MECHANISMS OF CONTACT DAMAGE TO HIGH STRENGTH CONTAINERS BY HANDLING MATERIALS

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ABSTRACT:

Damage mechanism to high strength glass containers has been evaluated at ambient and at elevated temperatures. Two models were developed to simulate the temperature distribution in the glass while contacting the handling material, and to calculate the thermal stresses induced and the crack extension in the containers. Results showed that cracks will extend if the stress intensity factor reaches a critical value ($K > K_{1c}$). The contact in general has reduced the glass strength, the characteristic strength, σ_g and the Weibull modulus β , Larger reduction was observed with sintered titanium at elevated temperatures.

1. INTRODUCTION

In the last three decades the economics of glass container manufacture has led to the development of lighter weight containers, while at the same time methods of handling, transporting and filling these containers have placed a greater need on the ability to retain glass strength and avoid surface damage. It has been recognized [1] that the materials used for handling glass, e.g. metal, asbestos, etc., were certainly capable of damaging the surface, at least to a degree which would affect the strength. This study found that the true criteria for the selection of such handling materials should be that they do not damage the glass. Therefore, they have investigated the effect of contact of different materials on glass strength while the bottle temperature range was from ambient up to 300 °C. It concluded that damage was caused by a combination of mechanical abuse and thermal shock. In a further study [2], it showed that contact with carbon-based materials was generally much less damaging to glass than contact with metals. It is well known that even so called pristine glass containers are weak, certainly by the standards of some other glass products. It has been shown [1] that glass can be damaged at an elevated temperature (300°C) when it comes into contact with materials commonly used for the moulding and handling of hot glass. However, consideration of these results, together with the results of diamond indentations [3] raises the question of the nature of the damage produced by contact. Glass itself is harder than many materials that are observed to damage it [1-2, 4]. For example, a metallic asperity on the surface of mild steel (VPN $\approx$ 100 kgf mm^{-2}) should itself deform plastically rather than indent the glass (VPN $\approx$ 500 kgf mm^{-2}). Yet, contact with mild steel is observed to produce a very large reduction in the strength of glass [5]. The present investigation was undertaken to obtain more understanding of contact damage to high strength containers by handling materials.

2. MATERIALS AND METHODS

To investigate the contact behaviour between high strength glass and the handling materials, it was necessary to produce high strength glass rods with near-perfect surfaces. This was done by polishing the as-received soda lime silica glass rods for 48 hours in a solution containing 1g ethylene diamine tetra-acetic acid (EDTA), 10 cc of 40% hydrofluoric

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acid, 600cc of tap water [6]. This solution was placed with glass rods of 70mm length and 8mm diameter in a high density polythene beaker. The beaker was maintained in a controlled temperature water bath at 30 °C. By this means it was possible to produce glass rods which consistently had bending strengths up to 2000 MPa in the uncontacted glass.

2.1 Method of Producing Controlled Contact Damage

The glass rods to be abraded were loaded into an apparatus designed especially to damage the glass rods in a controlled way as shown in Fig. 1, in which the apparatus could be used at temperatures up to 300 °C. The glass rod was loaded on to the supports which locate the central section of the rod below the contact material insert. The handling material was placed into the pivoted arm. On the other side of the arm was a small balance pan; this allowed the arm to be balanced for each material and a constant load equivalent to the force exerted by the action of gravity on a milk bottle, to be applied. The support inserts were made of graphite to minimise the damage to the ends of the rods, where the rest of the apparatus was constructed from stainless steel. Once under load, the rod was rotated through 360° three times before being carefully removed and subjected to stress to the point of disintegration in a four-point bending rig as shown in Fig. 1. This procedure was undertaken at room temperature and at 300 °C to assess the degree of damage caused by isothermal contact and by thermal shock contact. The latter was achieved by loading the rod into the abrasion rig with the pivoted arm detached and then placing it in a muffle furnace. Immediately upon removal from the furnace at 300 °C, the pivoted arm was reattached and the rod was contacted by the handling material under load at ambient temperature to enable the combined effect of abrasion and thermal shock to be assessed. The rod was then allowed to cool before being tested in four-point bending.

