Importance of Edge Finish on Thermal Tempering

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Abstract

The tempering process induces transient tensile stresses during early portion of tempering both on the surface and edges of float glass. Depending on the temperature and viscosity of glass these stresses may or may not be relieved by viscous relaxation before the permanent beneficial stresses begin to build in. In view of good quality of float glass the temporary tensile stresses can be sustained by the surfaces but not necessarily by the edges. Indeed, the edge quality which depends on the type of edge finish is inferior to that of tin and air side surfaces. Consequently, premature fracture may initiate at these edges if the combination of temporary tension and flaw severity is unbearable. For example, such a premature breakage occurs when the glass temperature is not high enough and the quench rate is too high! Glass breakage during tempering cuts down productivity and at the same time reduces glass quality.

In this paper we describe a novel technique for measuring edge strength and present data for different edge finishes. The effect of seaming and beveling on the strength of scored edge is presented. Fractographic examination of edge flaws is used to compare their severity as function of finishing process. Potential healing of these flaws during the heating portion of tempering process is discussed. The paper provides an estimate of temporary tension, based on tempering parameters, and assesses the probability of fracture from Weibull distribution of edge strength.

Sag measurements during flaw healing were also carried out for 3 mm thick glass specimens in the beam bending viscometer. The data show that such deformation can be minimized by optimizing heating rate and duration of tempering cycle. Indeed, certain trade-offs may become necessary for improving edge strength and minimizing glass deformation simultaneously during the heating portion of tempering cycle thereby preserving glass quality.

Introduction

Edge quality plays an important role during fabrication, shipping and installation of float glass products in automotive and architectural applications. The initial quality of edges is dictated by scoring and finishing processes which, in turn, depend on the diamond grit of finishing tool, type of coolant used, process speed, and edge support design for the glass template [1]. In the case of inferior edge quality, large flaws render it weak and difficult to sustain tempering stresses without premature fracture [2]. This leads to loss of production efficiency and often results in unacceptable economic penalty for glass manufacturers.

A classical example where edge quality plays a critical role is that of tempering of float glass, notably for automotive industry, where high tempering stresses are imperative for side and back windows from performance and safety points of view [3]. It is well known that during the early portion of air quench both the surface and edges experience temporary tension whose magnitude depends on glass temperature, glass viscosity and the cooling rate as shown in Figure 1 [4,5]. The temporary tension, as shown later in this paper, can approach 30 to 50 MPa which is more easily sustained by air and tin side of float glass, due to superior surface quality, than by its edges. Consequently, the edge finish for automotive application has to be of superior quality than that for architectural application where the temporary tension may be well below 30 MPa. Equally important are the aesthetic considerations for automotive windows whose edges are visible and require excellent finish for high quality.

The magnitude of temporary tension increases

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as the initial glass temperature decreases and the quench rate increases. Furthermore, at lower glass temperature both the viscous flow and stress relaxation are reduced due to higher viscosity. Hence the temporary tension is not only higher, it is present for longer time which increases the probability of fracture in the edge region. Again, to minimize such fracture, the edge quality must be improved. Air tempering at low temperature, commonly known as “cold temper”, may propagate edge flaws due to temporary tension but not lead to fracture. This is due to the fact that surface compression at the end of tempering cycle helps close the edge flaws which had propagated due to temporary tension. These “closed” flaws can be dangerous, however, since they may grow in service due to external stresses and lead to “delayed” failure. The latter can be minimized by increasing either the glass temperature or heating time to permit healing of edge flaws. Of course, this can undermine optical quality due to glass deformation which must also be controlled. Hence the trade-off between mechanical strength and glass deformation must be optimized by controlling heating rate, glass temperature, glass thickness, roller spacing and cooling rate.

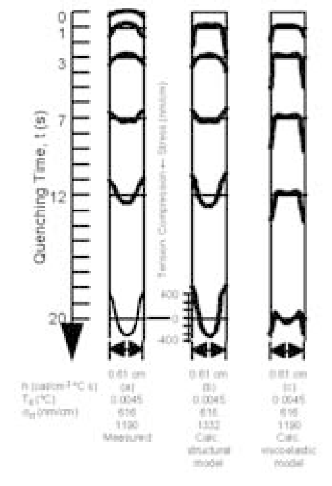


Figure 1. Development of transient and permanent stresses during air quenching

This paper will focus on different edge finishes, their initial strength and the effect of flaw healing on final strength. Several heating rates, glass temperature and cooling rates were used to measure their effect on edge strength and glass deformation. The data presented here may prove valuable to tempering equipment manufacturers and their customers.

