glass WORLDWIDE

Mechanism of stress generation during thermal shock events

Dr Wenke Hu and Gary Smay present results from a study into the effects of thermal shock on glass containers under different conditions.

For a steady-state heat transfer, a uniform temperature distribution will be maintained throughout the entire volume of an object as a function of time during the heat transfer cycle. Therefore, thermal deformation, either expansion or contraction, will also be uniform. If the object is unrestrained and can deform freely in response to the gradual temperature change, no stress will be generated in the object. However, if the object is constrained in some manner, then stress will be developed within the body of the object.

For a rapid heat transfer from one surface of an object with a low thermal conductivity, a transient temperature gradient will be created between the bulk of the object and the surface being suddenly either chilled or heated. If the object is allowed to freely respond to this thermal differential, the object will distort compared to its original configuration and no stress will be generated in the object. However, if the object is constrained in some manner, then stress will be developed both on the surface subjected to the thermal transfer and within the body of the object.

In the glass container industry, the example of rapid heat transfer is termed thermal shock. The constraint that is present is due to the relatively poor thermal conductivity of glass so that in the immediate onset of thermal shock, the glass surface being either heated or cooled assumes the new temperature and dimension, while the bulk of the glass object remains at the original temperature and dimension.

When considering glass containers, four types of thermal shock can be created:

- Type I: Rapid cooling of the outside surface of a hot glass container.
- Type II: Rapid heating of the inside surface of a cold glass container.
- Type III: Rapid cooling of the inside surface of a hot glass container.
- Type IV: Rapid heating of the outside surface of a cold glass container.

It has been well established that tensile stresses will be generated on the relatively cooler surfaces of glass containers for all four types of thermal shock [1]. For example, a type I and type II thermal shock will generate a tension stress on the outside glass surface, while type III and type IV thermal shock will generate a tension stress on the inside glass surface.

Type I and type II thermal shocks are of greatest importance in considering the overall general performance of glass containers. This is due to three key factors – the outside glass surface is the one that is more likely to exhibit strength weakening damage, glass only breaks under the influence of tensile stresses and both type I and type II thermal shock generates tensile stress on the outside glass surface [2]. While the creation of tensile stresses in the various types of thermal shock is well established[1], the manner in which the stresses are generated is not well understood. Therefore, the mechanism for the generation of tensile stress in type I and type II thermal shock was analysed in this study. The study used a model of a rectangular glass bar, which is simulative of a small physical segment from the sidewall of a glass container undergoing a thermal shock event.

General thermal effects

For any material, a change in temperature will result in either an expansion or contraction of the molecular structure and a corresponding change in volume. For simplicity, the discussion in this study was restricted to changes in length (it is understood that changes in the other two dimensions will also occur). For example, if a rectangular bar with a positive coefficient of expansion and with length L is subjected to a temperature increase of ΔT, the bar will elongate by ΔL, as shown in figure 1. Conversely, if the same bar is subjected to a temperature decrease of ΔT, the bar will shrink by ΔL, as shown in figure 2. The changes in length, either expansion or contraction, are given by the following equation

$$\Delta L = \alpha \Delta T L$$

If the bar is unconstrained, no stress will be developed within the bar.

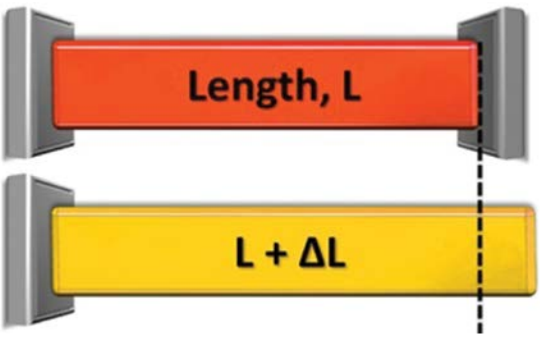

Figure 1: Expansion of a glass bar due to uniform, slow heating.

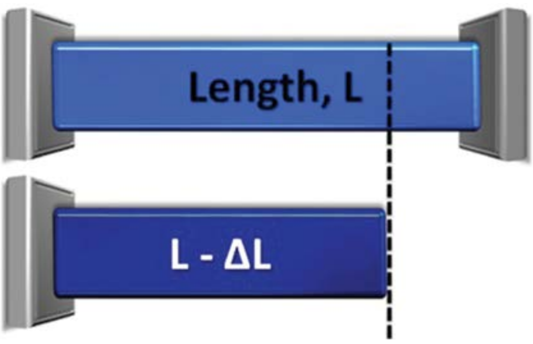

Figure 2: Contraction of a glass bar due to uniform, slow cooling.

