Explanation for Edge Bending of Glass in Tempering Furnace

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Keywords:
1 = Glass tempering 2 = Roller waves 3 = Quality

Abstract

Good visual quality is of great importance in tempered glass. Roller waves and other deformations are formed easily in the glass during the tempering process. In order to understand the formation of deformations, a theoretical model is needed. The influence of heat transfer, rollers, and processing parameters such as velocities and oscillation during the heating period can be studied using a theoretical model. Some examples of glass behavior during the heating period at high temperatures are presented in the paper. From the examples, the great influence of temperature and time on visual quality can be seen.

Introduction

Tempered glass is a very common building material. Many façades or windows are made from tempered glass because of its good strength. Usually those glasses are located in visible places and customers want tempered glass to have good visual quality. Tempering quality, like strength of glass, is usually high. In addition to tempering quality also visual aspects are becoming more and more important, although stresses are still the most important factor in considering the quality of tempered glass. There can be different kinds of visual faults in the glass. Some visual faults are caused by uneven heat transfer and some are caused by too high a process temperature. Some examples of visual faults are shown in Figs. 1-3. Some of those visual faults can be avoided by proper control of heat transfer. This paper concentrates on the formation of roller wave deformations.

In a glass tempering furnace the temperature of glass plate is over 600 °C at the end of the heating period. Thus, the relaxation time is so short that plastic deformations are produced and they are non-reversible. If the deformations are large enough, it is possible to see different reflections from the glass surface. In Fig. 4 the reflection of a vertical grid from a glass plate is seen and waves can be detected. Especially, they can be seen at the edges if a hot glass plate has been in the same position for a long time. During oscillations the movement of the glass plate is stopped many times for a short period of time. Plastic deformations are formed in a hot glass during that time if the glass is not supported. All changes on the glass surface show up as distortions.

Glass tempering and theoretical fundamentals of tempering stresses have been published in many papers [1-4]. Deformations of tempered glass have been much discussed and experimental results are available [5]. However, there are no studies dealing with the theoretical aspects of the origin of roller waves.

The aim of this paper is to present a theoretical background for deformations of tempered glass. In addition, this paper discusses what happens in the tempering process and why the deformations are produced, and the paper offers reasons explaining these phenomena. In this paper, the results of heat transfer during the tempering process have been ignored because they can be found in the literature [6-8].

Theoretical background for deformation

In a glass tempering process strains are produced by the change of the temperature field and the body forces. When glass temperature is high, glass is a viscous material and creeping phenomena occur. Creeping creates permanent plastic deformations in glass.

In taking temperature change into account the thermal strain ε_{th} is given by

$$(\varepsilon_{th})_{ii} = \alpha \Delta T \quad (1)$$

The body force equals glass density ρ multiplied by gravity g

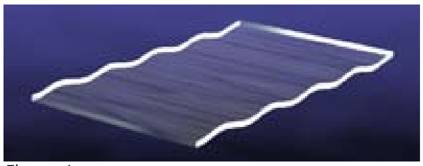


Figure 1
Roller waves

Figure 2
Curving

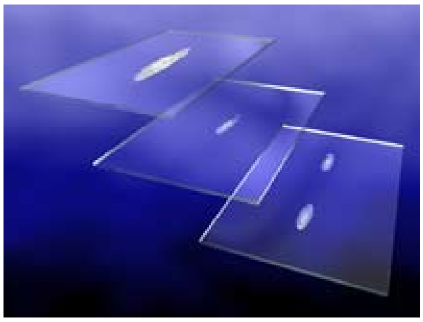


Figure 3
White hazes

Figure 4
Distorted reflection from glass surface due to roller waves

$$b = \rho g \tag{2}$$

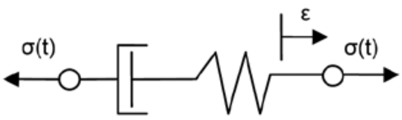


Figure 5
Maxwell model

Glass is a viscoelastic material. At low temperatures the behavior of glass is elastic because viscous effect is very slow. When the temperature exceeds the transition temperature, the influence of viscous behavior increases. The behavior of a viscoelastic material can be described using the Maxwell model, in which a spring and dashpot are in series, as shown in Fig. 5. In the model, a spring describes solid behavior and dashpot is for viscous behavior. General constitutive equation for the Maxwell model is given in [9]