Measurement Of Edge Strength

Figure 2 shows the four-point bend fixture for measuring edge strength via vertical bending [6]. The finished edge with grinding flaws is positioned at the bottom which experiences uniform tension under the load span ℓ during vertical bending. Since all of the edge flaws in this region are subjected to maximum tension, the failure will initiate at the worst flaw. In the conventional four-point bend test the glass specimen is positioned in horizontal plane which does not induce tension in all of the edge flaws. Hence the special test fixture in Figure 2 is ideal for characterizing edge flaws. The specimen height h and thickness t are chosen in such a way as to minimize buckling and twisting of the specimen which would initiate failure at the top edge. The latter is also avoided by supporting the ends of the specimen over a wide region; see Figure 2. Assuming pure bending within the load span the maximum tensile stress at the bottom edge can be calculated from Equation 1:

$$\sigma_{max} = \frac{3P(L-\ell)}{2t\,h^2} \qquad (1)$$

In this equation, P denotes load at failure and L denotes support span.

Four different edge finishes on float glass were evaluated using the four-point vertical bend fixture. These are (i) Sandbelt, (ii) Twin Seam, (iii) Twin Cut @ 6m/min, and (iv) Twin Cut @ 12m/min. Ten specimens of each edge finish, measuring 20 mm high and 3 mm thick, were tested at room

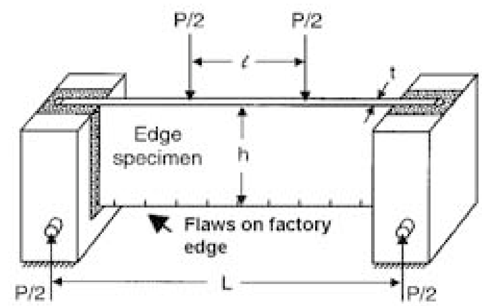


Figure 2. Four-point bend fixture for measuring edge strength

temperature on 100 mm support span and 50 mm load span at a cross-head speed of 2.5 mm/min. All of the 40 specimens failed from grinding flaws indicating the edge to be the weakest region of float glass.

Identical sets of specimens were heat-treated using three different heat-treat schedules shown in Figure 3. Their edge strength was re-measured and compared with that of nonheat-treated specimens to assess the effect of flaw healing. Tables 1, 2, 3 and 4 summarize edge strength data for the four different edge finishes.

Before we discuss these data, it should be pointed out that the slow heat treatments at 630°C and 660°C represent the temperature range employed in tempering of float glass, but the heating rate was two orders of magnitude slower

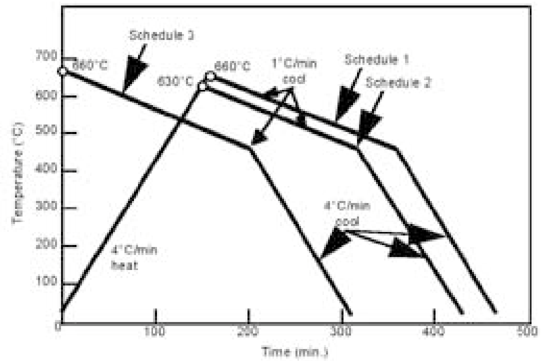


Figure 3. Heat-treat schedules for healing of edge flaws

Table 1. Edge Strength of Nonheat-Treated Float Glass

Edge Finish	N	Mean Value (MPa)	Min. Value (MPa)	Std Dev. (MPa)
Sandbelt	10	61.8	50.5	7.9
Twin Seam	10	60.8	35.7	17.0
Twin Cut @ 6 m/min.	10	77.2	71.4	5.3
Twin Cut @ 12 m/min.	10	64.1	47.0	9.4