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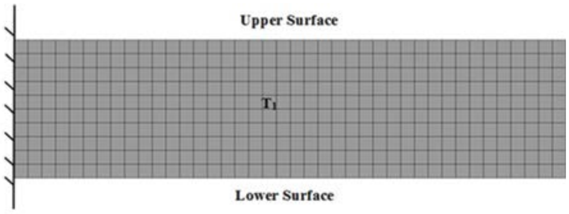

Figure 3: Finite element model of a glass bar subjected to thermal shock.

However, if the bar is constrained in some manner and is prevented from deforming according to the thermal differential, either compressive or tensile stress will be developed within the material.

As examples of these two simplistic situations, the following two sections will discuss how a glass bar will behave in response to a uniform, slow change in temperature and will identify the type of stress that will be generated:

Constraint upon heating a cold glass bar: Consider a cold rectangular glass bar with both ends constrained in such a manner that prevents any expansion or contraction in the length of the bar. If this bar is heated slowly and uniformly to a higher temperature, a new equilibrium length of the bar will be created, as defined by the magnitude of the new higher temperature and the coefficient of thermal expansion of the glass. However, since the bar is constrained to its shorter initial length, the chemical bonds of the bar will be compacted and compressive stresses will be uniformly developed along the length of the bar.

Constraint upon cooling a hot glass bar: Conversely, consider a hot rectangular glass bar with both ends constrained in such a manner that prevents any expansion or contraction in the length of the bar. If this bar is cooled slowly and uniformly to a lower temperature, a new equilibrium length of the bar will be defined by the magnitude of the new lower temperature and the coefficient of thermal expansion of the glass. However, since the bar is constrained to its longer initial length, the chemical bonds of the bar will be stretched and tensile stresses will be uniformly developed along the length of the bar.

Transient thermal mechanism (type I and type II thermal shock)

While such considerations as discussed in the previous section are interesting, a more realistic situation is one in which transient thermal gradients are created in the glass structure. A glass bar, which is fixed at one end and unconstrained on the other, is shown in figure 3. The initial temperature is set uniformly at T1 and the model is then subjected to a sudden cooling of the upper surface (simulative of a type I thermal shock) or a sudden heating of the lower surface (simulative of a type II thermal shock).

The response of the bar to these thermal differentials was determined through finite element analysis and these changes were examined to establish the method in which stress was created in the upper surface of the glass bar.

Discussion

Cooling the upper surface of a hot glass bar - Type I thermal shock: First, consider a glass bar subjected to a uniform, slow temperature decrease from T1 to T2, resulting in contraction in the length of the entire bar, ΔL, as shown by comparing figures 4a and 4b. As shown by the elements of the FEA analysis, the length of the bar has uniformly contracted and since there is no constraint on the bar, no stress will be developed in the glass.

Then, consider a situation in which the upper surface experiences rapid cooling from T1 to T2, while the lower surface of the bar is maintained at the original elevated temperature ▸

T1. In the initial stages of such a cooling event, the upper surface will assume the new lower temperature almost immediately and will attempt to shrink to an extent dependent on the new temperature and the coefficient of expansion of the glass. However, due to the relatively poor thermal conductivity of glass, the lower surface will still be at the higher temperature, T1. Thus, a temperature differential, ΔT, will be created from one surface to the other (regions intermediate between the upper and lower surfaces will experience a range in temperature between T1 and T2 and corresponding differences in length, as shown in figure 4c).

The thermal equilibrium position of the upper surface, due to its lower temperature, is consistent with the contracted distance, ΔL, as shown in figure 4b. However, the higher temperatures of the remaining sections of the glass bar only allow the upper surface to physically contract an amount equal to ΔL_1, as shown in figure 4c. Thus, the upper surface is physically constrained to a longer length than its thermal equilibrium position would dictate and a tensile stress will be generated in the top surface. The magnitude of this stress on the upper surface will be directly proportional to the difference between the thermal equilibrium position compared to the actual physical length, ($\Delta L - \Delta L_1$). Over time, the temperature differential will decrease and ultimately reach zero when the glass bar uniformly reaches equilibrium at the new lower temperature. When the new thermal equilibrium is reached, all stresses will also decrease to zero.

Heating the lower surface - Type II thermal shock: Now consider a glass bar subjected to a uniform, slow temperature increase from T1 to T3, resulting in expansion in the length of the entire bar by ΔL, as shown by comparing figures 5a and 5b (note that the temperature differential, ΔT, in this example is the same as in the first example). As shown by the elements of the FEA analysis, the length of the bar has uniformly expanded and since there is no constraint on the bar, no stress will be developed in the glass.