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta} \tag{3}$$

Using Eq. (3) the relation between the stress and strain can be found as

$$\sigma(t) = E\exp\left(-\frac{E}{\eta}t\right)\varepsilon \tag{4}$$

In this equation the factor of strain is the relaxation function G(t), which describes how stress changes as a function of time with a constant strain ε. Because strains can change and relaxation is time- and temperature-dependent, the whole history should be taken into consideration

$$\sigma = \int_0^t G(t-t')\frac{\partial \varepsilon}{\partial t'}dt' \tag{5}$$

Formed strains can be separated into deviatoric and hydrostatic parts [10]

$$\varepsilon_{ij} = e_{ij} + \delta_{ij}\bar{\varepsilon} \tag{6}$$

Analogously, stresses can be separated into shear and normal stresses

$$\sigma_{ij} = s_{ij} + \delta_{ij}\bar{\sigma} \tag{7}$$

When the stresses are separated according to Eq. (7), the stress response to corresponding strain can be written as

$$s = \int_0^t G_1(t-t')\frac{\partial e}{\partial t'}dt' \tag{8}$$

$$\bar{\sigma} = \int_0^t G_2(t-t')\frac{\partial \bar{\varepsilon}}{\partial t'}dt' \tag{9}$$

The time-dependence of relaxation with the generalized Maxwell model for the shear modulus $G_1(t)$ and bulk modulus $G_2(t)$ can be described using the Prony's series

$$G_1(t) = 2G_0\sum_{i=1}^{n} w_{1i}\exp\left(-\frac{t}{\tau_{1i}}\right) \tag{10}$$

$$G_2(t) = 3K_\infty + (3K_0 - 3K_\infty)\sum_{i=1}^{n} w_{2i}\exp\left(-\frac{t}{\tau_{2i}}\right) \tag{11}$$

In the equations above, G_0 is initial shear modulus, K_0 initial bulk modulus, and K_∞ final bulk modulus. The moduli above are related to the Young modulus E and the Poisson ratio ν by equations

$$G_0 = \frac{E}{2(1+\nu)}, \quad K_0 = \frac{E}{3(1-2\nu)} \tag{12}$$

Terms τ_{1i} and τ_{2i} are relaxation times of each Prony component of the shear modulus and the bulk modulus, and w_{1i} and w_{2i} are weight coefficients. Relaxation times are defined as in [10]

$$\tau_{1i} = \frac{\eta_i}{w_{1i}G_0}, \quad \tau_{2i} = \frac{\eta_i}{w_{2i}K_0} \tag{13}$$

in which η_i is viscosity.

The viscous properties of glass depend on temperature. If the relaxation function is known at a reference temperature T_{ref}, relaxation times at different temperatures can be solved using the shift function a(T). For a stabilized glass the shift function can be presented as in [10]

$$a(T) = \frac{\tau_{ref}}{\tau(T)} \tag{14}$$

where τ_{ref} refers to relaxation times in Eq. (13) at temperature T_{ref}. The shift function is solved from equation

$$\ln a(T) = \frac{H}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right) \tag{15}$$

where H is the energy of activation and R is the perfect gas constant.

At different temperatures glass behaves differently because of its viscoelastic behavior. At low temperatures glass is a solid-like material while at high temperatures it is more like a liquid. Structural relaxation takes into account the deviation of glass from its equilibrium state. Structural relaxation can be introduced by the change in properties due to change in temperature. The response function $M_p(t)$ of any property p(t) is presented as

$$M_p(t) = \frac{p(t) - p_2(\infty)}{p_2(0) - p_2(\infty)} = \frac{T_f(t) - T_2}{T_1 - T_2} \tag{16}$$

