Abstract

The claims on ensuring high quality of manufactured products and improving efficiency of the glass forming can be ensured by conventional methods of the forming cycle proposal already. The effective approach to the identification of weak points of glass forming cycle itself and its subsequent optimisation already in pre-manufacture stage is an application of tools of virtual modelling. Computer model enables monitoring of individual stages of the whole glass forming cycle and its application already in pre-manufacture stage allows reducing physical prototyping, the rate of product rejects and material waste as well as accelerating cost-effective product development.

In the paper the approach to the prediction, localisation and identification of potential technological problems is shown. Used methodology is based on the general concept of virtual modelling of glass forming cycle. The computational analysis is based on fully coupled thermo-mechanical strategy. Constitutive behaviour of glass melt is described through generalised non-Newtonian viscous model. Close attention is paid to reliability of acquired outputs and to the problem of prediction of technological defects already in pre-manufacture stage. Therefore, based on the analysis of defects and technological problems typical for manufacturing pressed assortment, criteria allowing their identification and localization are suggested.

In the contribution the process of optimisation of glass forming cycle is presented. Attention is aimed mainly to the problem of effective modification of temperature fields' distribution in glass forming tools. Due to the complexity of solved problem (quasi-stationary character of temperature fields in glass forming tools) determination of optimization criteria is not simple. Therefore time discretisation of the forming cycle, which allows focusing on two, from the technological point of view, the most important time intervals: molten glass feeding and pressing, has been used. In the conclusion new concept of controlled cooling of glass moulds is shown.

Keywords: Glass, forming, moulds, numerical simulation, FEM.

1. Introduction

Knowledge of melting and molten glass processing is one of the oldest well-known processes of manufacture, notwithstanding the glass making is based especially on trial and error and empiric methods up to now.

Particularly the forming process is the source of problems continually; it influences the effectiveness of the whole manufacture process as well as quality of final products on principle. Glass forming itself is the complex technological process, the goal of which is to obtain solid products with required shapes. Although there are many technologies using in the manufacture of glass, the physical basis all of them is
similar – required shape can be obtained when an external load applies to glass gobs with relatively low viscosity. Then the shapes created are fixed due to viscosity increasing during the annealing process.

Contemporary trends in automatic production of domestic glassware are characterised with orientation towards products with non-traditional shapes and sizes. The introduction of this non-standard assortment into the 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 optimization of the whole glass forming cycle is necessary even in pre-manufacturing stage.

Conventional methods of the forming cycle proposal allow neither effective evaluation of individual influences, which affect the course of the forming cycle, and their interactions, and consequently nor effective optimization of the course of the forming cycle. The effective method for monitoring individual stages of glass forming cycle and subsequent optimization is to use of comprehensive tools of virtual simulation.

2. Real glass forming cycle

Pressing is one of the techniques based on glass melt forming using forming tools for transformation of a glass gob into a required shape. Real glass pressing cycle is a complex and relatively sophisticated technological process comprising individual, mutually separated stages (feeding, forming, annealing) that are repeated cyclically (Fig. 1).

![Fig. 1: Individual stages of glass pressing cycle.](a) Feeding, (b) Pressing, (c) Glass cooling, (d) Mould cooling.

The forming cycle starts by feeding glass melt to the working cavity of a glass mould. After contact with the mould-working surface, the glass gob is deformed by its own weight. At the same time, an intensive heat exchange occurs on the interface between the glass melt and mould. It finds expression in considerable viscosity increase in surface layers of the glass gob as well as in temperature rise of the mould-working surface.

Pressing is the predominant operation of the whole forming cycle during which glass melt is submitted to considerable mechanical load, due to which the shape of glass with relatively low viscosity is changed within a very short time. Although this phase of the forming cycle is practically negligible from time point of view, it has
crucial influence on the production quality. In remaining part of the pressing cycle, the glass pressing is cooled in the glass mould, and the mould is prepared for the next forming cycle.

3. 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:

$$\rho \frac{d\mathbf{v}_i}{d\tau} = \mathbf{X}_j + \frac{\partial \mathbf{\sigma}_{ij}}{\partial x_j},$$

$$\rho \cdot c \cdot \frac{\partial T}{\partial \tau} = \text{div}(k \cdot \text{grad}T) - 3K\alpha T \dot{\varepsilon}_{kk} - s\dot{\sigma}_{ij} \dot{\varepsilon}_{ij},$$

where $\mathbf{X}$ is the body force, $\mathbf{v}$ is velocity, $\tau$ is time, $\mathbf{\sigma}$ is the Cauchy stress tensor, $\mathbf{\sigma}'$ 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, $\alpha$ is the coefficient of thermal expansion, $\dot{\varepsilon}$ is the strain rate tensor, $s$ is the fraction of viscous work that is converted into heat.