Table 2. Edge Strength of Float Glass Heat-Treated @ 630°C

Edge Finish	N	Mean Value (MPa)	Min. Value (MPa)	Std Dev. (MPa)
Sandbelt	10	80.0	60.3	10.3
Twin Seam	10	73.2	57.5	10.4
Twin Cut @ 6 m/min.	10	89.9	72.7	9.7
Twin Cut @ 12 m/min.	10	91.5	82.6	7.2

than that used in industrial tempering process (0.07°C/sec. vs. 5.1°C/sec.). Further-more, let us note in Table 4 that the fast heat-treat schedule at 705°C was used for only two types of edge finishes which are commonly employed in industry. The Twin Seam edge finish was not evaluated at 705°C. Similarly, the 12 m/min Twin Cut edge finish is not used for automotive application and hence was not evaluated at 705°C. The primary motivation for using fast heat-treatment @ 705°C, where glass was heated for only 120 sec., was to simulate the tempering cycle employed in industry. We will also report the edge strength data for specimens, with Sandbelt and Twin Cut @ 6m/min edge finishes, which went through the tempering cycle used in industry following the discussion of data in Tables 1, 2, 3 and 4. The Weibull distributions of strength data (summarized in Tables 1, 2, 3 and 4), which will help our discussion, are shown in Figures 4 and 5 for Sandbelt and Twin Cut @ 6m/min edge finishes [7].

As noted earlier, the best tempering results for float glass are achieved when the mean and minimum edge strength in annealed condition are respectably high and the standard deviation is low. Of course, the minimum strength represents the worst flaw where failure due to temporary tension can originate if either the strength is too low or temporary tension is too high. Table 1 shows that the Twin Cut @ 6m/min yields the best edge finish with high mean strength, high minimum strength and low standard deviation. The Twin Seam edge has the worst flaws with lowest strength and highest standard deviation. Table 2 shows that slow heat treatment at 630°C is quite effective in

Table 3. Edge Strength of Float Glass Heat-Treated @ 660°C

Edge Finish	N	Mean Value (MPa)	Min. Value (MPa)	Std Dev. (MPa)
Sandbelt	10	96.7	78.0	15.5
Twin Seam	10	74.5	68.9	6.5
Twin Cut @ 6 m/min.	10	102.2	82.0	10.1
Twin Cut @ 12 m/min.	10	90.4	70.5	14.3

Table 4. Edge Strength of Float Glass Heat-Treated Fast at Furnace Temperature of 705°C (120 secs.)

Edge Finish	N	Mean Value (MPa)	Min. Value (MPa)	Std Dev. (MPa)
Sandbelt	15	62.4	44.0	9.4
Twin Cut @6 m/min.	15	86.8	67.1	10.5

healing the worst flaws, as judged by improvements in minimum strength, although such slow heat treatments are not practical for industrial tempering processes. Comparison of Tables 1 and 2 shows that the minimum strength has improved by 19% for Sandbelt edge, 61% for Twin Seam edge, and 76% for Twin Cut @ 12m/min edge. However, the standard deviation is still high. The minimum strength of Twin Cut @ 6m/min edge has not improved significantly because this edge finish was the best before any heat treatment. Table 3 shows further improvement in minimum strength following heat treatment at 660°C with the exception of Twin Cut @ 12 m/min edge. But the standard deviations are very high except for the Twin Seam edge. Of course, heat treatment at higher temperature should heal the flaws even better but at the expense of optical quality due to deformation of float glass between the rollers. Table 4 shows that fast heat treatment at 705°C neither improves the minimum strength nor reduce standard deviation indicating that flaw healing, which is achieved by viscous flow, requires either the high temperature (i.e. low viscosity) or relatively longer time. This is also borne out by Figures 4 and 5 where the strength distributions for nonheat-treated and fast heat-treated edges are nearly identical.