The fictive temperature T_f can be calculated from Eq. (16) and it describes the difference from equilibrium state. In the calculation of the fictive temperature the whole thermal history has to be taken into account

$$T_f(t) = T(t) - \int_0^t M_p(t-t')\frac{dT(t)}{dt'}dt' \tag{17}$$

The response function $M_p(t)$ can be described by analogy with viscous relaxation as

$$M_p(t) = \sum_{i=1}^{n} C_i \exp\left(-\frac{t}{\lambda_i}\right) \tag{18}$$

The structural relaxation time λ_i is temperature-dependent and is analogous to the stress relaxation time in Eq. (13). When glass is not stabilized, the shift function of the relaxation time depends on the actual temperature and fictive temperature

$$\ln a(T) = \frac{H}{R}\left(\frac{1}{T_{ref}} - \frac{x}{T} - \frac{(1-x)}{T_f}\right) \tag{19}$$

The shift function Eq. (19) should be used during tempering both for stress and structural relaxation. In Eq. (19) the term x is a constant which depends on the material.

The thermal expansion coefficient depends on actual and fictive temperatures. Because the thermal expansion coefficient of a liquid glass α_l is about three times greater than the thermal expansion coefficient of a solid glass α_s, the change must be taken into account during tempering. The thermal strain equation depends on the difference between actual temperature and fictive temperature [1]

$$d\varepsilon_{th} = \alpha_s dT + (\alpha_l - \alpha_s)dT_f \tag{20}$$

Heat transfer

In a tempering process, the temperature field should also be known. Temperature distribution is calculated from the energy equation

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + S \tag{21}$$

Heat is transferred from the surface by convection. On the surfaces, is the boundary condition for the energy equation

$$q = -k\frac{\partial T}{\partial x_i} = h(T_s - T_\infty) \tag{22}$$

There can exist also radiation in the glass, but in this study that phenomenon has been ignored as its effect is small.

Modeling results

The commercial FE software ANSYS was used to solve the temperature field as well as stress and deformation fields. Thermal strains and relaxation times are connected to the temperature field. Calculation of the temperature field is based on the energy equation (Eq. (21)). Stress and deformation field calculations are based on the theory above. The governing equation of a viscoelastic material with thermal strains is [11]

$$\dot{\sigma}_{ij} + \frac{\mu}{\eta}\sigma_{ij} = 2\mu\dot{\varepsilon}_{ij} + 3\delta_{ij}\left[\lambda\dot{\varepsilon} - K\alpha\dot{T} + \frac{K\mu}{\eta}(\varepsilon - \alpha T)\right]$$

where λ and μ are Lamé constants

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}, \quad \mu = \frac{E}{2(1+\nu)} = G \tag{24}$$

Reference values of material properties and their temperature-dependency are given in Table 1. Constants for glass stress and structural relaxation curves at the reference temperature (T_{ref} = 869 K) are given in Table 2. They were taken from the article of Daudeville and Carré [1]. These material values are typical for soda-lime glass.

The main reason for glass deformation is high temperature. Glass

Young modulus E = 70 GPa
Poisson ratio ν = 0.22
Thermal expansion coefficient for solid glass $\alpha_s = 9\cdot10^{-6}$ 1/K
Thermal expansion coefficient for liquid glass $\alpha_l = 25\cdot10^{-6}$ 1/K
Thermal conductivity $k = 0.975 + 8.58\cdot10^{-4}\,T$ W/mK ,where T in °C
Specific heat for liquid glass ($T>T_g$ = 850 K) $c_{p,l} = 1433 + 6.5\cdot10^{-3}$ T J/kgK ,where T in K
Specific heat for solid glass ($T\leq T_g$ = 850 K) $c_{p,s} = 893 + 0.4\,T - 1.8\cdot10^{-7}/T^2$ J/kgK ,where T in K
Ratio H/R = 55000 K
Constant x = 0.5
Density ρ = 2530 kg/m^3

Table 1

Material properties

Deviatoric part		Hydrostatic part (K_∞/K_0 = 0.3)		Structural part	
w_{1i}	τ_{1i}	w_{2i}	τ_{2i}	C_i	λ_i
0.0552	$6.658\cdot10^{-5}$	0.0222	$5.009\cdot10^{-5}$	0.05523	$5.965\cdot10^{-5}$
0.0821	$1.197\cdot10^{-3}$	0.0224	$9.945\cdot10^{-4}$	0.08205	$1.077\cdot10^{-2}$
0.1215	$1.514\cdot10^{-2}$	0.0286	$2.022\cdot10^{-3}$	0.1215	0.1362
0.2286	0.1672	0.2137	$1.925\cdot10^{-2}$	0.2286	1.505
0.286	0.7497	0.394	0.1199	0.2860	6.747
0.2266	3.292	0.3191	2.033	0.2265	29.63