Glass is actually a viscous-elastic liquid over its whole glass forming range but, in the forming range, the elastic part of the deformation is almost negligible and therefore stress deviator tensor can be related to the viscous strain rate tensor through generalised non-Newtonian flow model:

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

where

$$\mathbf{\sigma}_{ij}' = \mathbf{\sigma}_{ij} + p \delta_{ij},$$

in which $p$ is the hydrostatic pressure, $\eta$ is highly temperature dependent viscosity that in the forming range can be described by Fulcher equation [1]:

$$\log \eta_0(T) = A + \frac{B}{T - T_0},$$

where $A, B, T_0$ are empirical constants.

When critical strain rate is exceeded, viscosity of glass melt is also dependent on the shear strain rate $\dot{\varepsilon}_s$ according to Simmons-Montrose equation [2]:

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

In the forming range the molten glass can be considered to be incompressible, thus the incompressibility condition ($\dot{\varepsilon}_{kk} = 0$) has to be satisfied. The real cycle of glass melt pressing is influenced by a whole series of factors, such as glass composition, used machinery, technological parameters, 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 particular
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
concrete machinery forming tools, etc.

Relatively good agreement between the numerical model and real forming
cycle can be obtained by means of verified inputs and simulations of sequences of
several forming cycles attaining quasi-static temperature balance in virtual forming
tools [3, 4].

4. Approach to prediction of technological problems

In the automatic manufacture of pressed glass, many technological problems
have occurred influencing substantially efficiency of the forming cycle and production
quality. When evaluating the course of temperature and strain fields in the glass melt
being formed and also in forming tools, it can be identified directly by means of the
virtual model:

- underpressing due to an insufficient pressing force of the press,
- glass melt sticking caused by the glass mould local overheating; under
  actual conditions the critical temperature of sticking is defined by the
  empirical relation [5]:

\[
T_S = \frac{A + B}{0.81 \log p + 1.26 \log \tau + 5.47} + T_0 \tag{7}
\]

where \( p \) is pressure, \( \tau \) is time, and \( A, B, T_0 \) are empirical constants (see
eq. 5),

- pressing deformation after its taking out of the mould as a consequence of
  insufficient amount of heat removed from glass melt during the forming
  cycle; for pressed assortment mean viscosity \( \eta = 10^7 \) Pas is usually
  considered to be the critical value.

Because of a limited knowledge of rheological properties of the glass melt
formed and owing to the used computational model, any prediction of defects caused
by bad glass workability is very problematic. In addition to an excessive creation of
chill marks on the surface of formed products, a viscous-elastic response can, under
the critical strain-time conditions, give rise to substantial transient stresses which
could be the source of some defects known as „checks“.

So, for an identification of areas where technological problems caused by the
“bad glass workability” can occur, the methodology was suggested proceeding from
the assumption that the surface quality of formed products is influenced by the local
interactions of temperature and strain rate. Then the level exceeding critical values of
the strain rate expressed in the \( k_M \) (8) coefficient serves as a criterion of defect
occurrences (above \( T_g \)).

\[
k_M = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_c},
\tag{8}
\]

where \( \dot{\varepsilon} \) is actual strain rate and \( \dot{\varepsilon}_c \) is critical strain rate for onset of shear thinning
The area, where the $k_M$ coefficient exceeds the limit value markedly, is critical from the technical point of view. The surface quality of products is always acceptable when $k_M \leq 1$ (glass melt formed has properties of non-Newtonian liquid).

5. Prediction of critical points of real glass forming cycle

In the automatic manufacture of pressed glass, especially the production of nonstandard products is problematic as far as shapes and dimensions. As an example of such assortment, a tall slender pressing (Fig. 2a) made of lead crystal (height – 250mm, weight - 2 kg) pressed using the mould (Fig. 2b) and water cooled plunger at 6-section turntable machine. Glass forming tools are made of steel – X12Cr25Ni20 (mould) respective ANSI 431 (plunger).

A specific problem of forming of this assortment is simultaneous pressing of 6 modifications differing in pattern shapes (“cuts”).

For the numerical modelling, small differences in shapes, given by dissimilarities of particular patterns, were neglected; attention was paid to an evaluation of the time development of basic characteristics of the forming cycle (temperatures, strain, strain rates) in connection with smooth products, i.e. products without “cuts”.

