MODELLING OF THE PRESSING PROCESS IN GLASS STEMWARE PRODUCTION: STRESS IN GLASS

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Critical stresses in glass created during and after pressing process are one of the concepts explaining glass damage in stemware production. Applicability of stress calculation in glass is investigated in real production process simulation with two main objectives: (i) to find critical product locations with high tensile stresses and (ii) to correlate them with responsible process steps. Simple thermo-elastic glass model without relaxation was adopted in a finite element method (FEM) computation on a 16-position carrousel system. Process simulation was finished before the product achieved annealing lehr. High tensile stresses were identified on the product bottom edge, where the glass touches the transport belt or the neighbouring product. This finding was in a very good correlation with observed defect called "cracked bottom" starting on the bottom edge already before entering annealing process. The presented modelling approach can be used for heat transfer optimisation during pressing and post pressing processes on the carrousel.

INTRODUCTION

Machine glass forming process generally requires fast cooling in order to apply high production speed to maintain low cost production. This may result in high stress values. They may become dangerous even if critical stress value in tension is not achieved [1]. A crack can be created or propagated if glass with tensile stress would come into a direct contact with a rough surface of a forming or transport tool. Glass may break already before annealing lehr. Stress measurement distinguishing between tensile and compressive stress is very problematic especially for complicated glass shapes.

Two important actions are available in order to minimise glass breakage, such as (i) modification of a product or forming tool design or (ii) optimisation of forming process with respect to heat transfer phenomena. Semi-empirical methods seems not to be anymore effective to neither of those two options [2]. Numerical methods were applied several times in order to optimise the forming process. The complexity of such calculations results in high demands on know- how and computation time. Those consequences are still at present becoming a limiting aspect of a wide spread of modelling of forming in industry. Two basic criterions are available in glass defect prediction by modelling: (i) thermal stress calculation [3] (ii) and critical deformation rates [4, 5]. Residual stress results from the combined effect of transient thermal stresses during cooling and its relaxation in the glass transition region [6]. If a distribution function of relaxation time is available, stress relaxation can be calculated. Naraynaswamy model of structural relaxation [7] or Masurin´s Relaxation Theory of Glass Transition model (RTGT) [6] are usually used in order to model relaxation phenomena.

A simple thermo-elastic glass model combined with Instant Freezing Theory (IFT) approach without structural relaxation is tested in this work in order to determine critical regions of the pressed product on a 16 position carrousel system with respect to high tensile stresses. While the previous paper [8] was focusing on model verification with experimental temperature measurements and stress calculation in the mould, this paper is focusing on glass behaviour.

MODEL

Pressing process modelling covers rather complicated glass-metal contact problem. Combination of heat transfer and deformation phenomena has to be applied in a non-stationary mode. A commercial finite element code was used to simulate the coupled thermal-deformation analysis of this contact problem.

Process description

Stem pressing process simulated in this study was performed on 16 position carrousel machine at speed of 24 products per minute. It corresponds to a residence time of 2.5 s at each position. Stem pressing and stem post-pressing follow after gob loading. Stem bottom edge melting by hydrogen burner is reserved for position 4. Three positions needed for stem bottom forced air cooling follow after stem bottom alignment by mechanical press. Stem is then taken out from carrousel. Glass was then regarded for modelling purposes as being cooled down in the surrounding air for 20 seconds, till it would achieve annealing lehr. In order to achieve numerical steady - state conditions, 8 working cycles had to be computed. Therefore all the presented results are related to the 8th process cycle. It started in time of 280 and finished in time of 320 s. The glass was taken out from the carrousel in time of 300 s. Figure 1 shows global view of the modelled setup with all forming tools and the glass. Axial axis of the stem was taken as the axis of symmetry.

Mould model

The moulds and plunger (Figure 1) were made of steel with specification ZF-2-X15CrNiSi25-20 (DIN 1.2782) and X23CrNi 17 (DIN 1.2787), respectively. The mould holder material was grey cast iron type 422305. Detailed information on mould modelling was provided in [8].