Table 2

Characteristics of shear and volume moduli and response function for structural part (T_{ref} = 869 K)

Figure 6

Cantilever beam, L = 10 cm, t = 4 mm

relaxation time decreases when the glass temperature rises above the glass transition temperature (about 550 °C). At the same time, the creeping velocity increases. In Fig. 7 is shown how glass temperature affects the bending of a freely supported cantilever glass beam in Fig. 6 after one second.

The longer the glass is at high temperature the more it creeps. The case of a roller-supported glass is shown in Fig. 8.

In the case where a hot glass is on the rollers, the deformations between the rollers and free edge are different, depending on the type of glass support. A free edge usually bends more than the rest of the glass. The degree of bend depends on the length of free edge. If the free edge is short, the section of glass next to the free edge has more effect and the free edge rises. Usually deformations of free edges have a determining influence on deformations of the entire glass plate. Deformations of a stationary glass plate on rollers are shown in Fig. 9. Glass thickness is 4 mm, length 1 m, temperature 630 °C, distance between rollers (a) 120 mm
(23) and distance between the left edge and the first roller (b) 60 mm. In the initial state, glass has only elastic deformation and after that glass creeps from the initial state. The influence of the free edge can be seen in both ends. If the length of the free end is longer, the plate bends much more. In this case the length of free edge is 60 mm at the left end and 100 mm at the right end. At the same time as that free edge drops, glass rises in the next gap due to the free edge. The free edge has minor influence in the center section of glass plate.

Usually during the tempering process the glass plate is in motion. In that case lengths of free edges change with time

Figure 7

Effect of temeprature on deformation of point 1 in cantilever beam

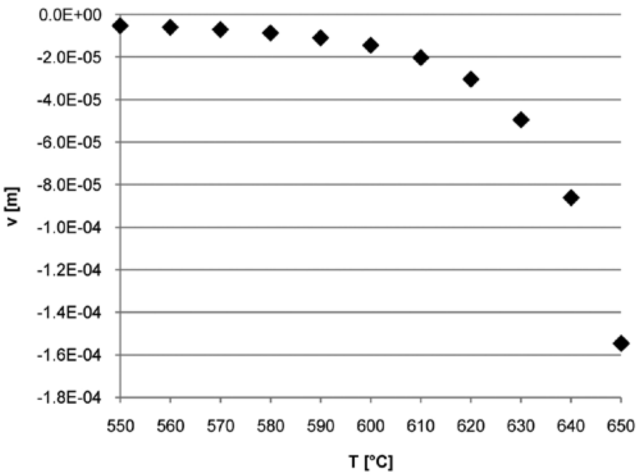


Figure 8

Roller-supported glass

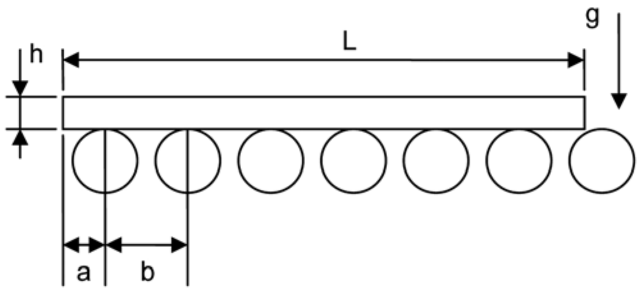
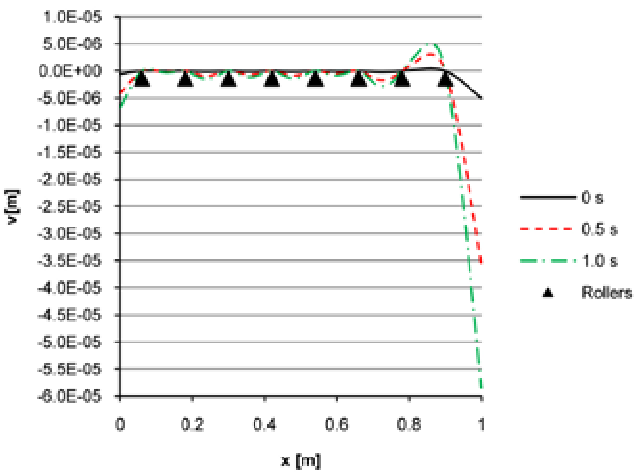


