THE INFLUENCE OF SURFACE TREATMENTS ON THE HERTZIAN IMPACT DAMAGE OF GLASS

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Circular plates of float glass 3 and 6 mm thick and clamped at a radius of 65mm have been impacted with 5mm diameter steel balls travelling at velocities in the range 5 - 50ms^{-1}. The critical velocity for the formation of a Hertzian ring crack has been determined as a function of the surface treatment. These treatments include chemical strengthening, thermal toughening, abrasion with silicon carbide, polishing with diamond pastes and immersion in cold and hot water and a hydrofluoric acid etch. The glass has also been impacted on both the 'tin' side and the 'air' side. The results are discussed in terms of the size, shape and spatial distributions of potential initiating flaws.

INTRODUCTION

The indentation and impact fracture of glass has attracted attention over the last 100 years and particularly in recent times when transparent screens are required for security visors, high speed vehicles, trains and aircraft. Although static indentation of a sphere against a semi-infinite solid has been given most consideration (1,2), the dynamic low velocity impact of simply supported thin plates is the most relevant problem. Some recent studies in this area have recently been reported (3,4) and this publication extends this work to include the influence of the surface condition of the glass. The initiation of Hertzian cracks was debated some decades ago (5,6) and is now of importance since novel surface treatments of plate glass are now being researched and assessed.

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The tensile stress created by an impacting sphere on a plate is confined to a narrow and shallow annulus around the periphery of the contact zone. The magnitude is a function of the impact velocity and the thickness of the target plate (4). This paper is concerned with the ability of the stress to cause Hertzian cracking as a function of size, shape and spatial distribution of flaws which are potential nucleating sites. This preliminary study indicates the improvement in "toughness" of commercially produced float glass which can be achieved by strengthening and toughening methods and water dissolution and etching treatments.

EXPERIMENTAL

An airgun was used to propel a steel ball 5mm in diameter along a 1m barrel to impact on the specimen. The velocity was determined and the gun pressure was set to obtain impact velocities between 5 and 100 ms^{-1}.

Specimens, 150mm diameter discs with thicknesses of 3mm and 6mm, were held in a clamp on a radius of 65mm, allowing the plates to bend. The impact sites were examined and photographed using optical and scanning electron microscopes. The formation of a ring crack was sufficient to mark the threshold velocity for damage. Several plates were tested to confirm a mean threshold velocity.

The as-received 3 and 6mm thick glass plates were tested on both the side which is in direct contact with the tin bath during production and the side which is exposed to the industrial air. Several plates were chemically strengthened and thermally toughened using conventional techniques.

Plates were abraded using 1000 grit SiC abrasive paper and some of these abraded plates were immersed in warm water (90°C). Plates were subjected to diamond polishing using 6, 3, 1 and ¼ micron grit sequentially.

As-received plates were immersed in water at 20°C for periods up to 250 days. Chemically strengthened and toughened plates were given similar treatment in water. Some plates were immersed in hot water (90°C) for periods up to 45 days. Plates were given etching treatments in a solution of hydrofluoric acid in order to remove surface layers off up to 195 microns.

RESULTS

The results were recorded in the manner depicted in fig. 1. Impact was made at increasing velocities until a faint ring crack could be observed. This was repeated up to seven times and the threshold velocity was taken as the value below which cracking was never observed. The as-received annealed 3mm thick float glass when impacted on the 'air' side has a threshold velocity of 30ms^{-1} whereas the annealed float glass on the 'tin' side has a threshold of 26ms^{-1} (fig. 1). The chemically strengthened 3mm thick glass has a threshold on the 'air' side of 45ms^{-1} whilst the 'tin' side has a threshold velocity of 39ms^{-1}. These differences are confirmed by the difference in the burst strength (fig. 1) when the plates are subjected to biaxial bending under pressure.

The plates of both 3 and 6mm thickness which had received the other treatments were impacted in a similar manner to determine the threshold velocities. The results are shown in fig. 2 as a function of apparent surface flaw size.

The plates which had received abrasion using 1000 grit SiC show a lower threshold than the as-received plates (see fig. 2). If these abraded plates are then immersed in hot water (90°C) for 15 days, the threshold approaches that of the as-received plates. Fig. 4 shows a surface which has been abraded with 1000 grit SiC, and fig. 5 shows the same surface after immersion in hot water for fifteen days. The sharp cracks within the scratches have been eliminated by the dissolution process. Diamond polishing of as-received 6mm plates down to a grit size of ¼ micron increases the threshold velocity by 6ms^{-1}.