![Fig. 2: (a) Geometrical model of the vase, (b) Glass mould.](image)

In Fig. 3 an evaluation of the strain and strain rate fields during the first forming stage, i.e. between the moment of feeding and start of pressing, is shown. When glass melt falls to the mould working cavity, considerable changes of the glass gob shape occur being in progress ca 0,5s (in the time interval between 0,45 and 1s from the moment of the glass melt feeding). In the following phase – up to the contact with the pressing plunger – deformations of the glass gob are minimal already; strain rate peaks reach overstepping value 100 s$^{-1}$ (true strain rate after dropping) in the course of the whole interval. Maximal drop in temperature of the glass melt having contact with the mould surface attained ca 400°C when the pressing was starting.

The pressing process itself (the first contact between the plunger and glass melt) starts delaying 3 s from the moment of the glass melt feeding. In the course of...
forming, the glass melt is forced into the working cavity which is created by the mould, plunger, and pressing ring. In the same time, owing to the enlarged contact area between the glass melt and forming tools, a process of glass surface cooling has been intensified step by step. That is accompanied by the viscosity increase.

**Fig. 3:** Distribution of strain rates in glass melt in the selected moments during the first stage of forming process:
(a) Time 0.45 s. (b) Time 0.47 s. (c) Time 3.3 s.

**Fig. 4:** Distribution of strain rates in glass melt in selected moments during pressing:
(a) Time 3.7 s. (b) Time 4.2 s. (c) Time 4.65 s.
During pressing, the area of the strain rate maximum is moved along the plunger nose upwards up its direction; maximal value of the strain rate increases gradually (during pressing) and it reaches value ca 25 s\(^{-1}\) (Fig. 4) in the final forming stage. The development of temperature fields at chosen moments of the forming cycle is given in Fig. 5.

![Temperature distributions in glass melt in selected moments during pressing: (a) Time 3.7 s, (b) Time 4.2 s, (c) Time 4.65 s.](image)

**Fig. 5:** Temperature distributions in glass melt in selected moments during pressing: (a) Time 3.7 s, (b) Time 4.2 s, (c) Time 4.65 s.

The criteria given in the chapter 4 were used when the virtual forming cycle was evaluated. On the basis of evaluation of the course of temperature fields and strain rate fields, it can be speaking that:

- **pressing force of the press is sufficient** – in the final phase of pressing, assumed force necessary for pressing mentioned assortment reaches ca 92% of the maximal pressing force of the press,
- during pressing, **the glass melt sticking will not occur** – identified temperature of the mould working surface lies under sticking temperature (ca 560°C); maximal temperature of the mould working surface in the moment of feeding, is approx. 460°C (maximal temperature during the pressing process is ca 546°C) - see Fig. 7-8 (in Fig. 6 distribution of temperatures in glass product in the moment of its taking out are shown – this calculation has been used for virtual model identification),
- when taking out the pressing form the mould, **spontaneous strains**
**will not happen** – assumed mean pressing temperature is approx. 560°C in the moment of its taking out; this temperature corresponds to viscosity of ca. 8.5 Pas which is sufficient for the pressing shape stability,

- based on the analysis of strain rates and temperatures evolution in the contact area of the glass melt and forming tools, **surface defects on lower part of the product external surface** can be assumed, because $k_M$ coefficient in the critical area (external surface limited by the pressing bottom and horizontal plane at a distance of about 70 mm from the pressing bottom) exceeds the limit value considerably (Fig. 9). Localisation of predicted defects on manufactured production is in relatively good accordance with operational experience (see Fig. 10).

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**Fig. 6**: Verification of the virtual model – temperature distribution in the moment of glass product taking out:

(a) Numerical model, (b) Operational measurement (infrared scanner AGA 782, wavelength 5–5.5 µm)
Fig. 7: Distribution of temperature fields in the glass mould:
(a) Time 0 s - glass feeding. (b) Time 5 s glass pressing (moment of pressing up).
(c) Time 88 s – product taking out.

Fig. 8: Distribution of temperature along working surface between point 1 and 2

Cycle time:
- 0 s
- 3.5 s
- 4.5 s
- 12 s
- 88 s

Temperature [°C]

Distance (from point 1 to 2) [mm]
**Fig. 9:** Distribution of coefficient $k_M$ along outer surface of pressing between point 1 and 2 for chosen times

**Fig. 10:** Areas with defects occurrence on outer surface of final production

### 6. Optimisation of glass forming cycle

From the mentioned example, it is obvious that technological problems in the automatic production of pressed glass are also caused by uneven distribution of temperature fields in forming tools. Therefore the optimisation process of the glass pressing cycle results often in modifications of the design and cooling of forming tools.

Based on a practical experience, the complex methodology was formulated optimising the real forming cycle course. The general computational program using
finite-element method (MSC-MARC) is a core of the system being complemented with special subroutines allowing the whole forming cycle to be simulated.