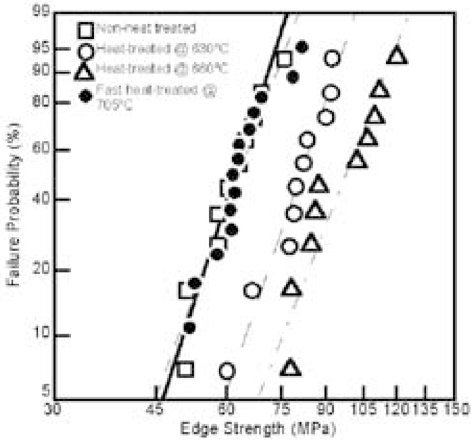


Figure 4. Weibull distributions of strength data for Sandbelt edge before and after different heat treatments

Table 5. Effect of Heat Strengthening on Edge Strength

Edge Finish	Heat Treatment	N	Mean Value (MPa)	Min. Value (MPa)	Std Dev. (MPa)
Sandbelt	None	10	61.8	50.5	7.9
	Heat Strengthened	10	142.3	107.1	24.8
	% Improvement	--	130%	112%	--
Twin Cut	None	10	77.2	71.4	5.3
	Heat Strengthened	10	153.0	110.8	24.1
	% Improvement	--	98%	55%	--

Next, we measured the edge strength of 3 mm thick specimens that had been through the heat strengthening process. For these we selected two types of edge finish, namely Sandbelt and Twin Cut @ 6m/min. These specimens were heated to a glass temperature of 630°C at 1°C/sec, held at 630°C for 0.3 sec and then cooled at 100°C/sec. In view of much faster heating and cooling rates there is less opportunity for the flaws to heal. Hence, almost all of the strength improvement is expected to come from heat strengthening. Table 5 compares the edge strength of nonheat-treated specimens with that of heat strengthened specimens for both types of edge finish.

The complete strength data are plotted as Weibull distributions in Figure 6 for Sandbelt edge and Figure 7 for Twin Cut @ 6 m/min edge. Both Table 5 and Figs. 6 and 7 show that the mean edge strength increased by 76 to 80 MPa and the minimum edge strength increased by 39 to 57 MPa. Table 5 also shows that the minimum edge

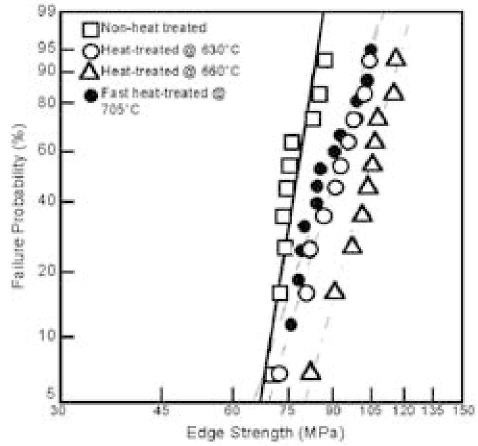


Figure 5. Weibull distributions of strength data for Twin Cut @ 6 m/min edge before and after different heat treatments

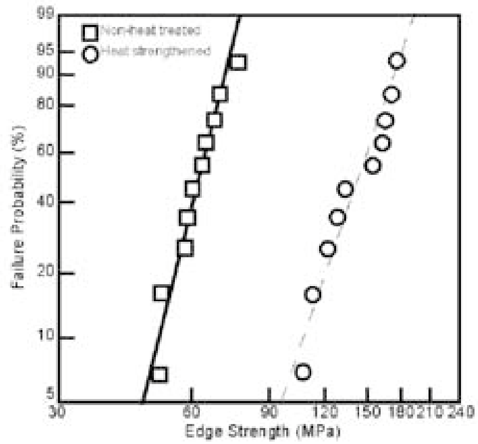


Figure 6. Weibull distributions of strength data for Sandbelt edge before and after heat strengthening

strength after heat strengthening is nearly identical for both types of edges (107.1 MPa for Sandbelt and 110.8 MPa for Twin Cut) whereas before heat strengthening Sandbelt edge was considerably weaker than Twin Cut edge (50.5 MPa for Sandbelt and 71.4 for Twin Cut). Assuming that the heat strengthening level was identical for both edges, the Sandbelt edge must have benefited more from flaw healing than the Twin Cut edge despite the fast heating rate. This is also borne out by Tables 1 and 2 where the minimum strength of Sandbelt edge increased by 10 MPa and that of Twin Cut @ 6 m/min edge increased by only 1 MPa when both were heat-treated to 630°C. This is also reasonable on physical grounds because the flaws in Sandbelt edge are deeper (more severe) than those in Twin Cut edge and hence are more likely to heal during the short heating cycle. Assuming an improvement of 10 MPa due to flaw healing, the data in Table 5 suggest a minimum edge compression of 47 MPa for Sandbelt edge and 39 MPa for Twin Cut edge due to heat strengthening. The average edge compression, based on mean value of edge

