Bull. Mater. Sci., Vol. 19, No. 5, October 1996, pp. 759–765. © Printed in India.

Study on elastic–plastic component in indentation fatigue of sodalime glass†

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Abstract. Fracture mechanics studies on glass by indentation has become predominant in recent times. Interest in it has become more prominent due to a large application of such materials in areas of engineering applications encountering fluctuating stresses induced thermally, mechanically or physically. However, glass subjected to repeated indentation at a point prior to crack initiation with subcritical loads phenomenological to metal fatigue has not been systematically investigated. Repeated indentation at a single point with different subcritical loads (0·1N, 0·15N, 0·25N, 0·50N, 1·0N) was performed till radial cracks occurred. The length of the diagonal was measured after each indentation, which was found to increase with indentation cycle eventually leading to crack initiation. This observation was analysed considering the elastic plastic component and the residual stress developed during each cycle. A mathematical model has been postulated to correlate the contribution of cumulative residual stress for crack initiation.

Keywords. Indentation; fatigue; elastic stress; yield stress; critical stress; residual stress; cracks; median; lateral; radial.

1. Introduction

The failure of glass under indentation fatigue has captured the imagination of several workers lately. The process involved the application of a ball, knoop or diamond indenter on a polished surface of glass with a critical load creating an impression by surface cracks. Indentation was then repeated with several critical/subcritical loads for the crack growth to occur leading to chipping. The interest has been primarily towards initiation of cracks with critical single indentation and its subsequent propagation to failure by repeated number of indentations at the same point. Crack propagation and fracture behaviour of glass was thus ascertained by Lawn *et al* (1981, 1983), Cook and Pharr (1990), Guiu *et al* (1991) and Sparks and Hutchings (1992). Their work on indentation fracture principles and application gave a picture of the damage morphology under different indenter. They identified the complexity of the crack pattern due to elastic–plastic mismatch stresses from which formation of three cracks namely median/cone, radial and lateral during one single cycle was observed. In compact structure glass (like normal sodalime glass), median crack was initiated during loading followed by radial and lateral crack during unloading. In open structure glass (like silica glass; borosilicate glass) where stress induced densification anomalicity occurs, cone cracking was initiated during loading followed by radial and lateral crack initiation during unloading. It was generally held that chipping occurred due to the removal of the material by the formation of the lateral cracks beneath the contact impression followed by its subsequent outward propagation and the final emergence of the material surface (Lawn *et al* 1981, 1983; Guiu *et al* 1991; Sparks and Hutchings 1992). Taylor (1950) while measuring hardness by pyramidal indenter had suggested the

†Paper presented at the poster session of MRSI AGM VI, Kharagpur, 1995.

concept of plastic deformation in glass. Later Johnson (1970), Evans and Fuller (1974), Marshall *et al* (1979) and Lawn *et al* (1981) correlated hardness with mean contact pressure and other properties of glass. Their work can be considered nearest to plastic deformation in glass prior to crack initiation and propagation under fatigue. True fatigue can only be considered when crack is initiated under repeated indentation at a singular point at subcritical loads and this has not been studied.

The present study on sodalime glass simulate the true fatigue condition by repeated indentation at a singular point at subcritical loads until cracks are initiated. Attempts have been made to analyse the localized elastic–plastic components affecting the deformed impression.

2. Materials and methods

Annealed sodalime glass sample with 5 mm × 5 mm × 4 mm was taken with optical polish on all sides. A Vickers indentation (Model HMV-2000, Shimadzu) was utilized for the indentation study. Experiments were conducted with different subcritical loads viz. 0·10N, 0·15N, 0·25N, 0·50N and 1·0N. Repeated indentation at each load was performed at each singular point simulating fatigue conditions without any movement of the sample avoiding any error in the measurements. This procedure was repeated five times at each load to generate five datas. The load was applied for 10 sec in each cycle under normal temperature (25 ± 2°C) and humidity (60 ± 5%). The diagonal length of the impression was measured after completion of cycles 1, 5, 10.... The experiment was discontinued the moment the radial cracks were initiated.

