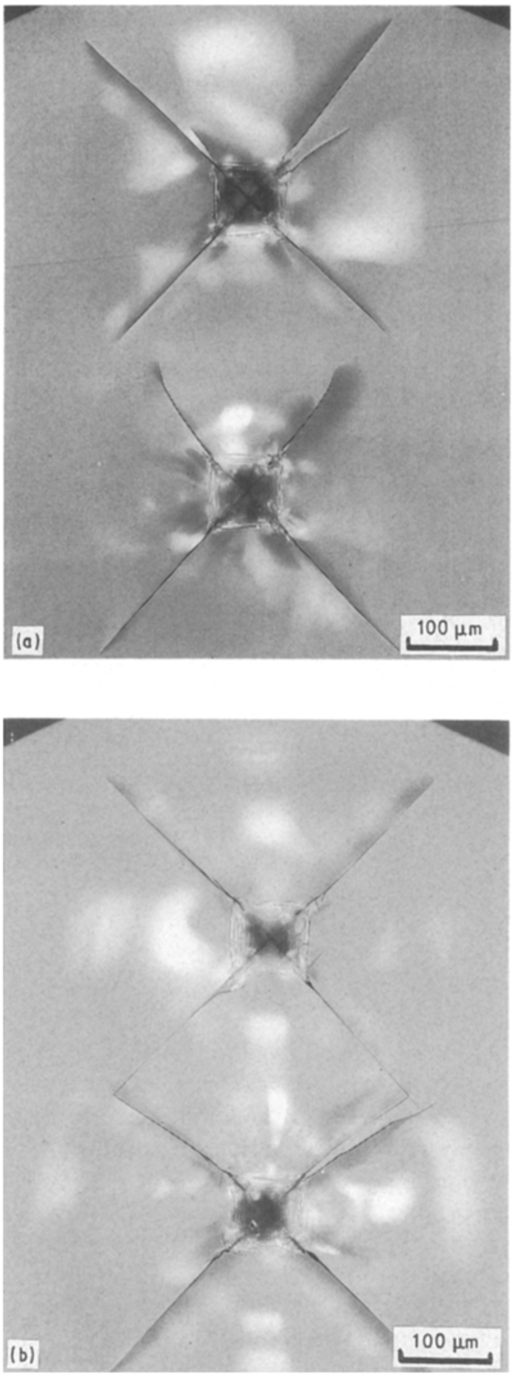

Figure 3 Crack interaction in Type II orientation in soda-lime glass with an indentation load of $P = 49$ N: (a) "as-indented", and (b) "annealed" conditions.

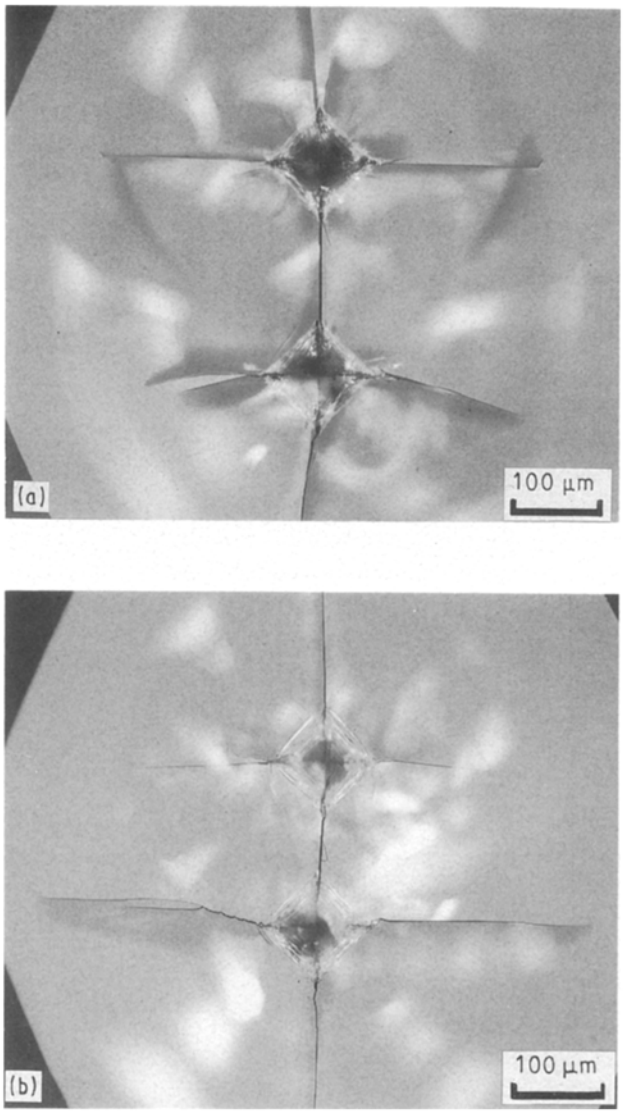

Figure 4 Crack interaction in Type III orientation in soda-lime glass with an indentation load of $P = 49$ N: (a) "as-indented", and (b) "annealed" conditions.

considering that the crack size in the second indent is much larger than that in the first indent, it can be inferred that the interaction is "attractive".