The treatment in water at 20°C for as long as 250 days did not produce any significant increase in the threshold velocities for as-received, strengthened, toughened or abraded plates. However, immersion in hot water (90°C) increased the threshold velocities after periods as short as 10 days. Improvement continues as the number of days in the hot water increases, and for the 6mm plates a threshold velocity of 30ms^{-1} was measured after 45 days. Immersion in a hydrofluoric etch removes the surface layers. This treatment is initially effective at increasing the threshold velocity, but longer etching times do not lead to any beneficial effect. The long-term treatment improves the threshold velocity of the 3mm plates to 43ms^{-1} and 28ms^{-1} for 6mm plates. Dissolution by either hot water or hydrofluoride etching leads to a constant threshold velocity which may be characteristic of the bulk material. The highest threshold velocity obtained by water dissolution and hydrofluoric acid etching of 3mm plates approach those of the strengthened and toughened 3mm plates (fig. 2).

The results (fig. 2) demonstrate that 3mm plates in the as-received condition have threshold velocities which are approximately twice those of 6mm plates. This derives from the greater elastic flexing of the thinner plates and the resultant reduction in the Hertzian stress around the contact zone.

DISCUSSION

The initiation of Hertzian cracks will be influenced by defects and flaws in the annulus of high stress around the area of contact. The size, shape, spatial density and distribution of these defects will determine the threshold velocity at which cracks are produced. The abrasion with fine SiC grit facilitates the initiation of ring cracking whilst dissolution of the surface layers removes potential flaws and increases the threshold velocity. Chemical strengthening and thermal toughening are effective in inhibiting Hertzian damage as the compressive stress, which is estimated to be 300MPa, opposes the initiation of the Hertzian crack from surface flaws. The effects of hot water dissolution and hydrofluoric etching become "exhausted" and improvements are not achieved by prolonged immersion or etching. It can be suggested that these highest threshold velocities are characteristic of flaws which exist in the bulk of the glass.

The value of the maximum radial tensile stress produced around the contact zone by a 5mm steel ball travelling at velocities V, is given by
$\sigma_{yy} = ((1-2\nu_1)/2)\pi^{-1}(5\pi\rho/3)^{1/5}(3k/4)^{-4/5}V^{2/5}$
where ν is Poisson's ratio, ρ is the density of the steel ball, and k is
$(1-\nu_1^2)/E_1 + (1-\nu_2^2)E_2$. The subscripts 1 and 2 refer to glass and steel respectively.

Using a given threshold velocity, it is possible to estimate the flaw size using the Griffith equation. These are shown in fig. 2. These calculations assume that a defect is suitably oriented with respect to the radial tensile stress and atomically sharp. This is not realistic and it is probable that the defects are not ideal Griffith cracks. Thus the estimated flaw sizes are much smaller than the "real" defects in the surfaces. Despite efforts using taper sections and various microscopic techniques, it has not yet been possible to identify and characterise the defects responsible for the initiation of the Hertzian cracks.

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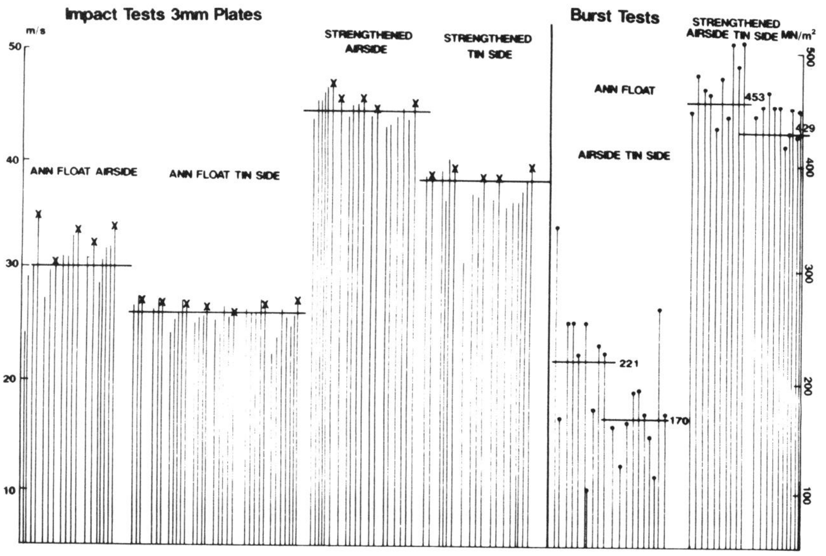

Fig. 1. Results for impact and burst tests on as-received float glass and chemically strengthened glass. The symbol X denotes Hertzian cracking.