3. Results and discussion

During repeated indentation with subcritical loads of 0·10N, 0·15N, 0·25N, 0·50N and 1·0N, it was observed that the diagonal lengths increased to a limit until hair line radial cracks were initiated. At 0·10N, 0·15N, 0·25N, 0·50N, and 1·0N the cracks were found to initiate at 65, 60, 30, 15, 2 cycles respectively (figure 1). Figure 2a shows the fatigue graph where load was plotted against number of indentation cycles needed to initiate radial cracks. A typical fatigue behaviour was apparent. Analysing this graph one can verify the observation made by Banerjee and Sarkar (1995) that incorporating a critical crack at the very first instance for fatigue study was not necessary. Once a crack was introduced with a critical load it acts as a griffith crack, which propagates rapidly for the material failure at a stress above fracture stress. Hence, whether this simulate true fatigue remains unexplained. The study conducted by Banerjee and Sarkar (1995) on sodalime glass showed that even without incorporating a crack a Griffith crack can be generated by repeated indentation with subcritical loads for the ultimate failure of the material. Load vs number of cycles plotted by Sparks and Hutchings (1992) while experimenting on sodalime glass with an initial critical crack, differs considerably from the present observation. The comparative results are shown in figure 2a, b as best fit power curves. The two equations are:

$$y = 378{\cdot}229\,x^{-0{\cdot}8054} \quad \text{(Sparks and Hutchings 1992)},$$

$$y = 1{\cdot}66066\,x^{-0{\cdot}6195} \quad \text{(Banerjee and Sarkar 1995)}.$$

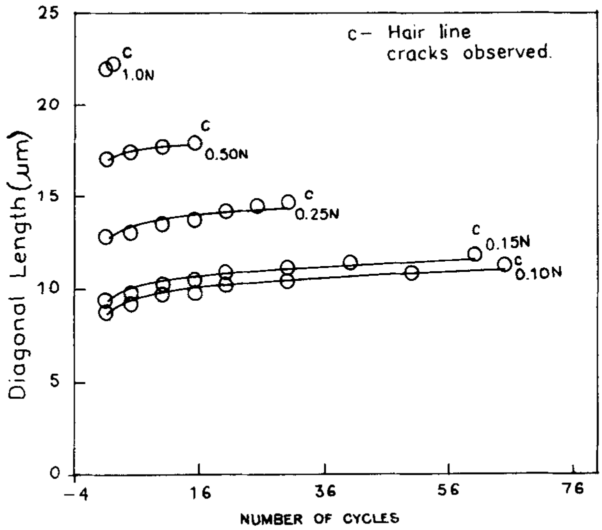

Figure 1. Gradual increase in the diagonal length with repeated cycles at loads 0·1N, 0·15N, 0·25N, 0·50N and 1·0N where '*c*' indicates the point of cracking (after Banerjee and Sarkar 1995).

When the results are plotted on a log–log scale the best fit curves are shown in figures 3a, b. The slopes(m) are $\simeq -0{\cdot}8$ and $\simeq -0{\cdot}6$ for Sparks–Hutchings (figure 3a) and Banerjee–Sarkar (figure 3b) respectively. Considering the values of 'm' it is apparent that there is a difference in the mechanism for propagating an existing crack and initiating a crack under repeated indentation simulating fatigue condition.

