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THE RELATIONSHIP BETWEEN THE MEDIAN/RADIAL AND LATERAL CRACKS OF VICKERS INDENTS IN SODA-LIME-SILICA GLASS

B. R. Whittle and R. J. Hand

Department of Engineering Materials, University of Sheffield, Sir Robert Hadfield Building, Mappin Street, Sheffield, S1 3JD, UK

ABSTRACT

The surface traces of Vickers indentations made in soda-lime-silica glass at loads varying between 5 kg and 16 kg showed good adherence to accepted models. The surface trace length of the median/radial cracks extended in the week after indentation relieving some of the residual stress resulting in an increase in the strength of the indented specimens. Specimens indented with less than 5 kg showed less adherence to the pattern of one median/radial crack at each corner of the indentation impression. A study of 10 kg indentations using confocal laser scanning microscopy showed that the sub-surface structure of the crack system is not adequately explained by present models. Although beneath the median/radial cracks the lateral crack rises towards the surface, between the median/radial cracks it propagates away from the surface meaning that they cannot be responsible for material removal around indentations. It is concluded that although the surface traces of Vickers indent flaws appear to be adequately rationalised and modelled, the shape of lateral crack and its interaction with the median/radial cracks is not yet understood nor even accurately recorded.

KEYWORDS

Vickers indentation, lateral crack, radial, median, glass, confocal microscopy

INTRODUCTION

Vickers indenters are frequently used to introduce a strength limiting flaw into brittle mechanical test specimens. In doing so the scatter observed in the results is reduced. Vickers indentations are a common method of introducing controlled damage because it is possible to precisely control the location and size of the critical flaw. Furthermore, the geometry of the cracks arising from indentation with a Vickers indenter is very reproducible and behaves in a manner representative of naturally arising flaws [1]. The system of cracks is commonly depicted as two semicircular cracks perpendicular to the surface and each other. They grow in depth during the loading phase of the indentation cycle and break through to the surface at some point during the unloading phase. Early work concerning indentation flaws considered the cracks which form on loading (median cracks) and the cracks which form on unloading (radial cracks) as separate phenomena but the current understanding is that median cracks can develop into radial cracks or radial cracks can develop into median crack shapes or that median cracks and radial cracks can develop independently and combine [2]. In the present work the cracks perpendicular to the surface are referred to as median/radial (M/R) cracks because they share characteristics of both types of crack. A third type of crack associated with Vickers indentations forms nearly parallel to the surface and is known as the primary lateral crack. This crack is widely believed to have an inverted conical form, propagating slightly towards the surface from an initiation point directly beneath the region of glass plastically deformed by the indenter and is independent of the M/R cracks [3].

Several studies have attempted to delineate the sequence of crack formation during and after indentation although the present state of understanding is that the extent and sequence of cracking is related to the maximum indentation load and hence there is no universal sequence of cracking. The formation and growth of M/R cracks has been extensively studied and predictive equations relating the indentation load to the M/R crack diameter have been demonstrated to be accurate. The lateral cracks have traditionally been less thoroughly investigated partly because they do not directly affect the strength of indented articles, partly because the stress field controlling their formation is complex and not straightforwardly modelled and partly because of difficulties in imaging the flaws. Nevertheless, an understanding of the lateral crack system is necessary since lateral crack chipping is thought to be responsible for material removal around indent sites [3]. In this paper we first show that the indentations used conform to the acknowledged relationship between load and size and the phenomenon of post-indentation crack growth. It is then demonstrated that there is an intrinsic link between these predictable M/R cracks and the lateral cracks. Furthermore, with the use of confocal laser scanning microscopy (CLSM) it is shown that the formation of lateral cracks and material removal are not linked.

EXPERIMENTAL PROCEDURE

Soda-lime-silica glass microscope slides (37 x 25 x 1.1 mm) were indented with a Vickers hardness testing machine for the standard duration of the Vickers hardness test, roughly 10 seconds. The diagonals of the indenter were aligned perpendicular to the longest edges of the specimen. The samples were then annealed at 540°C for 60 minutes, then cooled at 1°C/min. The length of the M/R surface trace was measured using Foster Findlay image analysis software. Samples for which the post indentation crack growth was monitored were not annealed but aged in laboratory conditions (22°C and 50 % relative humidity) for prescribed periods of up to two weeks.