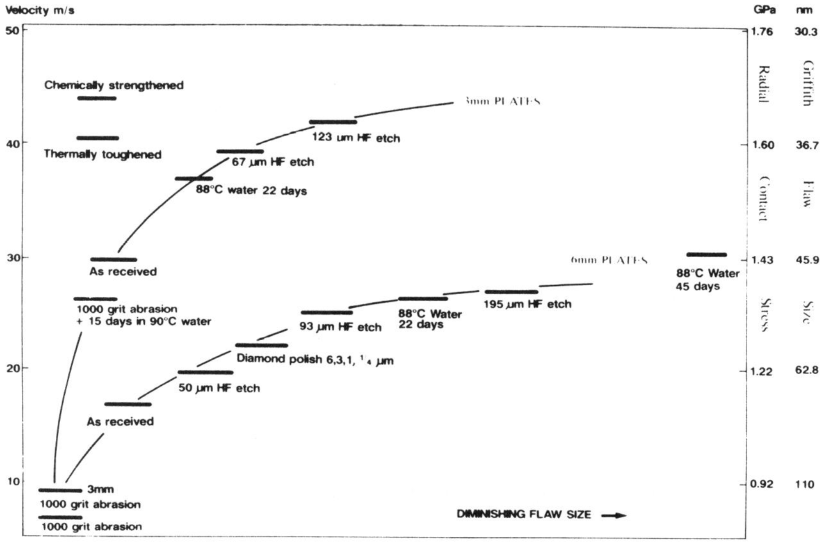

Fig. 2. The threshold impact velocities for 3mm and 6mm glass plates. The radial contact stresses and calculated Griffith flaw sizes are shown.

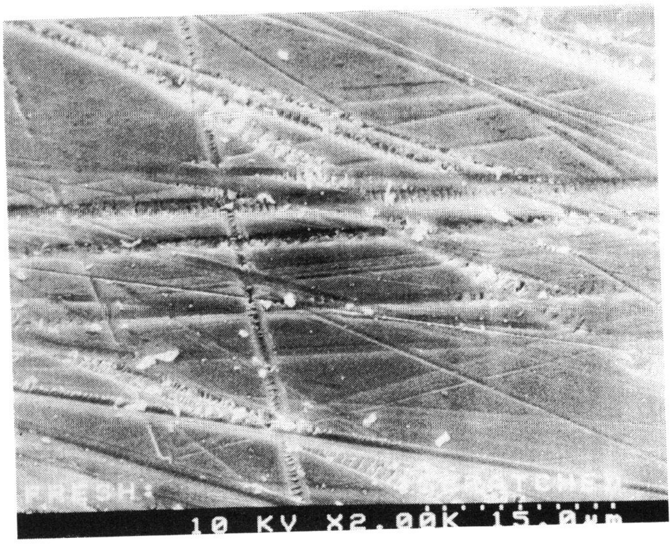

Fig. 3. Scanning electron micrograph of a glass surface abraded with 1000 grit SiC (magnification x 2000).

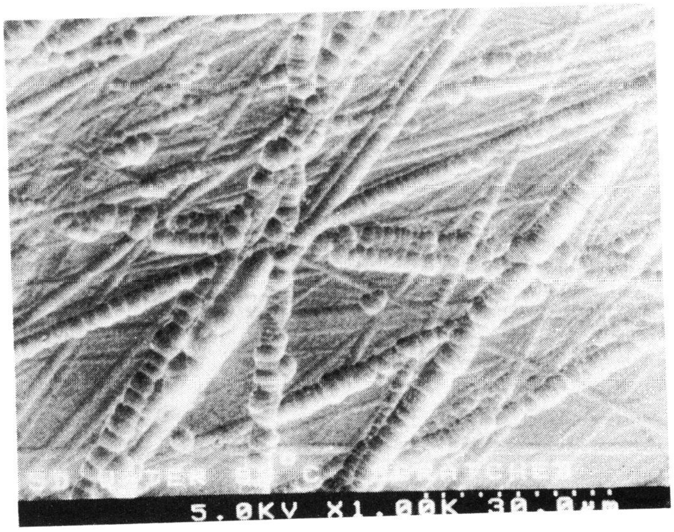

Fig. 4. Scanning electron micrograph of a glass surface abraded with 1000 grit SiC and immersed in hot water (90°C) for 15 days (magnification x 1000).