Optimisation of Glass Pressing Cycle in Pre-manufacture Stage

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Introduction

Contemporary trends in automatic production of pressed glass are characterised by orientation towards products with non-traditional shapes and sizes. The introduction of this non-standard assortment into manufacture process is related to a considerable growth of demands for the forming process. The claims on ensuring high quality of manufactured products considerably rise with increasing complexity of product to be formed. In order to achieve high production quality as well as to improve efficiency of the glass forming, the comprehensive optimisation of the whole glass forming cycle is necessary even in pre-manufacturing stage.

In the contribution the approach to the identification of the source of technological problems as well as to subsequent optimisation of the whole glass pressing cycle based on computational analysis is introduced. In the conclusion concept of controlled cooling is mentioned.

Numerical model

The glass forming process is a complex thermo-mechanical problem with the strong interaction between glass heat transfer and viscous flow of molten glass. Therefore numerical modelling of glass forming involves a coupled non-linear solution of heat and mass transfer. The equations of mechanical and thermal equilibrium in a set of Lagrangian coordinates are:

$$\rho \frac{dv_i}{d\tau} = X_i + \frac{\partial \sigma_{ij}}{\partial x_j}, \quad (1)$$

$$\rho \cdot c \cdot \frac{\partial T}{\partial \tau} = div(\lambda \cdot gradT) - 3K\alpha \Delta T \dot{\varepsilon}_{kk} - s\dot{\sigma}'_{ij}\dot{\varepsilon}_{ij}, \quad (2)$$

where X is the body force, σ is the Cauchy stress tensor, $\dot{\sigma}'$ is the time derivative of deviator stress tensor, T is temperature, k is thermal conductivity, c is the specific heat, K is the bulk elastic modulus, α is the coefficient of thermal expansion, $\dot{\varepsilon}$ is the strain rate tensor, s is the fraction of viscous work converted into heat.

The molten glass in the forming range can be considered to be incompressible, thus the incompressibility condition ($\dot{\varepsilon}_{ii} = 0$) has to be satisfied. The viscous stresses are related to the rate of deformation through generalised non-Newtonian flow model:

$$\sigma'_{ij} = 2\eta(T,\dot{\varepsilon})\dot{\varepsilon}_{ij}, \tag{3}$$

Viscosity of glass melt η is not highly dependent only on temperature according to well known Fulcher equation [1] but, when loads exceed critical limit, also on shear rates. The dependence of the true viscosity η_0 on shear component of strain rate $\dot{\varepsilon}_s$ can be expressed by Simmons-Montrose equation [2]:

$$\eta = \frac{\eta_0}{1 + \dot{\varepsilon}_s \eta_0 / \sigma_{lim}} \tag{4}$$

The real cycle of melted glass pressing is influenced by a whole series of factors, such as glass composition, used machinery, technological parameters, forming tools, etc. To get acceptable results, the simulation model must be able to address all these aspects. Special attention must be paid to a specification of material properties of individual components of the thermo-mechanical system including their temperature dependences as well as to a definition of the adequate courses of boundary conditions.

With respect to the complexity of the glass forming tools, the numerical model must contain a whole system of forming tools including their connections with a concrete machinery.

Numerical simulation of real glass forming cycle

In the Fig. 1 high slender hollow product (10" vase made of lead crystal) - typical representative of products start of their manufacture is often problematic, is shown. This thick-walled pressing of weight 1,9 kg is pressed on the 12–position turntable machines. Glass mould is made of steel X12Cr25Ni20, water cooled plunger of steel ANSI 430, and bottom and ring from grey cast iron. The basic parameters of glass forming cycle were derived from economical demands: total forming cycle time 156s; time from feeding to taking out 88 s, total pressing time 10,5 s; dwell between a moment of the drop of glass melt into the mould and moment of onset of pressing 3,2 s; glass gob temperature 1050°C; velocity of the movement of plunger during pressing 0,05 ms^{-1}.

