Abstract

A laser method for separating the strengthened glass and the effect of this process on edge quality and strength are reported. We have shown, for the first time to our knowledge, that developed laser based cutting technique enables clean full separation of the strengthened glass sheets having high level of ion exchange without spontaneous cracking or shattering. Nearly “flaw-free” edge was achieved after optimization of the laser cutting parameters and after defining of an optimum range of the central tension inside the glass. As a result, high strength of the edge of >500MPa is demonstrated for the first time.

Keywords: Glass; CO_2 laser; Laser Separation; Ion-exchange; Edge strength

1. Introduction

Strengthening of glass sheets through the process of ion exchange is well known [1-3] and used in numerous glass applications, including ophthalmic, optical components, and cover glass for mobile devices. The process involves the generation of compressive surface stress by substituting smaller ions in the glass, such as sodium or lithium, for example, with larger ions such as potassium, rubidium or cesium. The resulting compressive stress on the surface is counter balanced by tensile stress naturally generated in the interior of the glass. The strengthening process increases the ability of the glass to withstand high tensile and bending loads. To stress the glass to failure one must first overcome this surface compressive stress before loading to failure in tension. Therefore, one can effectively “strengthen” the glass and protect it against overstressing in the form of bending and flexure while in-service. The compressive stress also increases the ability of the glass surface to withstand damage from mechanical impact.

There are glass processes where it is desired to separate sheets of glass into smaller pieces after ion exchange. The presence of the damage resistant layer makes conventional mechanical and laser cutting of the ion-exchanged glass difficult or even impossible, especially at a high level of ion exchange. The increased effort required to mechanically cut the ion exchanged glass can lead to contamination from edge chips and edge defects that result in a weakened edge. Typically, the cutting process (mechanical or conventional laser one) entails spontaneous glass sheet breakage or shattering. Furthermore, if successful, the resulting edge is one where the underlying tensile region is exposed, and one must be concerned about the mechanical durability of this edge. In this paper we report on a laser method for separating the strengthened glass and the effect of this process on edge quality and strength.
In particular, the strength of the exposed tensile region and fatigue properties of the edge are explored. We have developed a laser based cutting technique that enables clean full separation of the strengthened glass sheets having high level of ion exchange without spontaneous cracking or shattering. A nearly “flaw-free” edge is created as evidenced by edge strengths in excess of 500 MPa. This is accomplished by optimization of the ion exchange conditions and laser cutting parameters.

2. Laser Separation of Ion Exchanged Glass

The method for laser cutting of glass uses carbon dioxide laser radiation at the wavelength of 10.6μm in a form of an elongated elliptical beam with the large ratio of the major-to-minor axes to heat the glass along the entire cutting line [4]. The concept of the laser separation method is schematically shown in Figure 1. The temperature gradient generated by the laser beam and by the following rapid cooling of the glass surface creates a transient tensile stress that propagates the crack initiated from a small flaw formed on the glass surface or on the glass edge [4-5]. In order to initiate the laser separation process the depth of the initial flaw should exceed the depth of the ion-exchanged layer. The transient tensile stress is controlled, so that the crack growth is stable [6]. However, just having stable crack growth is not enough; one must have control over crack velocity as well. It is well known that fracture surface roughness of glass increases with the increase in the velocity of the propagating crack. Figure 2 (a-d) contains images from newly created laser separation surfaces in a 1mm thick glass sheet. The glass used in this study is a commercial alkali-aluminosilicate (Corning 2317 Gorilla® Glass) especially designed for ion exchange to a deep depth and has a thermal expansion of ~ 9x10^{-6} 1/Co. The images in Figure 2 represent different separation conditions and internal glass central tension (CT) values in the range of ~26-45MPa. In Figure 2a the crack in glass with a CT~45MPa experienced a rapid transition from a smooth mirrored surface to strong mist and then to larger hackle features. These features are indicative of a high crack velocity that, in this case, was purposely created by excessive laser power and high internal tension. In Figure 2b-c crack propagation, in glass with the same 45MPa central tension, is controlled to be close or below the threshold for surface defect formation. As a result, a smoother surface with only slight mist was created. The key here is having control over the velocity of the moving crack tip. Figure 2d shows a mirror-like edge surface achieved by further optimization of the laser cutting conditions in glass with a lower level of ion exchange and, consequently, a lower central tension of ~26MPa. These fracture surface features may affect appearance, but they most certainly affect the strength of this surface. Note that by cutting the glass in this fashion one avoids the usual glass chipping associated with mechanical separation of glass sheets.