Figure 9

Glass deformation of stationary plate on rollers. Glass thickness 4 mm, length 1 m, temperature 630 °C.



and affect differently the rest of the plate. How deformations of a glass plate change with time is shown in Fig. 11. In this example the glass thickness is 4 mm, length 0.75 m, temperature 630 °C, distance between rollers (b) 120 mm, and distance between the left edge and the first roller (a) 20 mm at the initial state. Glass velocity is 500 mm/s. At the time 0 s glass has only elastic deformations. During the motion glass deforms. After six seconds glass is in a similar position as to the rollers and the difference between the initial state (only elastic deformations) and the new state (elastic and creeping deformations) can be seen.

Results from the same case as above are shown in Fig. 12. In that figure is shown what happens to glass when it moves over one gap. During the motion, the free edge of glass changes with time. The discontinuity of the edge motion occurs when it rises with the roller or drops from it. After the glass has moved for some time, it can be seen that the edge bends all the time down. The results show that the prediction of wave length and amplitude is quite difficult.

Conclusion

In the glass tempering process deformations are formed because of the rollers and the mass of glass. Hot glass is a viscous material and stress relaxation occurs. The hotter the glass the more viscous it is. Hotter glass makes the tempering quality better, but at the same time deformations increase and visual quality suffers. When the glass temperature is under the transition temperature, plastic deformations do not form and mechanical tempering is impossible.

High temperature glass creeps during its motion. The shape of deformed glass depends on the velocity-time distribution of the glass. Oscillation and velocity changes affect deformations. Also the roller distance influences on deformations. They are not much affected by quenching. When symmetrical, quenching has not much influence on the shape of frozen glass. In general, quenching starts in different places as glass goes forward. This may have some slight affect on deformations. A bow shape can form with asymmetric quenching.

Numerical modeling can be used in seeking to understand the behavior of glass deformations. Deformations of tempered glass can be measured, but what happens during the motion of the glass and because of temperature cannot be measured. There numerical modeling provides good assistance. In numerical solution there are also difficulties due to rollers. When the edge of glass rises with the roller or drops from it, there is a discontinuity of the edge displacement.

Although there exist a theory of viscoelastic behavior of glass, values of material properties and other parameters are hard to measure. Consequently, only the influence of modeling parameters on the results can be determined.

Figure 10

Glass deformation of stationary plate on rollers. Adjustment of graph in Fig. 9, showing deformations between supports.

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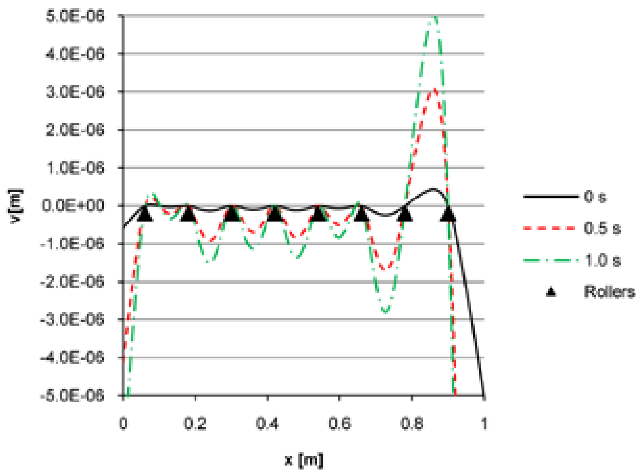


Figure 11

Elastic deformations (time 0 s) and deformations of glass in motion after 6 s.