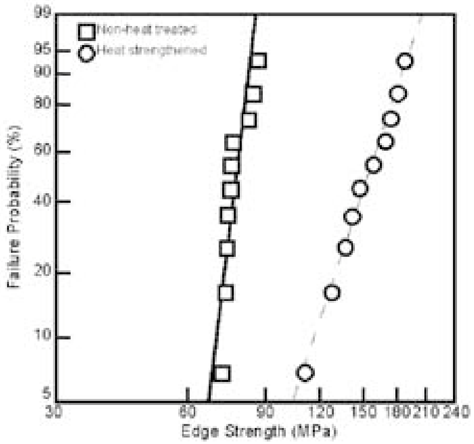


Figure 7. Weibull distributions of strength data for Twin Cut @ 6 m/min edge before and after heat strengthening

Table 6. Comparison of Failure Stress with Measured Strength

Edge Finish	Mirror Radius (m)	Failure Stress (MPa)	Measured Strength (MPa)
Sandbelt	0.00125	51.6	50.6
Twin Cut @ 6 m/min.	0.00056	77.2	73.8

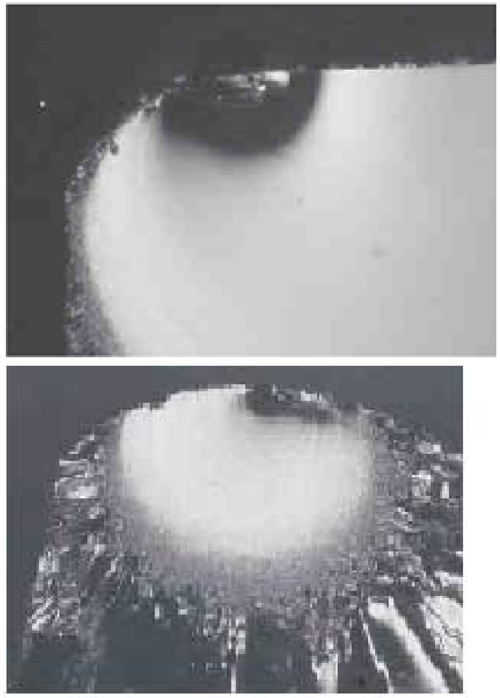
strength, is approximately 70 MPa for both types of edges. Photoelastic measurement of edge compression yielded a minimum value of 45 MPa in Sandbelt edge and 40 MPa in Twin Cut edge. The agreement between photoelastic values and those based on strength data is excellent.

The fracture surface of nonheat-treated and weakest specimens was also examined under the microscope. Figures 8(a) and 8(b) show the characteristic features of Sandbelt and Twin Cut edges respectively. We can estimate the failure stress from mirror radius R_m, which is measurable from these fractographs, using the empirical equation [8]

$$\sigma_f = A / \sqrt{R_m} \qquad (2)$$

where A is the mirror constant for float glass with a value of 1.82 MPa $m^{1/2}$. Table 6 lists the measured R_m values, failure stress given by Equation 2, and the measured edge strength for these specimens. It should be noted that the agreement between calculated failure stress and measured strength is again excellent!

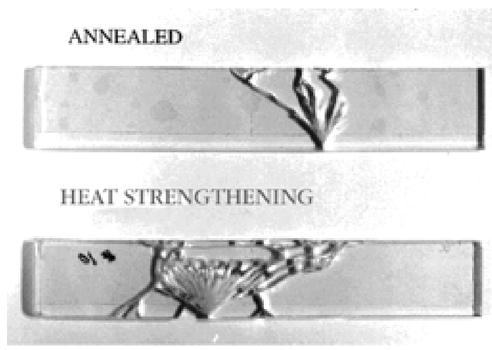
Finally, the fracture pattern of Twin Cut specimens before and after heat strengthening is shown in Figures 9(a) and 9(b). These figures show, as might be expected, that the number of crack branches which start at the worst edge flaw is much smaller for annealed specimen than for heat strengthened specimen. The number of branches is proportional to strain energy at failure which, in turn, is proportional to the square of edge



(a)

(b)

Figure 8. (a) Fracture surface of Sandbelt edge (30X); (b) fracture surface of Twin Cut edge (30X)



(a)

(b)

Figure 9. (a) Fracture pattern for Twin Cut edge before heat strengthening; (b) fracture pattern for Twin Cut edge after heat strengthening

strength. Since the heat strengthened specimen is nearly twice as strong as annealed specimen (mean strength), the number of crack branches should be 4X larger as depicted in Figure 8.