Samples which had been indented and aged for one week were prepared for CLSM by being sprayed with a fluorescent dye (Neopen W/W). The dye was allowed to penetrate the flaws for 15 minutes before being rinsed away by spraying with water. The samples were examined with a Leica TCS 4D confocal laser scanning microscope equipped with an argon laser which emits at a wavelength suitable for the excitation of the fluorescent dye. The top and bottom of the indent were identified and twelve micrographs were taken at intervals between these depths. The distance between the optical sections was of the order of 13-23 μm giving a total analysis depth of around 200 μm.

Vertical sections through the crack system away from the M/R cracks were prepared by indenting the sample then scoring across the indent using a diamond impregnated tungsten carbide cutting wheel. The samples were then snapped by hand and inspected to ensure that the fracture had followed the scored line and not deviated along a M/R crack. The resulting crack surfaces were polished so that the lateral crack profile could be seen.

RESULTS AND DISCUSSION

Normal indentation crack systems show a M/R crack propagating at each corner of the contact impression. Figure 1 shows the cross section of an indentation made at 10 kg. It is representative of the morphology of cracks formed at all loads of 5 kg and above. Its shape differs somewhat from the often reported morphology of indentation flaws but is in agreement with the results of Sglavo & Green [4] and Smith & Scattergood [5]. The lateral crack constrains the base of the M/R crack and as a consequence the downwards propagation of the M/R crack is curtailed and it assumes a semielliptical form. Indentations made with loads of less than 5 kg were not as reproducible as those made at higher loads. In many instances fewer than four M/R surface traces were recorded for 1 kg and 2 kg indentations and the cross-sections of these flaws frequently did not resemble the widely recognised appearance. Those indentations which did have properly developed M/R cracks tended to be less semielliptical than the cracks in Figure 1.

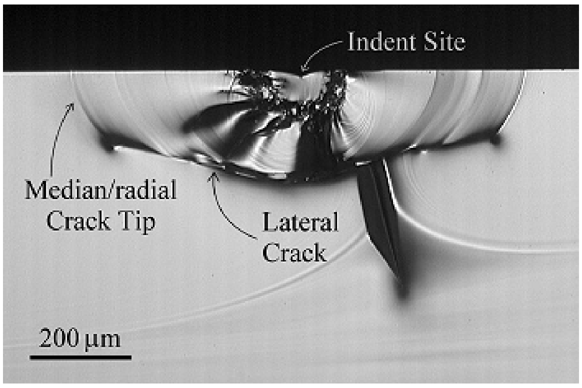

Figure 1 : Cross section of a 10 kg indentation aged for 1 week

Lawn *et al.* [6] predict that the length of the surface trace of M/R cracks after the removal of the indenter is given by

$$d = \left[\frac{\chi_r P}{K_{IC}}\right]^{2/3} \quad (1)$$

where d is half the crack diameter, K_{IC} is the fracture toughness of glass, P is the indentation load and χ_r is a dimensionless indenter-material constant for the residual component of the stress field. The relationship for the median component of the crack and the radial component have different values of χ_r. It is the radial component which is used here because the growth of the surface trace of the M/R crack is an aspect of radial crack behaviour. χ_r for the radial component is 0.049 ± 0.004. Figure 2 shows the results from the present investigation and the predicted values using Eqn. 1. There is close agreement between the model and the experimental results suggesting that the indentations resemble those observed in previous investigations.