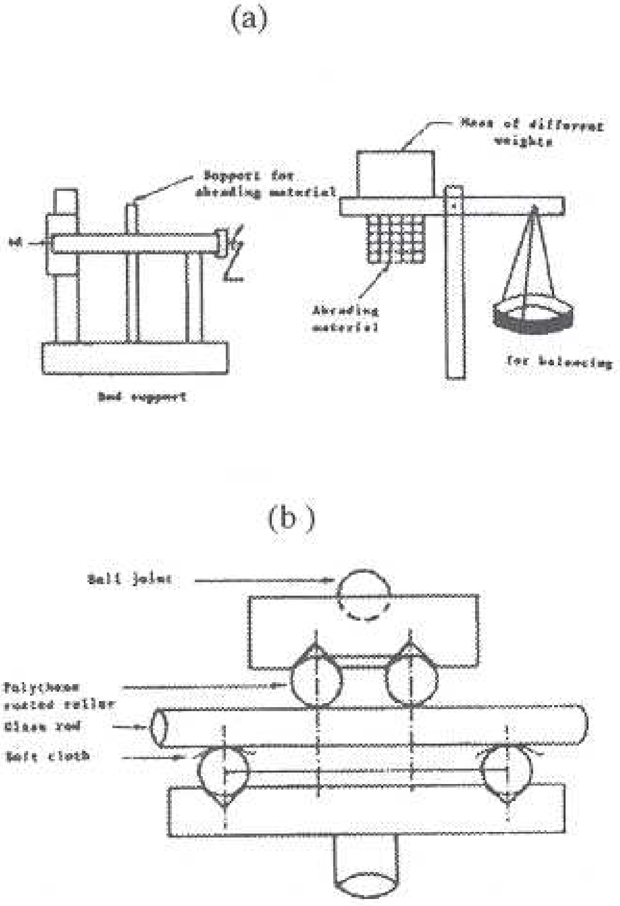


Fig. 1. (a) Apparatus for abrading the soda-lime silica glass rods; (b) Loading arrangement for the testing of glass rods strength.

3. DAMAGE MECHANISMS THE HYPOTHESIS

It is believed that damage can be caused to hot glass containers on contact with handling materials by two mechanisms as illustrated in Fig 2: (i) physical contact causing mechanical damage, (ii) rapid loss of heat from the glass to the handling material causing thermal shock damage.

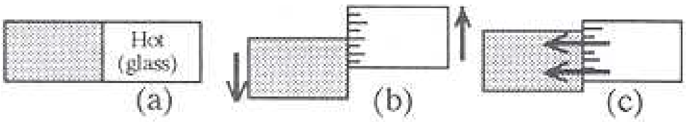


Fig. 2. *Basic model of crack interaction, (a) Glass contacts handling material, (b) Mechanical contact produces very small (invisible) cracks by abrasion, (c) Heat flow generates local tensile stress which acts on small cracks to extend them.*

The aim was to try and understand how these two mechanisms interact by understanding how damage affects the strength of the glass.

It is well established that surface flaws/cracks control the strength of glass. In a stressed solid containing a flaw, failure will only occur when the force at the crack tip is large enough to break the bonds between the atoms. This force on the atomic bonds at the crack tip can be characterized by a parameter K, known as the stress intensity factor. This parameter is proportional to the applied load, but is also a function of the crack length and the geometry of the component. Its exact value can be calculated using analytical and numerical methods. For a crack of length 2a in an infinite material, the value of K is given by

$$K = \sigma \sqrt{a\pi} \qquad (1)$$

where σ is the applied stress.

The strength of the bond is characterized by a parameter denoted K_{1c} which is known as the critical stress intensity factor and has the value of 0.76 MPa $m^{1/2}$ for glass. In terms of fracture energy, this is equivalent to a fracture energy of soda-lime glass $G_c = 8.3$ J/m^2 [7].

When $K \geq K_{IC}$ the crack propagates. The strength of glass is therefore given in terms of the flaw size as

$$\sigma = \frac{K_{IC}}{2.24} \sqrt{\frac{\pi}{a}} \qquad (2)$$

We found that strong glass, after isothermal contact with the most abrasive realistic handling material, had strengths of the order 200-300MPa. This is in agreement with the results obtained in [1]. The normal load used in most of the experimental work was equivalent to a milk bottle weight. This is essentially the minimum force that might be encountered during handling [5]. We have also experimented with higher contact forces. So it is not surprising that containers which pass quality control tests during bottle production only have strengths in the range of 30 MPa[1]. However we believe that there is a contribution from thermal shock which exacerbates any mechanical damage.