Then, consider a situation in which the lower surface experiences a rapid increase in temperature from T1 to T3, while the upper surface of the bar is maintained at the original cooler temperature T1. In the initial stages of such a heating event, the lower surface will immediately assume the new increased temperature T3 and will expand. However, due to the relatively poor thermal conductivity of glass, the upper surface will still be at the original lower temperature, T1. Thus, a temperature differential, ΔT, will be created from one surface to the other (regions intermediate between the upper and lower surfaces will experience a range in temperature between T1 and T3).

The equilibrium position of the lower surface, due to its higher temperature, is consistent with the expanded distance, ΔL, in figure 5b. The thermal equilibrium length of the upper surface remains at the original value, L. However, expansion of the hotter regions of the glass bar causes the upper surface to physically extend to a length, ΔL_2 as shown in figure 5c and a tensile stress will be generated in the top surface. The magnitude of this stress will be directly proportional to the actual physical length, (ΔL_2) of the upper surface. Over time, the temperature differential will decrease and ultimately reach zero when the glass bar uniformly reaches equilibrium at the new higher temperature. When the new thermal equilibrium is reached, all stresses will also decrease to zero.

Comparison of Type I and Type II: As shown in figures 4c and 5c, for the same temperature differential, the expansion of the cooler glass surface for a type I thermal shock is approximately twice the expansion of the cooler glass surface for a type II thermal shock. These differences account for the approximate two-fold difference in tensile stress magnitudes between these types of thermal shock, as determined in earlier FEA studies[3].

Conclusion

For different types of thermal shock, tensile stresses will be created on the relatively cooler surface. However, the mechanisms of tensile stress generation for type I and type II thermal shock are different.

For type I thermal shock, tensile stress is generated by the inability of the cold surface to physically contract to its thermal equilibrium length as determined by the new cooler temperature of the glass surface. This constraint is created by the expanded physical length of the hotter bulk glass.

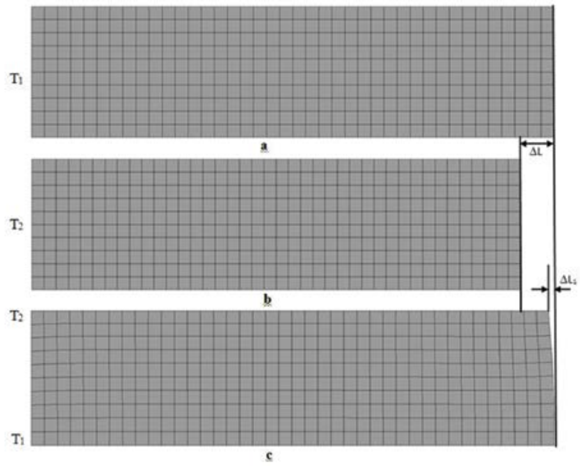

Figure 4: FEA response of cooling the upper surface of a hot glass bar.

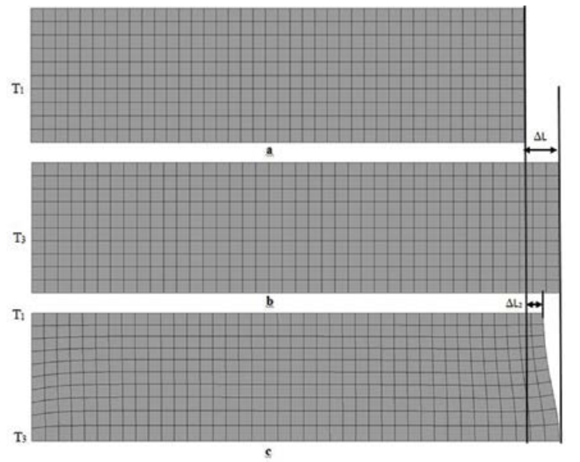

Figure 5: FEA response to heating the lower surface of a cold glass bar.

For type II thermal shock, tensile stress is generated by the physical expansion of the surface beyond its thermal equilibrium length, as determined by the original cooler temperature of the glass surface. This forced expansion of the physical length of the colder glass is caused by the expansion of the hotter bulk glass. ●

References:

1. J B Kepple and J S Wasylyk, Fracture of Glass Containers, in *Fractography of Glass,* Edited by R C Bradt and R E Tressler, Springer Science + Business Media LLC, 1994, New York, New York.
2. F W Preston, 'Stresses in Bottles and Jars from Differences in Outside and Inside Temperatures (Static Temperature Gradient)', *J.Am.Ceram.Soc,* 23 (1940), p119.
3. Unpublished results, American Glass Research.

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