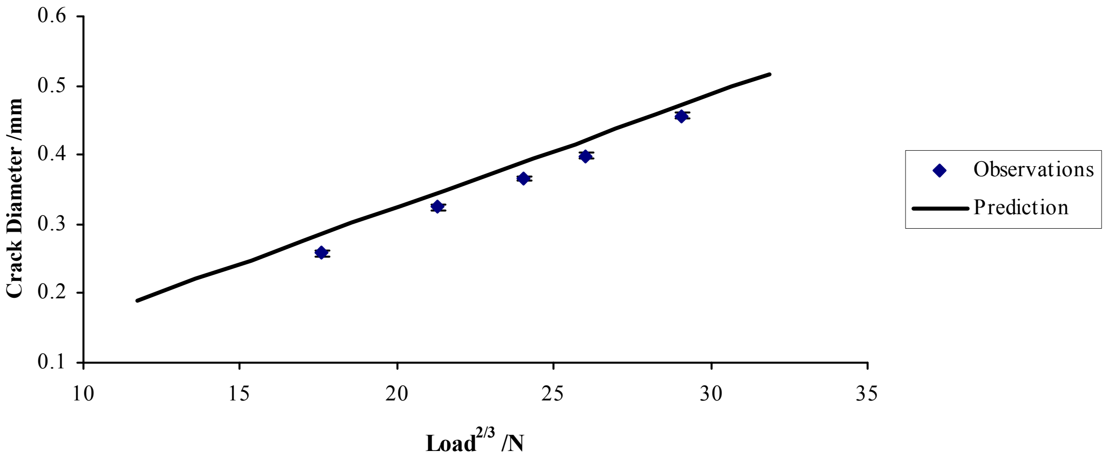

Figure 2 : Comparison of experimental observations with Eqn. 1

Residual stresses arise from indentations because the region directly beneath the contact area between the indenter and the glass plastically deforms resulting in permanent deformation. The material around the plastically deformed region is elastically deformed during indentation and attempts to recover when the indenter is removed. The residual stress is responsible for post indentation crack growth of both M/R and lateral cracks. Upon ageing the M/R cracks grow in length by almost 20 %. Figure 3 shows that the growth was initially rapid and saturated after a period of approximately one week. This broadly agrees with the work of Lawn *et al.* [7] although it is difficult to qualify exactly when growth has saturated. This further emphasises that the indentations investigated in this study behave in the same way as those which have been studied in previous investigations.

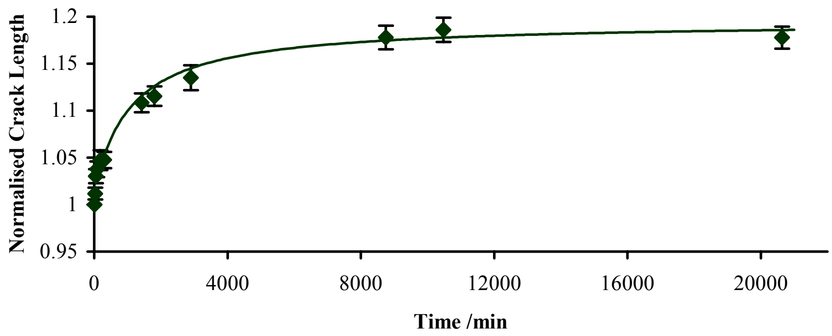

Figure 3 : Post indentation growth of the median/radial surface trace of a 10 kg indentation. The line is for guidance only.

Lateral cracks are often linked with material removal since it is popularly believed that they rise to intersect with the surface. While this is undoubtedly true for secondary lateral cracks which nucleate on the periphery of the contact site close to the surface, the results of this investigation indicate that the primary lateral cracks which form underneath the plastically deformed region do not propagate to the surface. Figure 4 shows 12 confocal micrographs focussed at depths increasing in 14.6 μm increments.