The hypothesis is, therefore, that the total contact damage comes about by the action of thermally-induced stresses which can propagate mechanically produced flaws. To investigate this further, a computer model was set up to calculate the temperature distribution in the glass while contacting the handling material. This enables calculation of the thermal stresses present. The temperature distribution was calculated using the Carslaw and Jaeger approach [8] for a semi-infinite composite solid shown in Fig 3.

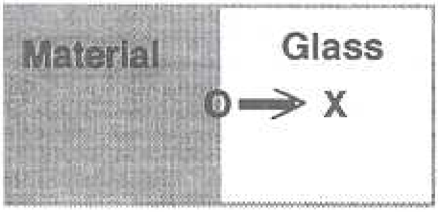


Fig. 3. Diagram of a semi-infinite composite solid.

The region x > o is glass with initial temperature T_o and current temperature T_g. Its properties: thermal conductivity K_g density ρ_g and specific heat capacity C_g. The region x < o is a handling material with initial temperature zero, and current temperature T_m. The properties were as follows: k_m is its thermal conductivity, density ρ_m and specific heat capacity c_m It is assumed that there is perfect thermal contact between the two materials once they come into contact at time t = 0. This means that

$$T_g = T_m \qquad x = 0; t > 0 \qquad (3)$$

and no heat is lost at the boundary so the heat flux is continuous

$$K_g \frac{\partial T_g}{\partial x} = K_m \frac{\partial T_m}{\partial x} \qquad x = 0; t > 0 \qquad (4)$$

The solution to this problem is given in equations 5 and 6 as

$$T_g = \left\{ \frac{P_g T_o}{P_g + P_m} \right\} \left\{ 1 + \left(\frac{P_m}{P_g}\right) erf\left(\frac{x}{2}\sqrt{J_g t}\right) \right\} \quad (5)$$

$$T_m = \left\{ \frac{P_g T_o}{P_g + P_m} \right\} \left\{ 1 - erf\left(\frac{|x|}{2}\sqrt{J_m t}\right) \right\} \quad (6)$$

where J is the thermal diffusivity which is related to density ρ, specific heat capacity C, and thermal conductivity k, i.e. $J = K_i / C_i \rho_i$ and $P_i = K_i J_i^{-1/2}$ where i can be glass (g) or material (m) and erf denotes the error function. In our problem only equation 5 is of interest as the thermal stresses in the contact material are not important. This solution was chosen as it is believed to simulate the true situation very closely. The effects of the contact on glass temperature is believed to be restricted to a narrow surface layer, so that the use of a solution for an infinite solid is a realistic approximation.

A programme was written to calculate T_g at $1 \mu m$ intervals from 0-1500 μm at any stated time. The data from this programme were used by a second programme which calculated the thermal stress intensity factor in the glass. It was decided that the best way to do this was to calculate the stress intensity factor at different times for varying crack lengths.

Equation 1 is the simplest expression for K and holds only for a thin semi-infinite solid plate. In most cases a geometry factor must be introduced which takes account of such things as the proximity effects of boundary surfaces or other cracks, orientation of the cracks and the shape of the crack. These factors can be found in many references of expressions for K in various situations [9].

The simple expression 1, also only applies if the same stress is applied over the whole length of the crack, i.e. the material is being subjected to a homogeneous stress. In this problem the stress is caused by a temperature distribution which changes over the length a of the crack. In a material with modulus ***E*** and coefficient of thermal expansion α the stress can be calculated using equation 7 below.

$$\sigma = (T_o - T_g)\, \alpha E \quad (7)$$

In an inhomogeneous stress field [10], K is given by

$$K = 2\sqrt{\frac{a}{\pi}} \int_0^a \left\{ \frac{\sigma}{(a^2 - x^2)^{1/2}} \right\} dx \quad (8)$$

The integral sums the effect of the varying stress over the length of the crack. Using equation 7 into 8 to get a new expression for K

$$K = 2\alpha E\left(\sqrt{\frac{a}{\pi}}\right) \int_0^a \frac{T_o - T_g}{\sqrt{a^2 - x^2}}\, dx \quad (9)$$

This expression was used in a second programme to calculate K at a certain time for cracks varying in size from 0-1500 μm. The trapezium rule was used to evaluate the integral.