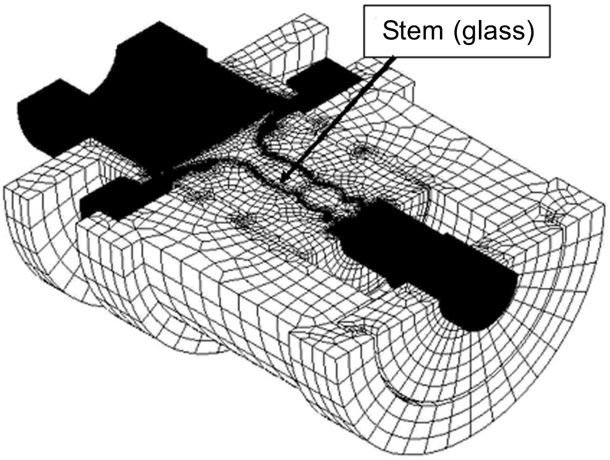


Figure 1. Half cut of a set of all forming tools and glass corresponding to the pressing step. Stem length has a value of 84 mm.

Governing equations

In order to simplify the calculation, the mould in this paper was modelled as filled with glass from the beginning [3]. Therefore no large deformations were present and fluid dynamic phenomena were neglected. If Cauchy stress tensor [9], $\boldsymbol{\sigma}$, is defined as

$$\boldsymbol{\sigma} = -P\mathbf{I} + \mathbf{T} \tag{1}$$

where P is pressure, $\mathbf{I}$ is the unit tensor, and $\mathbf{T}$ is extra stress tensor, then the equation of mechanical equilibrium [10-11] (conservation of momentum flow) can be expressed as following

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = 0 \tag{2}$$

where $\mathbf{b}$ is body force vector.

Conservation of energy is the next equation to be solved

$$c_p \rho \frac{\partial T}{\partial \tau} = \lambda \nabla^2 T \tag{3}$$

where T is temperature, τ is time, λ is thermal conductivity, c_p is specific heat capacity, ρ is glass density. The constitutive equation is needed for stress tensor in order to close the set of Equations (2-3):

$$\varepsilon = \mathbf{D}^{-1} \cdot \boldsymbol{\sigma} + a\Delta T \tag{4}$$

where ε is deformation strain vector, $\mathbf{D}$ is stiffness matrix, α is the coefficient of thermal expansion.

The model is based on solid mechanics theory where material deformations and stresses were the main results. However, in order to cope with glass transformation, Instant Freezing Theory (IFT) approach was adopted [6, 12]. IFT considers the transformation range of glass as a single solidification temperature. This simplification creates discontinuity in the material behaviour at transformation temperature. Glass above T_G is treated as a stress free fluid (relieved in seconds). Glass below T_G is understood as an elastic structure without any stress relaxation. Because of the presented material discontinuity only stresses below T_G value were exploited.

Measured coefficient of thermal expansion had a value of 113×10^{-7} K^{-1} in temperature range 20-300°C. Both the temperature dependent thermal conductivity, λ, and specific heat capacity, c_p, for soda lime glass in range between 20 and 1200°C (including radiation) were adopted from literature [1]. Glass density was 2554 kg/m^3 and experimentally determined T_g had value of 524°C.

Initial and Boundary conditions

Initial gob temperature was 1061°C. This value corresponded to a temperature measured by thermocouple just before glass leaves the platinum pipe of the feeder. Fourier type of boundary conditions was employed according to scheme of the modelled set-up presented in detail in previous paper [8]. Therefore effective heat transfer coefficients, α in W/m^2 K were adopted together with surrounding temperatures. Non-ideal thermal contact was supposed for metal–metal interface between working tools. Glass-metal interface was characterised by time dependent heat transfer coefficient [13].