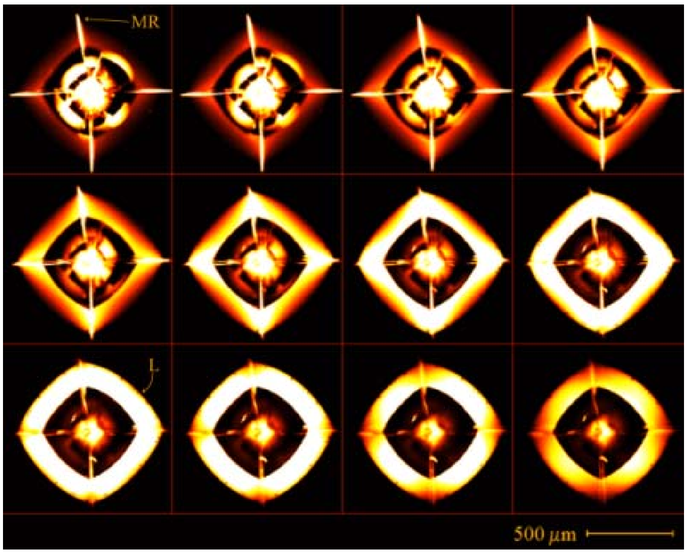

Figure 4 : Confocal images of a 10 kg indentation at depth increasing in 14.6 μm increments. MR indicates the median/radial and L indicates the lateral crack.

Confocal microscopes display images as light or dark depending on whether the corresponding part of the image is in focus. The parts of each micrograph which appear bright are the parts which lie within the focal plane. Between the M/R cracks the ring delineating the lateral crack appears bright at the inner edge before the outer edge indicating that the inner edge is shallower than the outer edge and thus showing that the lateral crack is extending away from the surface. This appears to contradict Figure 1 since this micrograph clearly shows the lateral crack following the base of the M/R crack towards the surface. However, this is merely indicative of the complex three-dimensional form of the lateral crack. Figure 4 does not contradict Figure 1. It simply demonstrates that the lateral crack does not have a uniform profile in rotation. Beneath the M/R cracks it propagates towards the surface. Between the cracks it propagates away from the surface.

As the analysis depth increases the signal from the lateral crack increases in intensity in the region between the perpendicular M/R cracks which shows that the lateral crack is furthest away from the surface at this point. Figure 5 shows sections cut through a 10 kg indentation which show the profile of the lateral crack. They confirm the trends indicated by the confocal results. Figure 5b particularly shows that the lateral crack dips away from the surface between the M/R cracks. Figure 5c shows that the lateral crack profile beneath the contact point curves sharply away from the surface. This is not well illustrated by Figure 4 because, it is believed, when the excess fluorescent dye was removed from the surface of the specimens, the dye in the widest parts of the crack was also flushed away.

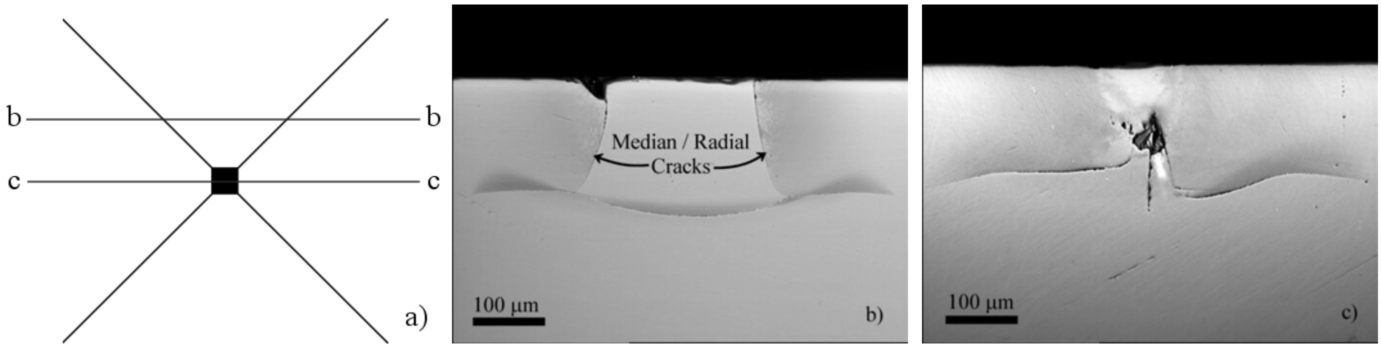

Figure 5 : Vertical sections through a 10 kg indentation flaw. a) shows the section paths where line b-b indicates the section in b) and line c-c indicates the section in c)

The complex shape of the lateral crack in relation to the M/R cracks is shown schematically in Figure 6.