4. RESULTS AND DISCUSSION

4.1 Temperature Distribution and Stress Intensity Factor

The temperature distribution curves obtained from the first program at different times ***t*** in the glass with the contact material at ambient and the glass at 600 °C are shown in Fig. 4. It can be seen that as time passes, the temperature at the interface is constant, but the depth from which heat is lost increases. The value of the stress intensity factors was evaluated from the temperature distributions representing contact with some materials considered. Each curve in Fig. 5 shows how K changes for increasingly large cracks in a single temperature distribution at time *t*. The horizontal line on each plot shows the critical value of the stress intensity factor K1c for soda-lime glass which is 0.76 $MNm^{-3/2}$. The form of all the families of curves is the same and the value of K increases to a maximum and then falls off. This is very important in understanding how cracks grow. Because the glass is subjected to an inhomogeneous stress field, once the crack starts to propagate, it does not always lead to catastrophic fracture. If we look at Fig. 5, we see that in a glass container handled for 0.01 of a second by carbon compact, no crack propagation takes place if the flaws present are less than 65μm. If a crack is greater than 65μm, a crack of 260 μm will be produced. However if it is handled by titanium compact for the same time, no crack propagation takes place if the flaws present are less than 30μm. If the crack is greater than 30μm, a crack of 470μm will be produced. Any cracks which propagate will be of a size that can detected optically, and account for the low bursting strength of real containers.

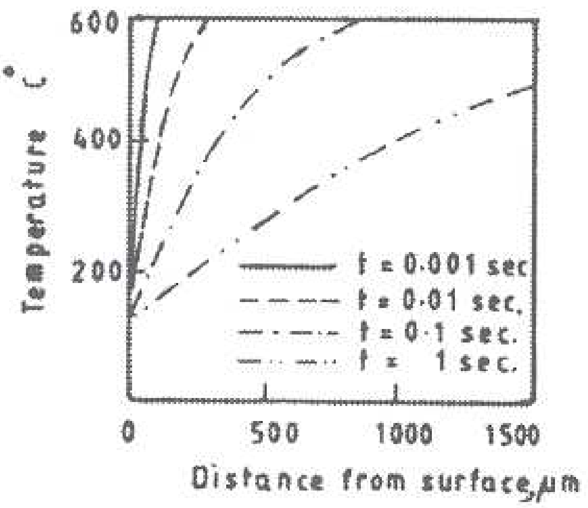


Fig. 4. Temperature distribution in glass after contact with carbon compact at various times (t).

What does this add to the understanding of contact?. It is fair to say that although the ideal hot glass handling material would have no thermal conductivity and cause no mechanical damage, this is not possible. Considering the data produced from the computer model, it can be said that if a material can produce minimal mechanical damage, which consists of cracks of a size that the thermal stresses present do not propagate, then it will approach the ideal as nearly as we can expect in reality.

4.2 Effect of Isothermal and Thermal Shock Contact on The Strength of Glass

The results of the experiments determining the strength drop of high strength glass after contact with handling materials at ambient or elevated temperatures are presented in Fig. 6. We observed strengths in the region of 2000MPa in etched, uncontacted glass. This implied that we had eliminated all cracks larger than 90nm (see Fig. 7) from the specimen surface. These cracks were very small, of the order of 300 atm spacings. In terms of the theoretical limit,