Estimate Of Temporary Tension

The instantaneous tension during first few seconds of quenching is given by [5]

$$\sigma_i = \frac{E}{1-\nu}(\alpha' \Delta T) \qquad (3)$$

where E, ν and α' denote Young's modulus, Poisson's ratio and thermal expansion coefficient of glass in the transformation range and ΔT denotes sudden drop in surface temperature. While the elastic properties change with temperature, their values can be estimated from room temperature data if we assume the constancy of Bulk modulus K defined by

$$K = \frac{E}{3(1-2\nu)} \tag{4}$$

This assumption is equivalent to saying that the compressibility of float glass does not change with temperature which is reasonable. The room temperature properties of float glass and its thermal expansion coefficient in the transformation range are as follows[1]:

E = 72.4 GPa
_ = 0.22
_ ’ = 170 x 10^{-7}/°C

The Bulk modulus K is then calculated to be

K = 43.1 GPa

Since the instantaneous tension is predominantly relieved by viscous flow above the transformation temperature, any temporary tension that is sustainable by glass must occur near the annealing temperature. The Young’s modulus of float glass is 10% lower at annealing temperature, i.e. E = 65.1 GPa. Assuming constancy of K, we obtain a value of 0.25 for ν at annealing temperature. Substituting these values along with α' into Equation 3, we obtain

$$\sigma_i = 1.475 \Delta T \tag{5}$$

The instantaneous tension given by Equation 5 will relax with time τ_r to a final value given by Equation 6 [9,10]:

$$\sigma_f = \sigma_i \exp\left(-\tau / \tau_r\right) \tag{6}$$

where _$_r$ is the relaxation time given by

$$\tau_r = \frac{6(1-\nu)\eta}{E} \tag{7}$$

in which η denotes glass viscosity at surface temperature. Table 7 summarizes the computation of instantaneous tension and its final value after one second (i.e. τ = 1 sec) for different values of surface temperature T_s prior to quenching. The annealing temperature of float glass was assumed to be 546°C. It is clear from this Table that the temporary tension does not start building until the glass surface has cooled to below 620°C. Furthermore, the maximum value of temporary tension on the surface is estimated to be 42 MPa. Its value at the edge will be 25% lower due to uniaxial state of stress, i.e. no Poisson effect. Thus the edge will experience a temporary tension of approximately 32 MPa.

Below 580°C the temporary tension decreases and permanent compression begins to build in. Based on these estimates the edge quality must be such that it can sustain a temporary tension of 30 to 40 MPa.

Table 7. Estimate of Instantaneous and Temporary Tension

T_s (°C)	ΔT (°C)	σ_i (MPa)	η_s (Pa.s)	τ_r (sec)	σ_f (MPa)
660	114	168	1.2×10^{8}	0.012	0
640	94	138	4.5×10^{8}	0.045	0
630	84	124	1.1×10^{9}	0.096	0
620	74	109	2.5×10^{9}	0.21	1
610	64	94	6.1×10^{9}	0.45	10
600	54	80	1.4×10^{10}	1.00	29
590	44	65	3.4×10^{10}	2.30	42
580	34	50	8.1×10^{10}	5.50	42