Fig. 1. Concept of laser separation of strengthened glass sheet
The method for laser cutting of chemically strengthened glass in this study is based on a modification of the CO2 laser technique described in [4, 5]. The laser process parameters, such as laser power, beam translation speed and laser beam size are adapted according to the particular properties of the tempered glass, such as compressive surface stress, central tension and sheet size. One key complication for this glass condition is that the center tension region places tensile stress on the propagating crack. Thus, one has two driving forces acting on the crack, the laser induced stress and the center tension. If the center tension is high enough, it can propel the crack by itself, usually in an unguided fast fracture condition. Thus, the level of central tension the surface strain induced by the laser technique must be correlated with the level of center tension. It needs to be high enough to produce stable crack growth by overcoming the compressive stress of the ion exchanged layer, but not too high to avoid fast, unguided crack propagation. If the crack growth is not stable, it will leave behind a rough fracture surface. A second complication is that if the power is too high, one can thermally damage the glass surface near the newly created edge resulting in weak edges. Finally, if the crack is allowed to propagate too fast, it creates mist and hackle, as shown in Figure 3a, as it reaches the exit side of the separation line. Even crack bifurcation is possible at the end of the separation line. If the crack velocity is controlled, no mist or hackle is observed (Figure 3b). Thus, for a given glass
composition one finds, that there is a threshold central tension, where one can generate a relatively defect free separation surface.

Fig. 3. Images of the fracture surface at an exit side for optimum laser set-up and different glass central tensions: (a) central tension of ~45MPa, (b) central tension of ~26MPa

3. Strength of Laser Separated Edges of Strengthened Glass

Strength testing of the laser separated glass parts in conventional four-point bending technique [7] mimics the flexure of the glass plate anticipated during in-service use. During the test the edge between the larger flat surface and the newly created laser cut surface is placed in tension, as shown in Figure 4a. With this test one can quantify the strength of the flaw population at the edge in a stress state relevant for in-service use. The median strength for glass parts with a center tension of as high as 45MPa is around 500MPa, whereas typical 4-point bend strengths for ion exchanged parts for this glass can be closer to 700MPa. What one finds is that the failure for the laser separated edges does not originate at the corner intersection between the flat surface and the newly separated surface. Rather failure originates on the face of the newly separated surface from the fracture surface features shown in Figure 2a despite the fact that they are away from the edge. This means that even the “horizontal” edge strength is impacted by the presence of fracture surface features. This makes sense since the fracture surface features are indeed flaws and tensile stresses created by bending exist.

Fig. 4. “Horizontal” (a) and “vertical” (b) 4-point bending tests [7]
Separating glass sheet after ion exchange exposes the center tension region to moisture. It is well known that flawed glass when exposed to stress in the presence of moisture can weaken through the process known as subcritical crack growth or fatigue. In this case the central tension is the driving stress and the flaws directly over the exposed central tension region are the ones at risk. The flaws here are the fracture surface features shown in Figure 2a, created during the laser separation process. Thus, it is of interest to understand the impact of these fracture surface features on the strength of the laser separated surface. To do this one can orient the glass in a four-point bend fixture in such a way that the newly created laser separated surface is now in uniform tension as shown schematically in Figure 4b. The load span for this study is 12mm and the support span is about 25mm. The strength results in Figure 5 characterize “mist” and “mirror” laser separated surfaces presented in Figures 2a-b and 2c-d and also compare “horizontal” and “vertical” four-point bending techniques in case of edges with mist. Figure 2a illustrates strong fracture surface features originated during laser separation of the glass with approximately 45MPa of central tension. Optimization of the laser process and reduction of the central tension down to 26MPa resulted in almost mirrored laser separated surfaces, as it is shown in Figure 2c and especially in Figure 2d. The relatively “flaw-free” mirrored surface has nearly double the strength with values reaching over 500MPa. This strength level corresponds to flaws that are on the order of 1 to 5 microns. From a long term reliability perspective this strength difference translates to at least $10^3$-$10^5$ reduction in failure probability for the mirrored surface.

Fig. 5. Probability plots for chemically strengthened glass sheets separated by a CO2 laser. The plots represent the strength of “mist” and “mirror” laser separated surfaces and compare “horizontal” and “vertical” four-point bending (4PB) techniques for edges with mist.
Conclusion

A CO2 laser-based cutting technique enables full separation of a chemically strengthened glass sheets with a high level of ion exchange. Edge strengths of laser separated edges are linked to the presence of fracture surface features formed during separation event. High edge strengths were accomplished by optimizing the ion exchange process to generate a central tension in the range of 26MPa and by controlling the velocity of the crack tip during separation.

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References