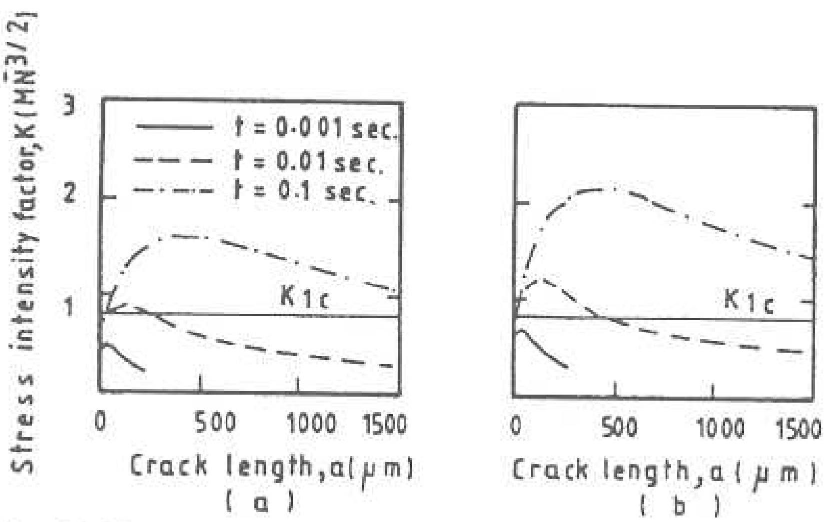


Fig. 5. Stress intensity factors calculated by the second model for cracks in the thermal stress fields resulting from contact between: (a) carbon compact, (b) titanium compact and hot glass.

the upper level of strength observed was about 1/3 of the theoretical limit for perfect glass as shown from the relation between critical stress and critical crack radius in Fig. 7.

In Fig. 6 the Weibull distribution [11] was merely regarded as a means of linearising the data which facilitates a graphical interpretation of the results. The cumulative frequency F is given by the relation :

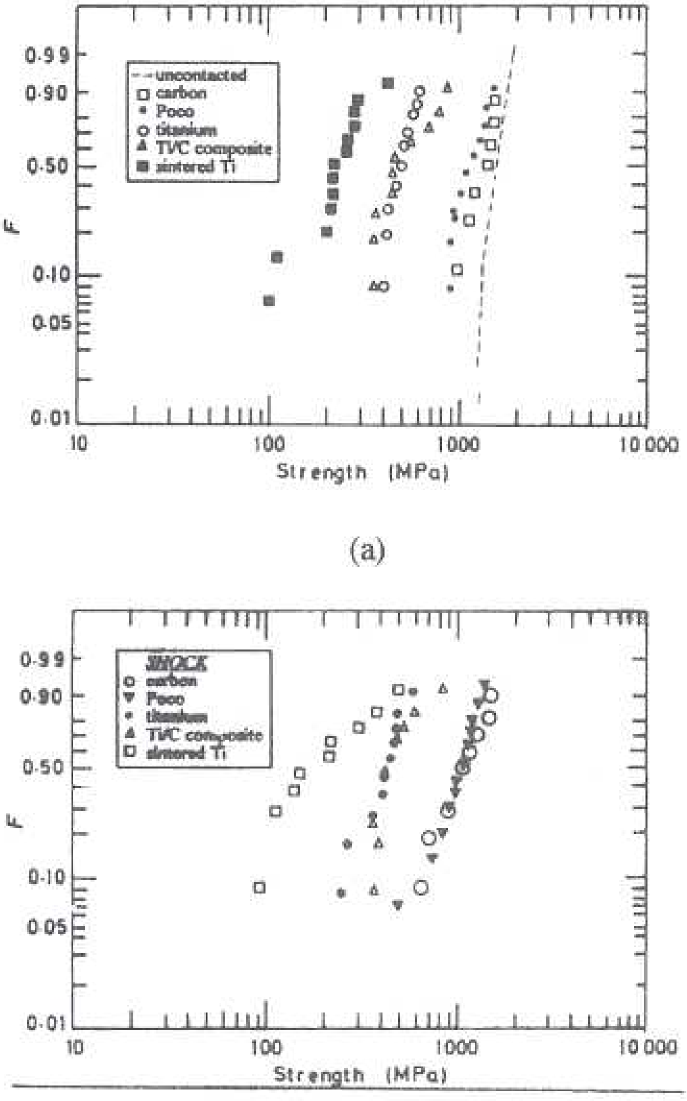
$$F = 1 - \exp\left[-\left[\frac{\sigma_F}{\sigma_s} \right]^{\beta} \right] \qquad (10)$$

where σ_F , is the failure stress, σ_s is the characteristic strength of the distribution, and β is the Weibull modulus. The Weibull modulus for the uncontacted glass is of the order $\beta = 10$. This is quite a large value for a brittle material like glass and is a measure of the reliability of the polishing procedure. A low value of β indcates a large amount of scatter of strength and a high value represents very little scatter. These very good results gave us great confidence in going on to assess the effect of contact in producing damage in glass.