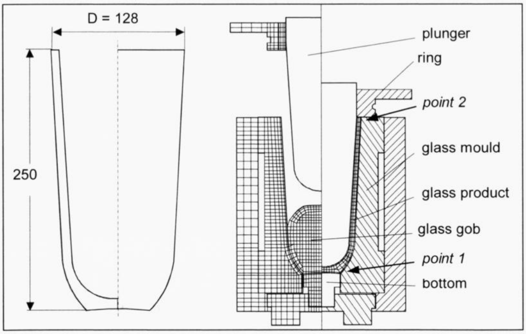

Figure 1. Glass product and simplified FEM model

The boundary conditions were chosen so as to correspond to measurements being taken for the assortment already produced on specified machinery. Critical points of numerical simulation are specification of the contact heat transfer coefficient (used time dependence in according with [3]) and definition of friction conditions in the interface bettwen glass and mould (used stick-slip model with overshoot parameter α=1,1).

Results of virtual analysis of initial glass forming cycle (primary design) give a series of important information about the forming cycle course. Shear components of Cauchy stress and normalised deformation rates (normalised with regard to critical deformation rates for onset of non – Newtonian flow) in formed glass melt, initiated by plunger movement, increase gradually during pressing (Fig. 2). Supposing the static friction coefficient is μ=0,5 peak values of shear stresses in the final stage of pressing exceed aprox. 50 MPa. Due to high dependence on friction conditions and used numerical model it is difficult to assess actual values, therefore graph in Figure 2 is expressed in the form of normalised shear stresses (with regard to maximum value of shear stress). Peaks of shear stresses moves downwards along the outside surface of pressed melt together with the plunger movement

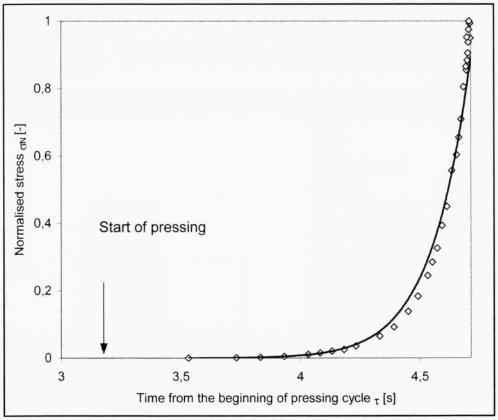

Figure 2. Development of peaks of shear stress during glass pressing

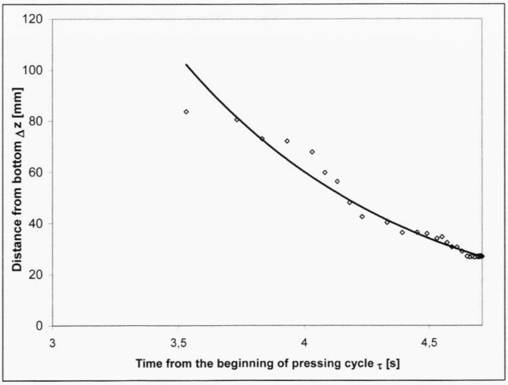

Figure 3. Change of position of peaks o shear stresses during pressing

(Fig. 3). In the final stage the peak of shear stress can be found on the outside surface of pressed product approx. 25mm above its bottom.

Weak point of analysed glass forming cycle is a distribution of temperature fields in glass mould. Differences between maximum and minimum values of temperatures along working surface of glass mould at the moment of feeding exceed approx. 140°C (Fig. 4, 7). Therefore this glass pressing cycle is relatively problematic from technological point of view because it requires high level of parameter stabilisation. Small deviation from optimum state can result in serious technological problems (checks initiation when low part of mould is too coold and glass sticking when central part of glass exceeds sticking temperature).

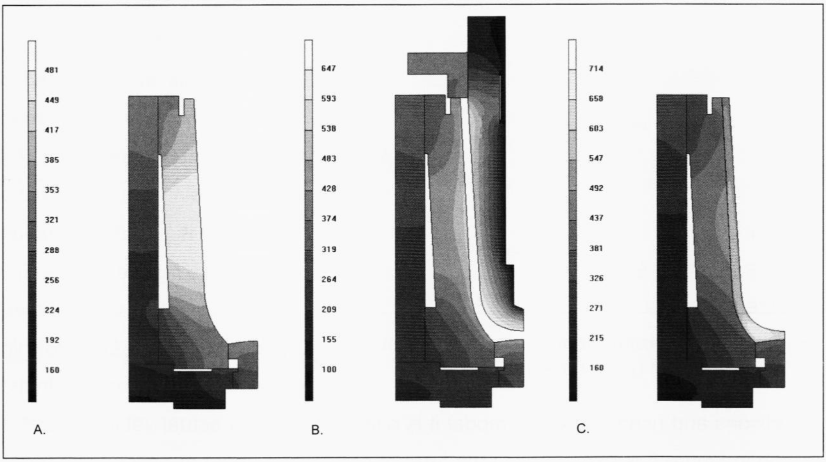

Figure 4. Distribution of temperature fields in the system forming tools – glass melt initial state
a. moment of glass feeding; b. final stage of glass pressing; c. taking out