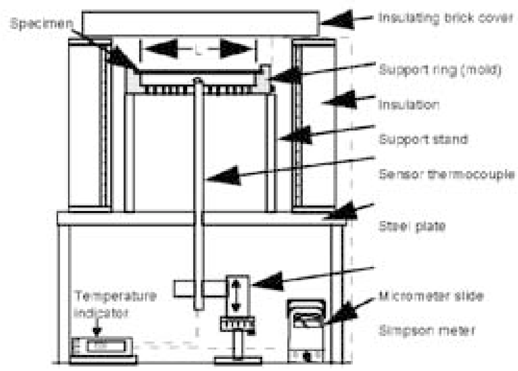


Figure 10. Beam bending viscometer

Deformation At High Temperature

The high temperature deformation was measured in the beam bending viscometer [11] shown in Figure 10. Float glass specimens, 3.8 mm wide and 3 mm thick, were supported on a span L of 51.1 mm and loaded at the center. As the glass is heated at 10C/min, the center load applied by the sapphire hook causes deformation which is recorded by LVDT (linear voltage differential transformer). It is difficult to measure deformation without the load because the other end of sapphire hook is connected to LVDT. Two different loads were used, namely 158 g and 30 g, which corresponded to a stress of 3.45 and 0.65 MPa respectively. The glass specimen was heated to 575°C and the deformation recorded continuously; see Figure 11. It is clear that at higher stress the deformation begins at lower temperature and progresses rapidly.

The deformation of float glass in a tempering lehr is caused by its own weight and its magnitude depends on, in addition to temperature and time, roller spacing. To simulate glass deformation in the tempering lehr, the stress in the beam specimen due to its weight was calculated to be 0.02 MPa. The deformation curves in Figure 11 were shifted to reflect this value of stress as shown by the dotted line. It is clear from this figure that high temperature deformation of glass specimen due to its own weight is small. Moreover, the total heating time in a tempering lehr is small compared with 60 minutes for our test. Hence the deformation will be further reduced.

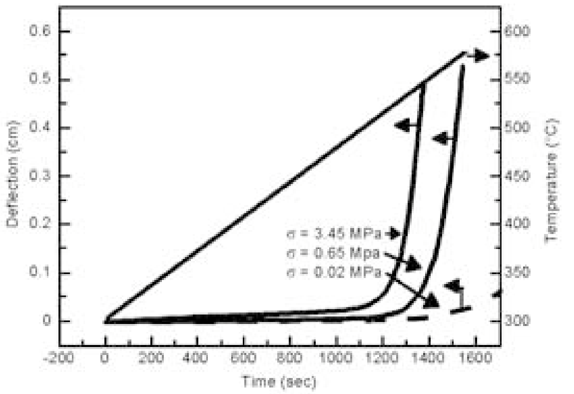


Figure 11. Deformation of glass specimen as function of stress, temperature and time

These measurements indicate that glass deformation can be controlled and the edge flaws can be healed during the heating portion of tempering cycle. To verify this hypothesis we need to anneal the tempered specimens and re-measure their edge strength. In addition, the edge strength that is most meaningful is the one measured at high temperature where the temporary tension occurs during air quenching. The authors are working on such measurements and will present the data, hopefully, at GPD 2003.

Summary & Conclusions

The key objectives of our paper have been met. We will summarize these and the key results.

i) edge quality plays an important role both from mechanical point of view and optical point of view;
ii) high quality edge finish ensures high strength and can sustain high temporary tension during tempering thereby improving temper quality without breakage;
iii) high quality edge finish also results in aesthetic appeal which is important for automotive applications where the edges are exposed;
iv) the best way to assess edge quality is to measure its strength in the 4-point vertical bend fixture which stresses all of the edge flaws;
v) Twin Cut edge finish is superior to Sandbelt edge and has 25% higher strength;
vi) edge flaws can be healed by controlling glass temperature and the heating rate resulting in 30 to 60% increase in strength (for slow heating);
vii) rapid heating and short duration representative of industrial tempering process do not increase the edge strength significantly;
viii) heat strengthening increases the edge strength by 50 to 100% provided the initial strength is high enough to sustain temporary tension;
ix) based on glass viscosity and shear relaxation time, the temporary tension during tempering of float glass is estimated to be 30 to 50 MPa;
x) high temperature deformation of float glass depends on glass thickness, glass viscosity, roller spacing and the duration of heating cycle; beam bending viscometer yielded low values for glass deformation if the stress due to its own weight is very small;
xi) future measurements of edge strength will be carried out following tempering and annealing to help quantify flaw healing during tempering;
xii) future measurements of edge strength will also be carried out at high temperature to quantify the available strength for sustaining temporary tension during air quenching.

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