When $\sigma_s = \sigma_F$ in equation (10), F = 0.63 which indicates that σ_s is the tensile stress at which 63% of the specimens in a batch have failed and 37% have remained intact. To linearise the data and also to be able to interpret it, equation (10) was rearranged so that the term $\log_{10} \ln \left[\frac{1}{1-F} \right]$ was plotted against $\log_{10} (\sigma_F)$ using the facility available in the MATHCAD package. Ideally this gives a straight line. The axes of the Fig. 6 were then redrawn so that F is shown against σ_F where the scales of the graphs are heavily distorted.

Figure 6(a) gives the results for tests completed with the glass at room temperature so that all the damage was the result of mechanical contact. The effect of contact between glass and carbon compacts is shown to have little surface damage. Its characteristic strength (σ_s) and mean strength are 1400 ($\beta = 5$) and 1300MPa respectively. This result can be counted an excellent result as far as application in glass handling materials was concerned because the strength after contact with carbon was not much different compared to that of uncontacted glass. It also gives a good fit to the Weibull distribution. Poco (glassmate) graphite based material ($\sigma_s =$ 1289MPa, $\beta = 4.8$) caused also a low reduction in glass strength and showed a good fit to the Weibull distribution. Contact with titanium produced a large amount of damage to the glass because of low characteristic strengths of glass which had fallen to 603MPa with Ti/C composites, 527 MPa with titanium compact and 270MPa ($\beta = 2.56$) with sintered titanium compact. The sintered titanium compacts produced the larger reduction in glass strength at ambient temperature. That might be due to a formation of hard regions of TiO in the materials during sintering. The results also suggest bimodality in the distribution of strength (Fig. 6 (a)).

Figure 6(b) depicts the results of the thermal shock investigation where the glass rods at 300°C and the handling materials remained at ambient temperatures. It is clear that, compared to isothermal contact, thermal shock contact has reduced the glass strength more. The characteristic strength has dropped with all materials due to thermal stresses generated by heat flows. For instance, with sintered titanium, the characteristic strength has dropped from 270MPa ($\beta = 2.56$) to 252MPa ($\beta = 1.66$) due to thermal stresses in addition to the above reasons of hard phases.



(a)

(b)

Fig. 6. Weibull plot showing the distribution of strengths in etched soda-lime glass rods: (a) before and after isothermal contact with different materials; (b) after thermal shock (300 °C) contact with different materials.

5. CONCLUSIONS

1. Contact of the above-mentioned handling materials with glass at

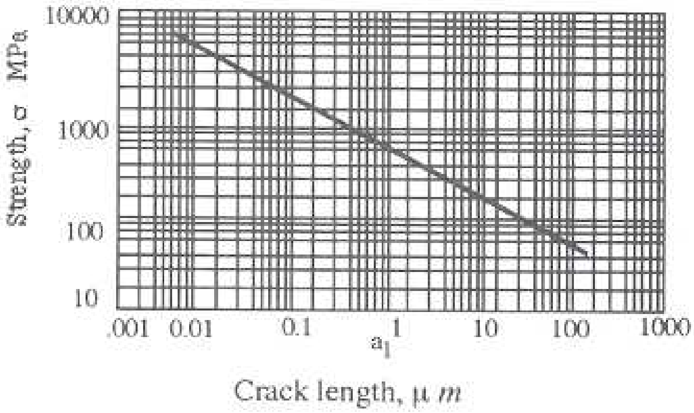


Fig. 7. The relation between strength and critical crack size in soda-lime glass rods.

ambient temperatures results in a loss in glass strength and greater damage at elevated temperatures as shown by comparing the strength of the etched glass rods before and after contact.

2. When a temperature difference exists between the glass surface and the handling material, particularly if the material is at a lower temperature than the glass, then transfer of heat from the glass to the material can result in a temperature gradient within the glass surface, and hence to a thermally induced stress field.
3. Carbon compact is less damaging than contact with other materials.
4. Cracks propagate faster on contact with titanium compared to that contacted by carbon or Poco materials.

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