RESULTS AND DISCUSSION

Figure 2 shows temperature distribution in a stem 20 seconds after taking glass out from the carrousel (process time of 320 s). Rather high temperatures are still present in the locations with big mass of glass. The surface temperatures are generally in a range of 400-500°C. The only exception is the bottom edge with values about 200°C (top left in Figure 2). It is obvious that the bottom edge cools down much faster as the other parts of the glass semi-product. The mentioned location can be expected to be a critical one with respect to possible thermally induced stresses.

Calculation of stress profile in glass bottom

Taking into account Instant Freezing Theory approach, only locations with temperature values below T_g (525°C) were used for stress calculation. Figure 2 shows that the relevant part of the product fulfilling the given temperature condition is represented by stem bottom, except of its centre. The edge of the bottom cools down below T_g several seconds after the end of the pressing moment (τ = 285 s). Therefore only stem bottom stress calculation will be presented in this paper.

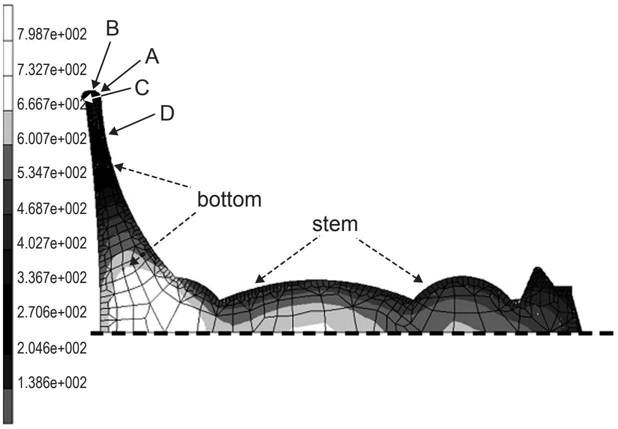


Figure 2. Axi-symmetric view of a temperature distribution in a glass stem in a process time of 320 s. Dashed line represents axis of symmetry. Stem length has a value of 84 mm.

Figure 3 depicts calculated values of tangential stress in glass bottom for a process time of 287 seconds. It corresponds to the moment just after pressing step, when the top side of glass bottom is still in full contact with a mould. Because of high temperatures, only a region in the distance of about 3 cm from the bottom tip was of interest for our stress calculation. From a practical point of view mostly tensile stresses (positive values in Figures 3 and 4) are regarded as a critical factor in glass technology. The reason is that glass breaks easily in tension, while the same glass is very stable in compression (negative values in Figures 3 and 4). The bottom tip of the stem is the critical position where tensile stress occurred (Figure 3) in this early stage of process. Unfortunately, this is the position where the glass bottom comes into a full contact later on its transport way to the blowing machine or to the annealing lehr either with the conveyor belt or whatever other part of the equipment. High tensile stress gives a chance for a micro-crack occurrence already on a carrousel. This can be very dangerous later on with respect to possible crack propagation. Calculated tangential stresses had one order higher magnitude as the radial ones with same profile.

Development of tensile stresses can be seen easily in Figure 4. This situation corresponds to process time of 320 seconds (20 seconds after glass leaves the carrousel). According to calculation the area of the tensile tangential stress increased significantly. Tensile stress was identified on both surfaces of the bottom. The cal-

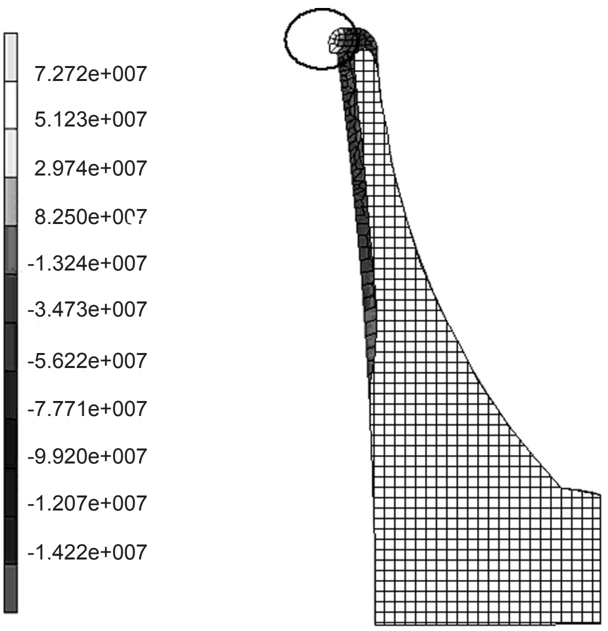


Figure 3. Axi-symmetric view of calculated values of tangential stress in the glass bottom just after pressing (τ = 287 s). Circles depict areas with tensile stress. The checky pattern represents area where no stress was calculated because temperature was lower than T_g.