Another important observation was the increase in the diagonal length of the deformed cavity by repeated indentation as seen in SEM (figure 4). This was reported for the first time by Banerjee and Sarkar (1995). It indicates that plastic deformation plays a pivotal role in the initiation of radial cracks. Previous workers (Cook and Pharr 1990; Guiu *et al* 1991) showed that during indentation all the three cracks namely, median, lateral and radial initiated in one single cycle, first during loading and the other two during unloading. Hence the increase in the deformed cavity without initiating surface cracks, justifies the concept of plastic deformation in glass (Taylor 1950). Also subsurface cracks were not observed under SEM till radial cracks occurred which are in agreement with Cook and Pharr (1990). The above experiment was different from that of the previous workers since it was conducted without incorporating an initial crack in the glass sample, thus simulating true fatigue condition for ultimate failure of the material. Moreover, sodalime glass being a compact/normal glass the concept of densification anomalous behaviour does not arise (Arora *et al* 1979).

3.1 *The model*

To analyse the above phenomena, consider a stress σ_a applied on a prepared surface of a glass at a localized zone. The applied stress being greater than the yield stress (σ_y) but less than the critical fracture stress (σ_c) of glass, a small localized zone deformed plastically. Consequently, a plastic strain (ε_p) developed. The corresponding stress σ_r

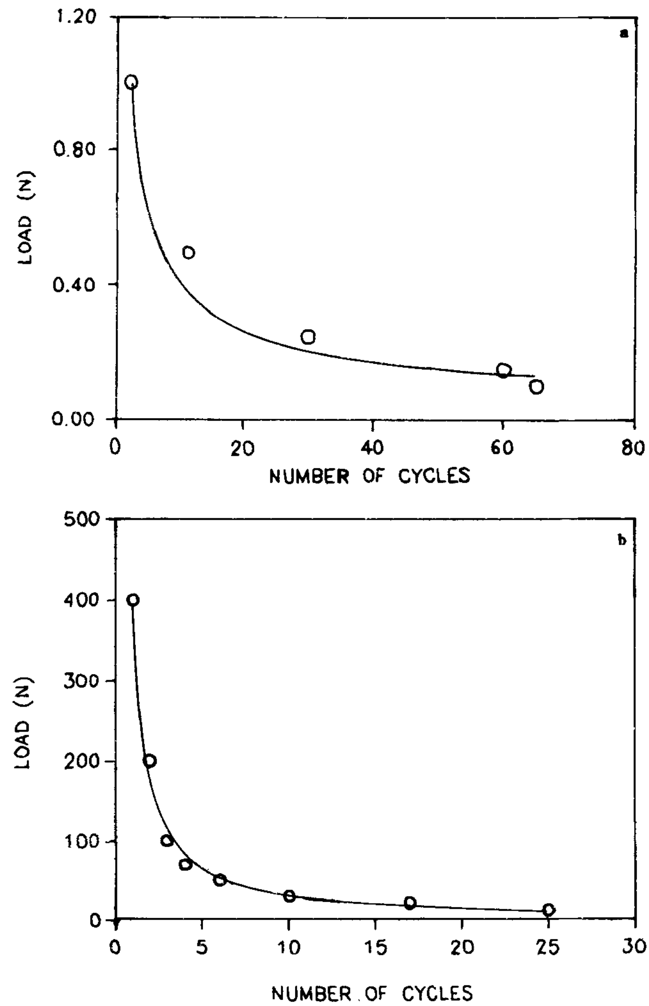

Figure 2. Power fitting fatigue graph showing load to number of cycles at cracking (**a**) Banerjee and Sarkar (1995) and (**b**) Sparks and Hutchings (1992).

balanced the applied stress σ_a from further penetration into the material. Hence at equilibrium

$$\sigma_r^{pl} = \sigma_a, \tag{1}$$

where σ_r^{pl} is the stress in the plastic region.