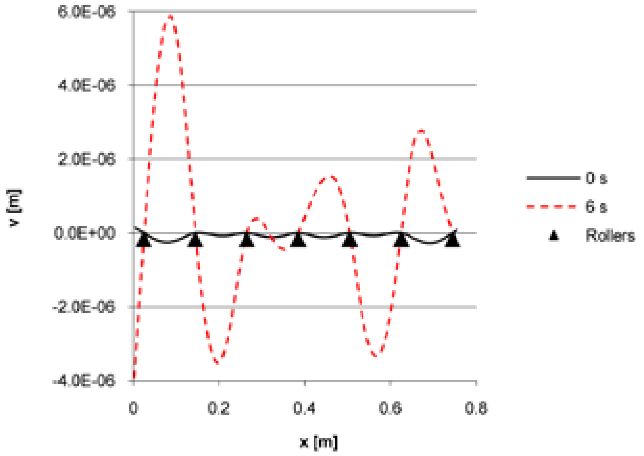
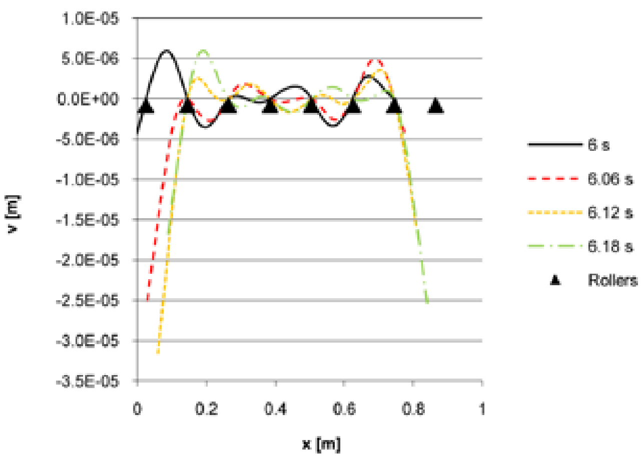


Figure 12

Glass deformations over one roller gap.



Acknowledgements

The authors wish to thank the Glaston R&D unit for discussions and images. Thanks are also expressed to CSC (IT Center for Science Ltd) for the possibility to use the ANSYS program in the research.

References

[1] Daudeville L., Carré H. Thermal Tempering Simulation of Glass Plates: Inner and Edge Residual Stresses, Journal of Thermal Stresses, 21, 1998, pp. 667-689.

[2] Narayanaswamy, O. S., Stress and Structural Relaxation in Tempering Glass, Journal of the American Ceramic Society, 61: 3-4, 1978, pp. 146-152.

[3] Gardon. R. The Tempering of Flat Glass by Forced Convection, Proceedings VIIth International Congress on Glass, Bryssel, Belgium, 1965.

[4] Aronen, A., Karvinen, R. How to Affect Residual Stresses in Glass Tempering, Bos, F. et al. (eds.). Challenging Glass, Conference on Architectural and Structural Applications of Glass, May 2008, Delft University of Technology, the Netherlands, pp. 303-312.

[5] Abbott M., Madocks J., Roller Wave Distortion - Definition, Causes and a Novel Approach to Accurate, On-line Measurement. Glass Processing Days Proceedings. 18-21 June 2001, Tampere, Finland, pp. 226-230.
[6] Karvinen, R., Rantala, M., Pesonen, T., Heat Transfer in Glass Tempering and Forming Process, Advanced in Heat Transfer Engineering, ed. by B. Sunden and J. Vilemas, 4th Baltic Heat Transfer Conference 2003, pp. 217-225.
[7] Rantala, M., Karvinen, R., Heat Transfer Under an Impinging Jet at Long Nozzle-to-Surface Distances, Proceedings of 13th International Heat Transfer Conference, August 2006, Sydney Australia, 12 p.
[8] Jalkanen, E., The High Performance Low-E Tempering Process, Proceedings of Glass Performance Days 2007, June 2007, Tampere, Finland, pp. 675-678.
[9] Ottosen, N.S., Ristinmaa, M., The Mechanics of Constitutive Modeling, Elsevier, Amsterdam, 2005.
[10] Scherer, G. Relaxation in Glass and Composites, John Wiley & Sons, Inc., USA, 1986.
[11] Boley, B., Weiner, J., Theory of Thermal Stresses, Dover, Mineola (NY), 1997.