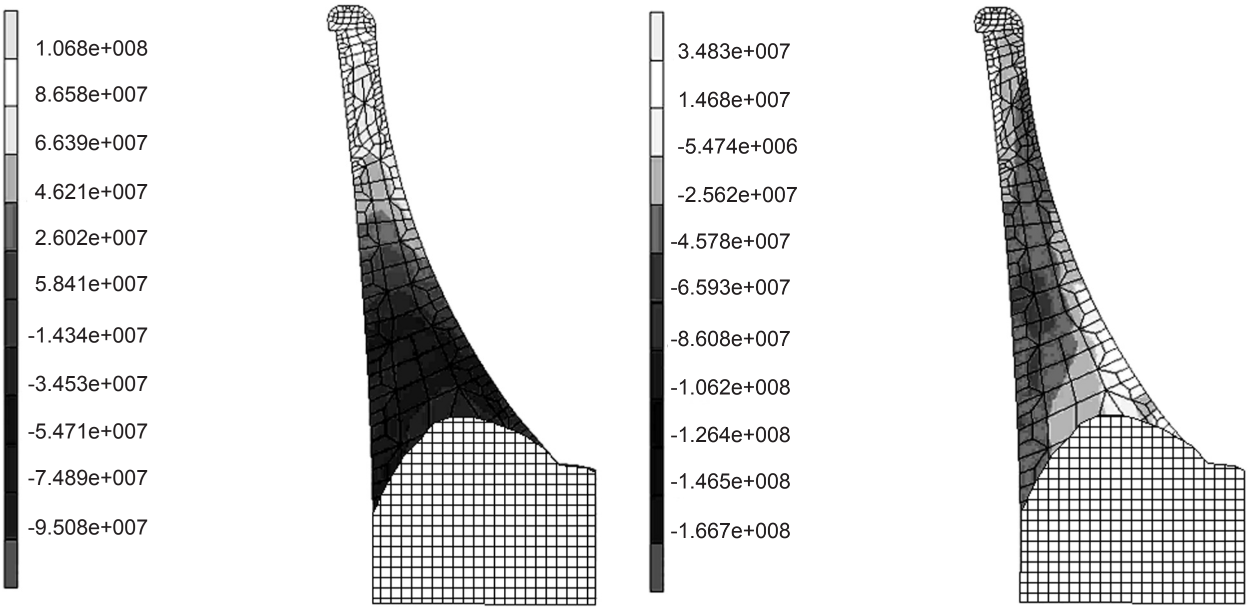
culated radial tensile stress has about one magnitude lower values again (Figure 4b). However, new critical position with tensile stress were identified by calculation at the top of the bottom closer to the stem. This position is of interest from two points of view: (i) it is in a direct contact with a specific sliding system just after glass taking out from carrousel and (ii) the shear mark is in a very close neighbourhood. Both these facts enhance a chance for a crack formation. The tensile stresses in the mentioned part of the bottom were computed only in the later stages of process in order to fulfil Instant Freezing Theory constraints ($T < T_g$). Computation with full visco-elastic model is necessary to verify this location as critical.

Stress time-course calculation in glass during working cycle

The coldest part of the pressed product during process is the edge of the bottom (Figure 2). It gives a good chance to exploit the simplicity of the Instant Freezing Theory approach, which accepts stress only below T_g. Change of calculated stresses in the neighbourhood of the glass bottom tip can be followed during process with a clear objective: to find process steps where high stresses may become dangerous.