Crack interactions with free surfaces for the glass and ceramic specimens are depicted in Fig. 5. The indentation loads of $P = 9.8$ and 98 N were used in the glass and ceramic specimens, respectively. As seen in Fig. 5, regardless of the materials used, the cracks emanating from the horizontal impression corners deviated in a direction toward the free surface. The cracks initiated with a certain deviation angle, and then reoriented with a gradual increase in deviation angle as the cracks approached the free surface. It should be noted that the size of the deflected crack in the presence of the free surface was greater than those of the regular as-indented cracks away from the free surface. Based on these results it can be concluded that the interaction of a crack with a free surface is "attractive", similar to the results seen in the "annealed" conditions of Types I, II and III orientations. This attractive mode of interaction with a free surface is manifest if one considers that the material constraints near the free surface (plane stress) are much less than those in the bulk material direction (plane strain), thereby providing the free surface as a preferential site of crack propagation. The energy available for the crack propagation process is greater under plane stress condition.

3.2. Crack propagation angle in Type I interaction

The direction of the cracks originating from the second impression corners, which is defined as the crack propagation angle, θ, was determined for the crack interaction in Type I orientation in soda-lime glass.

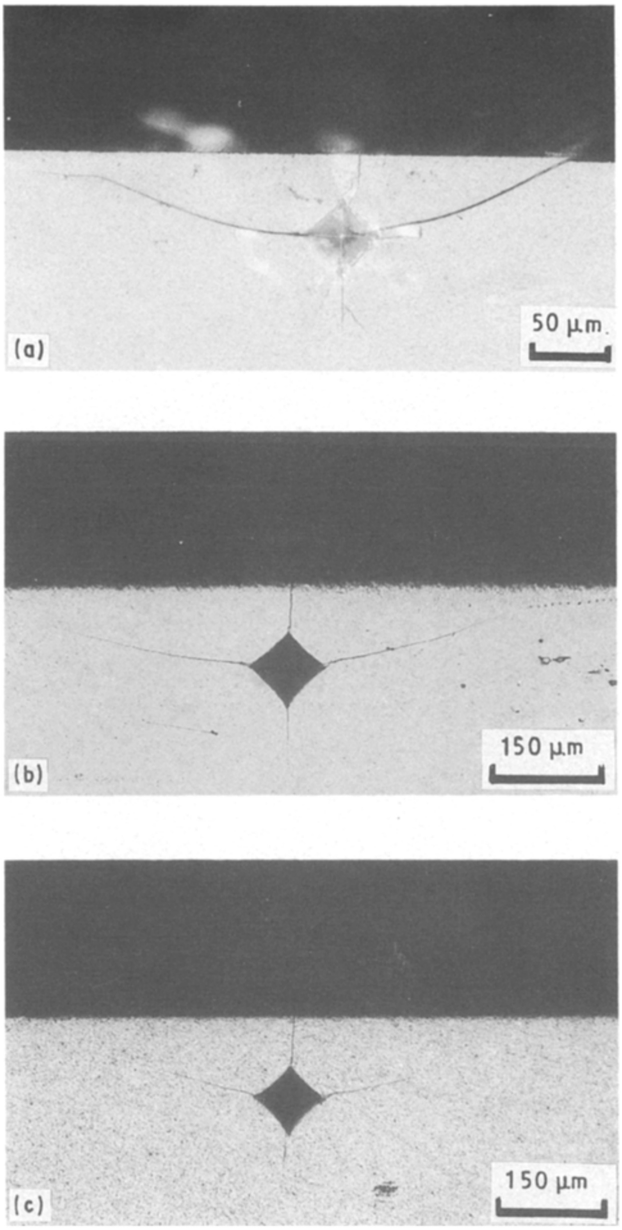

Figure 5 Interaction of cracks with free surfaces (Type IV orientation): (a) soda-lime glass ($P = 9.8$ N), (b) Si_3N_4 ($P = 98$ N), and (c) SiC whisker-reinforced composite Si_3N_4 ($P = 98$ N).