The optimization process itself is based on a two-stage strategy. In the first stage, the basic technological parameters (boundary conditions) are optimized. In the following stage, attention is focused on evaluation and subsequent optimization of forming tools design and cooling.

With respect to the quasi-stationary character of temperature fields in glass forming tools, it is difficult to determine optimization criteria allowing the distribution of temperature fields to be evaluated effectively 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: molten glass feeding and pressing.

A determination of the optimization criteria, which depend on the predicted problem, is the important step of the whole optimization process. Great numbers of optimization standpoints can exist, while some of them can act against each other. Therefore, solving this class of optimization tasks, it is suitable to characterize the optimal state on the basis of minimization of weight functional including different points of view. A reduction of the forming cycle, optimization of heat removal from glass melt and its uniformity, distribution of temperature fields and temperature gradients in glass melt and the mould, distribution and course of strain rates during the pressing process as well as a service life of the glass mould can serve as presupposed optimization criteria. Taking some of these criteria into consideration (amount of removed heat from glass melt during the forming cycle, uniform distribution of temperatures along the working surface of the glass mould, minimization of the working cycle time), it is possible to describe the purpose functional generally as follows [6]:

$$J_s = \mu \cdot \rho \cdot \int \nabla^2 T \cdot dV + \mu_2 \int \nabla T \cdot dV + \mu_3 \tau$$

(9)

where: $\mu$ is weight coefficient, $\rho$ is sensitivity factor

Minimization of the purpose functional $J_s$ is achieved by a modification of computational model parameters. Optimized technological parameters (boundary conditions) and a theoretical proposal of the forming tool design and cooling are the results of the optimization process.

The given optimization process was also used for the design and cooling modifications of above analysed glass moulds. A fundamental problem of the analysed assortment production lies in considerable temperature differences along the mould-working surface when glass melt is fed (lower part of the mould is substantially colder than central part; the differences reach up to ca 130°C, see Fig. 8. These differences influence negatively stability of the whole forming cycle and quality of final production. Based on the initial analysis of the suggested forming cycle course, several alternatives for the modification of the mould design and cooling were prepared. When calculations were carried out, an optimization algorithm was applied (equation 9); the main optimization criterion was to minimize the temperature gradient along the mould working surface when glass melt was fed as well as to minimize the temperature peaks during the forming process.

The optimization process gave data necessary for modifications of the glass mould design. From the practical point of view, the most important part of the
optimization process is a proposal of actual technological or design modifications. The effective way of such modification of the mould design is the approach based on the global modification of temperature fields that allows controlling temperature fields distribution in the whole body of glass forming tools. Such design of forming tools ensures their reliable functioning and high quality of products manufactured in relatively wide range of technological parameters. In this concrete case, the practical realization is based on the simplest method – application of thermo-exchange elements.

Fig. 11: Distribution of temperature fields in the glass mould – optimised solution: (a) Time 0 s - glass feeding. (b) Time 5 s - glass pressing (moment of pressing up). (c) Time 88 s – product taking out.

The distribution of temperature fields in the optimized glass mould in the moment of feeding and in the course of the pressing process is presented in Fig. 11.

It results from the Fig. 12, where the distribution of temperatures along the working surface in the moment of feeding respective pressing is drawn up (in agreement with plot in Fig. 8), that this technical solution allowed substantial reducing maximal temperature differences along the working surface in the moment of glass melt feeding for about 80°C, from ca 130°C at the optimization process beginning up to ca 50°C at the solution realized; maximal temperature was reduced by ca 50°C during the pressing process. As a result of a homogenisation of temperature fields, $k_M$ coefficient value decreased by ca 85% in the critical area. Moderate grow of coefficient $k_M$ can be observed in the central area of formed pressing [8].

Besides significant improving stability of the glass forming cycle and production quality, this optimized solution allows the total cycle time to be reduced significantly (for about 10%).
Fig. 12: Distribution of temperatures along working surface between points 1 and 2

7. Conclusion

In the paper possibilities of use of virtual simulation tools for the monitoring of glass forming cycle are shown.

Possibilities to detect and localize technological problems are demonstrated using the example from technological practice. The optimisation approach, based on global modification of temperature fields, allowing the reliable functions of forming tools working in relatively wide range of technological parameters, is presented.

Results of the numerical simulation were verified in the praxis. Glass moulds of the initial design were the source of technological problems - pressed products had many defects (especially checks) in the product bottom part. On the contrary, outstanding feature of the glass moulds having optimized designs was relatively high production quality.

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Reference


[8] MATOUŠEK, I.: Prediktivní optimalizace v procesu tvorování skloviny, Sklář a keramik, 2006, roč. 56, č. 9, s. 198 – 205. ISSN 0037-637

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