Figures 5 and 6 show the computed results for four chosen nodal points signed as A, B, C and D. Their position is depicted in Figure 2. Temperature time course in all four chosen locations shows a non-monotonous profile. Such a profile was not observed in the calculated glass surface of the stem presented in previous paper [8]. It is caused by the fact that the plunger was pulled up after pressing step (τ = 285 s) and the rim bottom was remelted by powerful hydrogen burner (τ = 287-289 s). A presence of forced air cooling focused on the bottom (τ = 292.5-300 s) contributed also to decrease of temperature as it is seen at nodal points A, B and C. Glass heating up after product take out from the mould (τ = 303 s) is caused by the fact that the metal mould as a good heat conductor on the top side of the bottom was replaced by air (insulator). Figure 5 shows that temperature values of nodal points A, B and C are below T_g after pressing step. Therefore they fulfil basic assumption of Instant Freezing Theory for stress calculation in glass. Temperature behaviour of glass on the top of the bottom (nodal points D) allows us to apply stress calculation only for the later period of working cycle.

Figure 6 shows calculated values of tangential stress. Tensile stresses have positive values. The stress values increase in nodal points A, B and C during cooling periods. This trend is interrupted by bottom rim melting using powerful hydrogen burner (τ = 287-289 s). The further stress increase between 290 and 300 s of process time corresponds to situation when bottom is being cooled down by external air cooling (see chapter Process description). After product take out (τ = 300 s) the tensile stress is decreasing. It reflects a short temperature increase caused by internal re-heating of the surface by releasing glass-mould contact (Figure 5). However, rather high value of tensile stress is still present in



a) b)

Figure 4. Axi-symmetric view of calculated values of tangential (a) and radial (b) stress in the glass bottom 20 s after product left carrousel (τ = 320 s). The checky pattern represents area where no stress was calculated because temperature was lower than T_g.

this process phase. It corresponds to the moment of a transport of glass for example on the conveyor belt. Points A, B and C represent the edge bottom of the stem, which is in a direct contact with conveyor material during transport. Figures 3 and 4a showed that this location is the most sensitive in this product.

The other location represented by nodal point D (Figure 2) was also taken into consideration. Its temperature time course (Figure 5) allowed us to apply the stress calculation only for periods later as 298 s. It is obvious (Figure 6) that point D gets into tangential tension. That means that this location is still regarded as risky for crack creation and propagation in the later stages of the stem transport. Such an analysis is very useful in case of optimising glass product transport into annealing lehr. The critical glass product positions have to be prevented from a direct contact with other material.

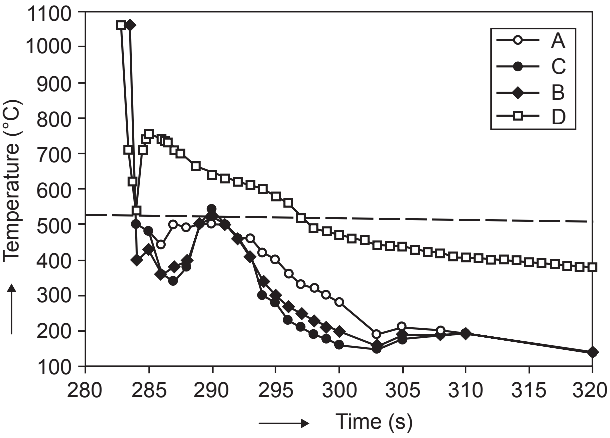


Figure 5. Calculated temperature during pressing cycle in glass for different nodal points in the bottom of stem (see Figure 2). Dashed line represent T_g value of glass.