Since elastic zone lies underneath the plastic zone and stress being a continuous vector, it decreases and at the elastic–plastic boundary becomes

$$\sigma_r^{pl} = \sigma_y. \tag{2}$$

As the indentor was unloaded, the compressed material recovered due to the recoverable elastic stress from the elastic zone lying beneath the plastic zone thus, reducing the diagonal length from the original first length when the indentor was fully within the formed cavity shown schematically in figure 5. Thus, at the surface around

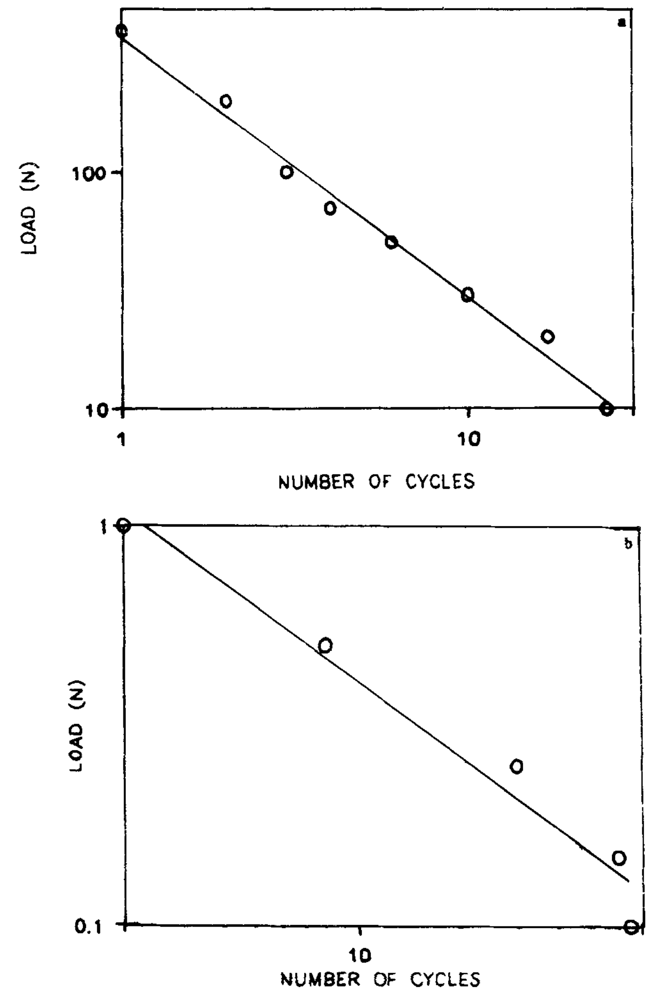

Figure 3. Best fit curve plotted in log–log axis: (**a**) Sparks and Hutchings (1992) and (**b**) Banerjee and Sarkar (1995).

the point of application the stress is zero, but due to elastic recovery the elastic stress reduces by a quantity $\alpha(\sigma_r^{el})$, where σ_r^{el} is the elastic stress generated from the elastic zone and α is a scalar quantity within the domain $(0 < \alpha < 1)$. Hence, the resultant residual stress (σ_r^*) in the material is given by a coupled equation

$$\sigma_r^* = (\sigma_r^{pl} + \alpha\sigma_r^{el}). \quad (3)$$

The direction of this residual stress is towards the surface.

On imposing a new impression during the second indentation when the indentor meets a new surface at the cavity produced by the first impression the diagonal length increases but not to the same dimension as in first cycle due to the residual stress opposing the applied stress. This process was repetitive thus increasing the diagonal lengths at each cycle, but in decreasing magnitude due to cumulative residual stress built up at each cycle. The magnitude of this residual stress at 'n' number of cycles can