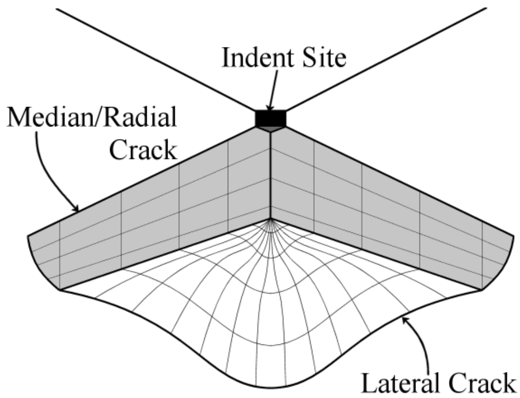

Figure 6 : Schematic diagram of the shape of the lateral crack in relation to the median/radial cracks.

It has previously been thought that the extension of the lateral cracks should not be influenced by the presence of M/R cracks [3] however these results show that this is not the case. The proximity to the M/R cracks has changed the direction of crack propagation since no other factor can account for the localised perturbation of the crack direction towards the surface. This is because the stress field far from the indent site is independent of the shape of the indenter [8]. The lateral crack is not perfectly circular. It has extended further along the M/R cracks than between them. It is interesting to note that both Figure 1 and Figure 4 show that the tip of the M/R crack and the lateral crack beneath it are exactly coincident. No circumstances were encountered where the lateral crack and the M/R crack did not share the same terminus. This does not contradict the observations of Lawn *et al.* [7] and Ritter *et al.* [9] who both observe that initially the lateral crack diameter grows faster than the M/R crack until the diameters are almost equal. Despite observing different initial growth rates, the position of the M/R and lateral crack tips can still be coincident. This is because the M/R crack grows in a semicircular shape but is truncated by the intersection with the lateral crack and thus becomes more semielliptical. Figure 7 illustrates how this truncation results in the lateral crack diameter growing faster than the M/R crack diameter.

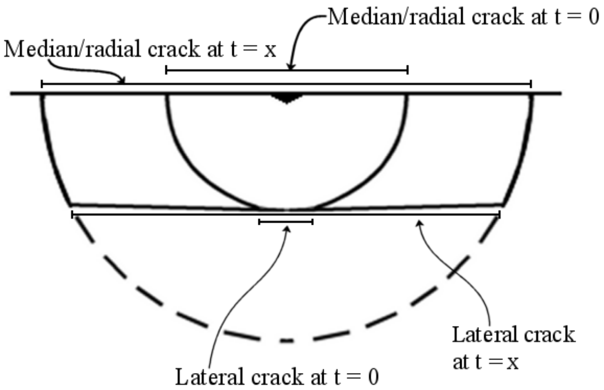

Figure 7 : Diagram of an indentation before and after post indentation crack growth showing the relative sizes of the median/radial and lateral cracks.

CONCLUSIONS

In this investigation indentations in soda-lime-silica glass made with a Vickers indenter at a variety of loads have been closely observed. Lateral cracks have been shown to propagate away from the surface between the M/R cracks. This means that they are not responsible for material removal around indentation sites. The difference should be recognised between the primary lateral cracks, which are as reproducible as M/R cracks, and the secondary lateral cracks which form much more randomly close to the surface and result in material removal. Since the extent of secondary lateral cracking has not been demonstrated to be explicitly dependent on the degree of primary lateral cracking it is erroneous to link material removal to the formation of primary lateral cracks beneath the deformed region of the indent.

It has also been demonstrated that the M/R cracks cause deflections in the direction of lateral crack propagation since beneath M/R cracks the lateral crack is drawn towards the surface. The tips of the lateral and M/R cracks are always coincident which is concordant with a model of M/R and lateral crack growth where the M/R crack grows as a semicircle truncated by an expanding lateral crack.

The above conclusions contradict two tenets of the current understanding of lateral crack behaviour. The new observations brought to light in this investigation cannot be dismissed by arguing that the indentation flaws studied were not the same as those used to generate the accepted models because of the adherence to acknowledged post indentation crack growth behaviour and the relationship between indentation load and surface trace diameter. Although the surface traces of Vickers indentations appear to be adequately rationalised and modelled, the shape of the lateral crack and its effect on the M/R cracks is not yet understood nor even accurately recorded.

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