Optimisation of the glass forming process

As mentioned above small variations in glass composition, gob temperature, the cooling situation and other factors can affect both the course of glass forming cycle and products quality dramatically. Because no process is entirely free from variation and it is not possible to stabilise all parameters of forming process attention has to be pay to some decisive aspects and stabilise them by only a few parametrs.

Technological problems in the automatic production of pressed glass are very often caused by uneven distribution of temperature fields in forming tools. As it was shown above marked inhomogenities in distribution of temperature fields along vertical axis in glass mould are characteristic especially for forming high slender hollow products and products with complicated shapes. Therefore the optimisation process of pressing cycle is usually oriented to modifcation of glass forming tools desing and cooling.

On the basis of practical experience, a methodology for the optimisation of the forming cycle course was developed (Fig. 5) coming from the detailed analysis of the pressing cycle course and the sensitivity analysis of basic factors influencing glass forming.

The starting point of the whole optimisation cycle is the analysis of development of deformation, stress and temperature fields in glass melt, i.e. the identification and localization of possible technological problems connected with the subsequent optimisation of technological parameters. In the subsequent step of optimisation process attention is focused on the forming tools design and cooling. An initial design of forming tools comes from the analysis of the basic tendencies of development of temperature fields. This analysis is the starting point for the optimisation of forming tools [4]. With respect to the quasi-stationary character of the temperature fields in glass forming tools, it is difficult to determine optimisation criteria allowing effective evaluation of the distribution of temperature fields in the course of the whole forming cycle. An effective solution is a time discretisation of the forming cycle, which allows focusing on two – from the technological point of view – the most important time intervals: melted glass feeding and pressing. In this case, optimisation criteria mean a minimisation both of temperature peaks and temperature differences along the working surface of glass forming tools. Optimised technological parameters and a theoretical proposal of forming tool design and cooling are the results of such optimisation process.