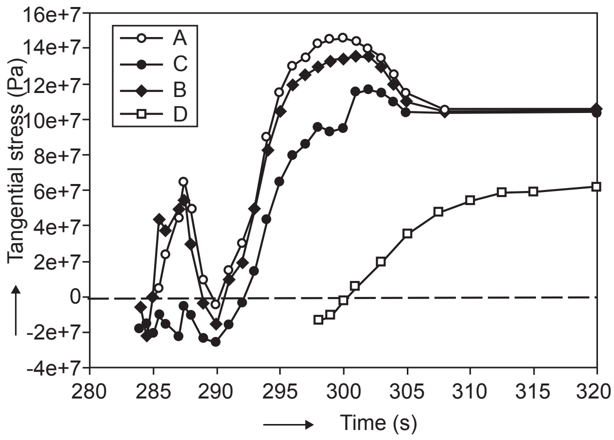


Figure 6. Calculated tangential stress during pressing cycle in glass for different nodal points in the bottom of stem (see Figure 2). Positive and negative values represent tensile and compressive stress, respectively.

It is obvious that at least two critical aspects of the pressing production could be identified in the presented approach: (i) critical location of the glass product (the edge of the stem bottom in Figure 3) and also (ii) critical process steps (direct cooling down of the bottom by external air cooling and transport of glass on conveyor belt). The last mentioned situations create or propagate micro-cracks in a direct contact with foreign surface. The calculation pointed out that contact area of a stem standing on the conveyor belt is under tensile stress, which is very dangerous for glass breakage till the products achieves annealing lehr. The authors are aware of the fact that tensile stress is not the only cause of crack formation. Concept of critical deformation rates might be also very helpful [2, 4].

Crack observation in production

Rather simple stress calculation approach was applied without considering structural relaxation. Therefore no quantitative links were made to critical stress values causing glass breakage. In spite of that fact critical locations of the tensile stress were identified. They do not have to create crack visible on the line, but they may initiate micro-cracks which are propagated between carrousel and annealing lehr if the glass is in contact with foreign sharp surface. Cracked bottom is one of the most common defects in stemware production (Figure 7). It is usually observed before or after annea-ling lehr. The crack analysis proves that this type of the crack originated on the tip of the bottom edge. This is in a very good accordance with a critical location proposed by tensile stress calculation (Figures 3 and 4a). For other types of cracked bottom defects annealing process simulation is necessary together with more sofisticated glass model including structural relaxation.

Figure 7. Detail of a real stem bottom from production with a radial crack (in a white circle)

CONCLUSIONS

Glass model based on solid mechanics theory without structural relaxation was applied in order to identify the most critical areas of the stem in stemware product with respect to high tensile stresses: the edge of the stem bottom. The stress generation is closely related to two critical process steps - intensive bottom air cooling and transport of stem on conveyor belt. Critical location corresponds very well with real occurrence of cracks in production. This type of modelling can be regarded as a useful tool for process understanding and process optimisation in order to prevent glass damage during forming and before annealing.

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MODELOVANIE PROCESU LISOVANIA PRI VÝROBE ÚŽITKOVÉHO SKLA: NAPÄTIE V SKLE

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Vznik kritického napätia počas a po procese lisovania je jeden zo spôsobov vysvetľujúcich poškodenie lisovaného skleného výrobku. Použitie výpočtu kritických napätí sa vyšetrovalo v reálnom výrobnom procese s dvoma hlavnými cieľmi: (i) určiť kritické miesta výrobku s najväčším ťahovým napätím a (ii) nájsť ich koreláciu s odpovedajúcimi časťami procesu. Bol použitý jednoduchý termo-elastický model skla bez relaxácie v MKP výpočte pre 16-pozičný karuselový systém. Simulácia procesu bola ukončená predtým, ako bol výrobok ochladený v tunelovej chladiacej peci. Vysoké ťahové napätia boli zistené na spodnej hrane výrobku, ktorá sa dotýka dopravného pásu a susedných výrobkov. Toto zistenie bolo vo veľmi dobrej zhode s bežne pozorovaným defektom nazývaným „prasknuté dno", ktoré sa začínalo práve na spodnej hrane výrobku už pred vstupom do chladiacej pece. Tento spôsob modelovania sa ukázal ako výhodný pre optimalizáciu prestupu tepla počas a po lisovaní skla v reálnom výrobnom zariadení.