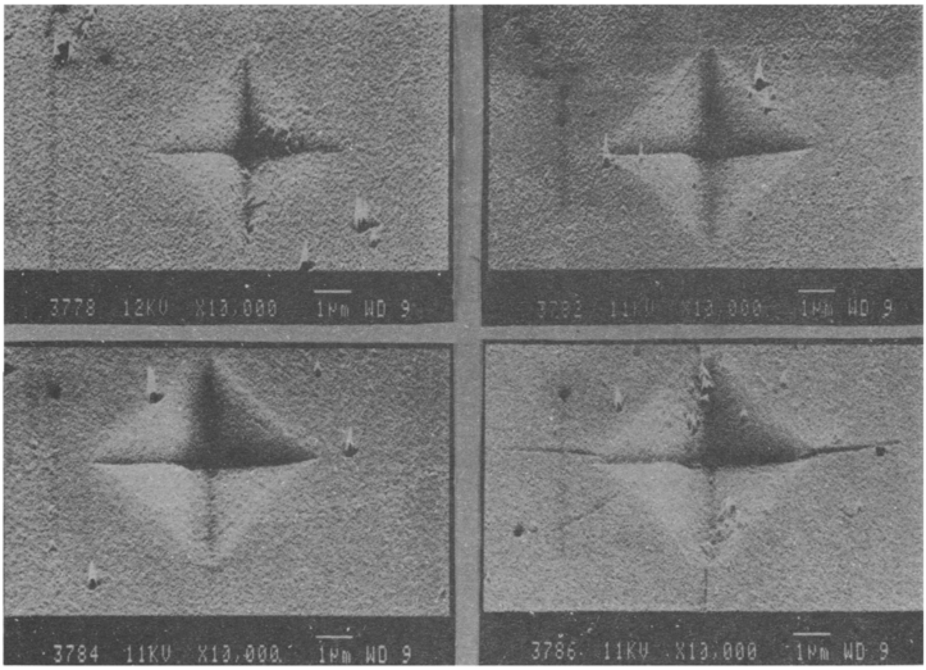

Figure 4. Scanning electron microscope (SEM) at 0·1N load showing the increase in the indentation diagonal length with no. of cycles (Number-3778 cycle 1; Number-3782 cycle 15; Number-3784 cycle 30; Number-3786 cycle 65; hair line crack).

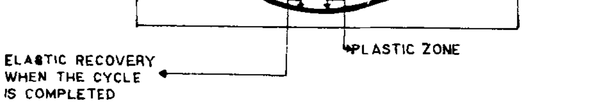

Figure 5. Schematic diagram showing the elastic recovery of the plastic zone after the indenter is unloaded.

be calculated by modifying (3)

$$\sigma_r^n = \sum_{j=1}^{n} (\sigma^{pl}_{r_j} \rightarrow \alpha_j \sigma^{el}_{r_j}), \tag{4}$$

Here σ_r^n denote the cumulative residual stress and $\alpha_{j+1} < \alpha_j$; $\sigma^{el}_{r_{j+1}} < \sigma^{el}_{r_j}$. It was obvious from (4) that the plastic deformation increased progressively due to the increase in the plastic stress and decreased in the elastic recovery in subsequent cycles. Neglecting other components, fracture stress is given by

$$\sigma_f = \sigma_a + \sigma_r^n. \tag{5}$$

Analysing (4) and (5) one can conclude the formation of surface crack even if the load is very small and number of cycles 'n' is very large. It was imperative that though glass is a brittle material it undergoes fatigue damage assisted by plastic deformation and cumulative residual stress due to repeated cycling.

4. Conclusions

It was observed that the diagonal length of the indentation in sodalime glass continued to increase with repeated indentation at subcritical loads till radial hair line cracks were formed. The number of cycles to cracking varied with applied load. It was apparent that the increase in the plastic region was due to imposition of a new impression at every indentation when the indentor meets a new surface at the cavity produced by the previous impression. Moreover, due to the cumulative residual stress developed per cycle opposing the applied stress, the increase in diagonal length gets progressively small from the previous cycle. It was demonstrated from the model that surface crack can be observed even if the applied load is very small and number of cycle 'n' is very large. It is thus imperative that this failure under fatigue loading is phenomenological to metal fatigue.

Acknowledgements

The authors thank Prof. Arabinda Roy, Department of Mathematics, University of Calcutta, Prof. D C Agarwal, IIT Kanpur for valuable suggestions and Dr K K Phani, Composite Division, CGCRI for the experimental work on Vickers Indentor. The authors also thank Mr S K Das, National Metallurgical Laboratory, for SEM facilities.

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