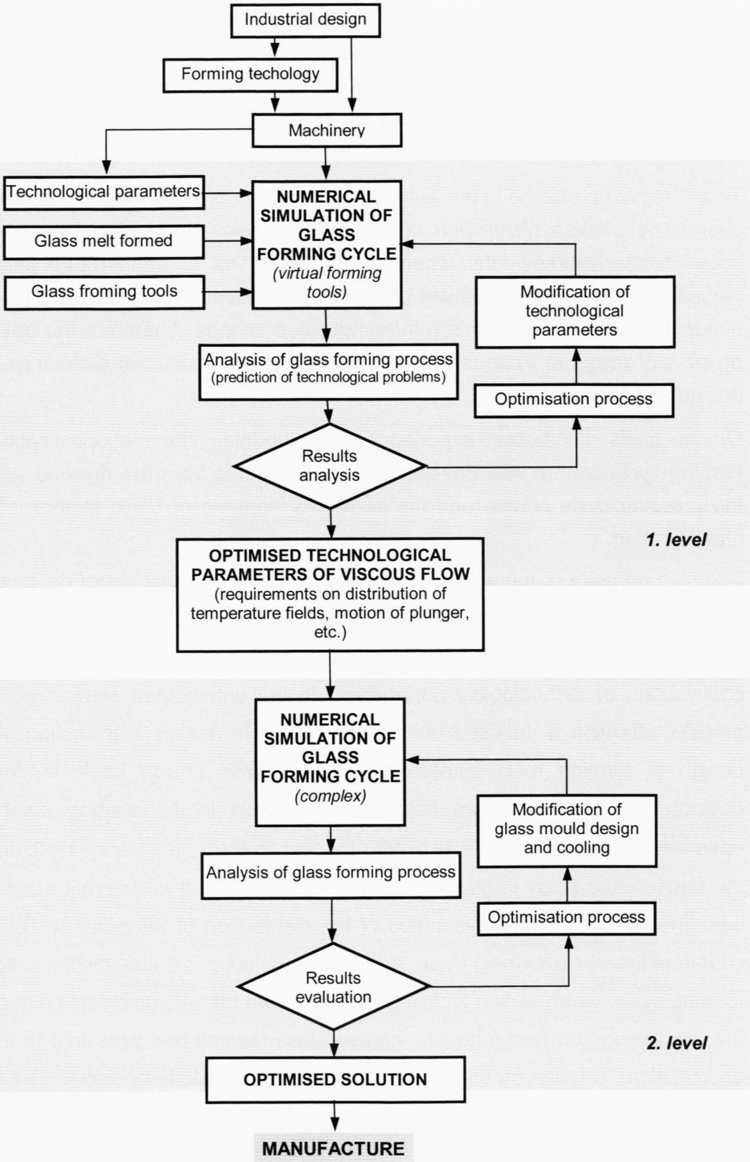

Figure 5. Two level optimisation scheme

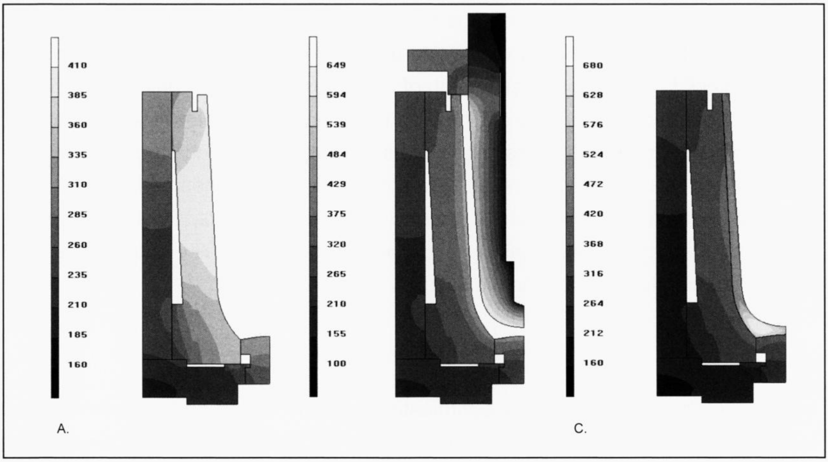

Figure 6. Distribution of temperature fields in the system forming tools – glass melt optimised solution
a. moment of glass feeding; b. final stage of glass pressing; c. taking out

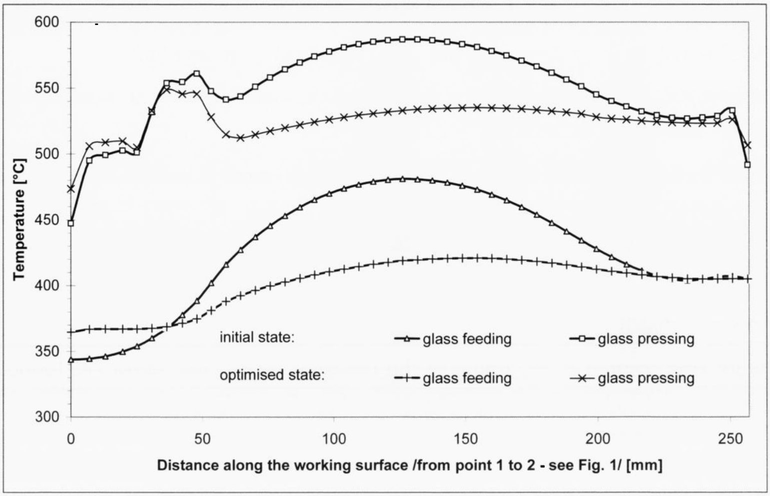

Figure 7. Distribtion of temperatures along working surface of the mould (initial and and optimized state)

From the practical point of view, the most important part of the optimisation process is a proposal of concrete technological or design modifications. The effective way of modification of glass mould design is the approach based on global modification of temperature fields that allows controlling temperature field distribution in the whole body of glass forming tool. Such design of forming tools ensures reliable functions of forming tools and high quality of products manufactured in relatively wide range of technological parameters. Possibilities of use of the optimisation strategy are shown in Fig. 6 and 7. In this concrete case the practical realisation has been based on the simplest method – application of thermo-exhange elements. Besides significant improving stability of glass forming cycle and production quality optimised solution allows reducing total cycle time significantly.

Conclusion

In the contribution the complex optimisation strategy based on the optimisation of technological parameters of the forming cycle as well as on the optimisation of design and cooling of forming tools is suggested. The optimisation approach, based on global modification of temperature fields is shown.

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