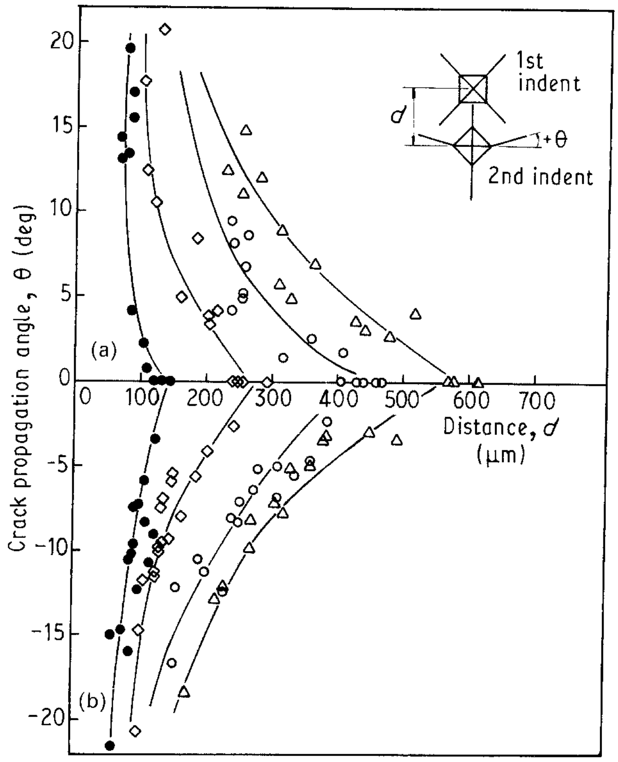

Figure 6 Propagation angle of second indent crack as a function of distance between two indents for different indentation loads under Type I orientation in soda-lime glass: (a) "annealed" condition, and (b) "as-indented" condition. *P*: (●) 9.8 N, (◇) 19.6 N, (○) 49.0 N, (△) 68.6 N.

The angle was measured from the slope of the tangent to the crack path at the indent vertex. The resulting plot is summarized in Fig. 6, where the angle was plotted against the distance, *d*, between the two indents for the different levels of indentation loads from 9.8–68.6 N. The positive angle is taken such that the crack deviates upward from the horizontal impression diagonal; and the negative is taken such that the crack propagates downward from the horizontal diagonal. Fig. 6 includes the data obtained from both the "as-indented" and the "annealed" conditions.

Consider first the propagation angle for the "as-indented" condition. All of the emanating cracks from the second indent propagate against the nearby first indent cracks, giving rise to the negative propagation angle ($-\theta$). For a given indentation load the propagation angle (absolute value, $|\theta|$) increases with decreasing distance between the two indents. The increasing rate of the propagation angle with respect to the distance, *d*, is more significant at the lower load than at the higher load. This indicates that both the increasing load and the decreasing distance result in the higher repulsive interaction, thereby yielding a greater propagation angle.

For the "annealed" condition, the propagation angle is all positive, attributed to the "attractive" mode of interaction. Except for the sign of the crack propagation angle, the trend is much the same as that observed in the "annealed" condition in terms of dependency of the propagation angle on indentation load and distance, *d*. Actually, the plot in Fig. 6 is seen to be approximately symmetric with respect to the *d* axis. This indicates that the indentation load as well as the distance between two indents are the two key factors affecting the absolute value of propagation angle. In their experimental and finite element analyses of crack interaction in Type IV orientation, Lardner *et al.* [16] found that the propagation angle toward the free surface increased with increasing indentation load and decreasing distance between free surface and indent. Therefore, the functional behaviour of the propagation angle with respect to indentation load and distance appears to be the same either in the interaction at the free surface or in the interaction for the "annealed" condition. This implies that the cracks in the first indent serve as a free surface, once they are free from indentation-induced residual stresses upon annealing.

3.3. Implications

In this paper emphasis was placed on experimental observations of crack interactions between two controlled indentation flaws. The crack propagation mode has shown to be a strong function of stress field around crack tip. Analytical formulations of the interaction of arrays of microcracks ahead of a major macrocrack have been proposed [17–19]. However, their major objectives were to obtain the effective stress intensity factors under simple remote loading and simple crack configurations. The crack system used in this study, however, involves the complex local stress field produced by the complex nature of the indentation process. This complexity in the indent crack system inhibits a facile analytical solution for the propagation angle and size of the cracks deflected as a result of interaction. Although not presented here, a prediction of crack propagation angle in the Type I "repulsive" interaction was made based on the simplified representation of the residual stress field as a single point-force acting on the crack centre [1] in conjunction with the maximum stress criterion [20]. The prediction, however, was not in good agreement with the experimental data obtained in this study. A detailed knowledge on local residual stress field in conjunction with crack initiation at the sub-threshold flaw configuration [4] is thus a prerequisite. A future work is needed on this subject.

Notwithstanding such complexity of the local stress field, the technique presented in this paper can provide qualitative information on how one indent crack interacts with another under various conditions (geometry, local stresses, etc.). This technique may be extended to characterize the interaction of a crack with locally confined material zones such as locally stressed regions, damage or process zones, free surfaces, or interfaces with two dissimilar material system [15]. A typical example of the locally stressed regions could be found in damage zones produced by sharp or blunt particle impact with high kinetic energy.

4. Conclusions

The crack interactions between two adjacent indents were demonstrated using indentation technique in soda-lime glass. The mode of crack interaction, either "repulsive" or "attractive", was governed by the residual stress field produced by the indentation. The repulsive mode occurred when a second indent was placed near the first as-indented cracks, causing a crack emanating from the second indent corners to deviate away from the tip of the nearby first indent crack. On the other hand, the attractive mode of interaction occurred when a second indent was introduced near an annealed first indent. This caused the crack originating from the second indent corners to propagate toward the tip of the first indent cracks. The crack extension was always greater in the "attractive" mode than in the "repulsive" mode. It was also observed that the crack propagation angle for Type I interaction is a function of the indent load and the distance between the two indents. The interaction of a crack with a free surface was similar to the "annealed" conditions of Types I, II and III with the cracks extending toward the free surface.

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