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Study of the glass press molding process

Diplomová práce

Studijní program: N2301 – Mechanical Engineering
Studijní obor: 2302T010 – Machines and Equipment Design

Autor práce: **Selma Kunosic**
Vedoucí práce: doc. Ing. Tomáš Vít, Ph.D.

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Author: **Selma Kunosic**
Supervisor: doc. Ing. Tomáš Vít, Ph.D.

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R u l e s   f o r   e l a b o r a t i o n :

The aim of this thesis is to obtain an accurate material model for glass that can be used in finite element (FE) analysis of the glass molding process. A thorough understanding of the deformation behavior of the glass specimens was acquired by performing uniaxial compression tests. The elasto-viscoplastic model will be utilized for the glass material at the molding temperature to construct the FE model, and a suitable set of parameters for this material model will be verified by comparing the simulation results to the experimental data.

The main topics of the thesis:

1. Literature overview.
2. Overview of the GPM theory, overview of material models.
3. Determination of appropriate parameters of material model.
4. Numerical test (FEM).
5. Development of methods for evaluation of the results.
6. Design of experiments for evaluation of material models.
7. Comparison FEM results and experiments.

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[1] **ASKIN, G., STANDRIDGE, R., 1993.** *Modeling and Analysis of Manufacturing Systems.* **John Wiley, New York.**

[2] **MALACARA, D., 2001.** *Handbook of Optical Engineering.* **CRC Press.**

[3] **DRIGGERS, R. G., 2003.** *Encyclopedia of Optical Engineering.* **CRC Press.**

[4] **UHLMANN, D. R., 1986.** *Glass: Science and Technology, Vol. 3: Viscosity and Relaxation Hardcover.* **ISBN-13: 978-0127067032**

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Dedication

I dedicate this thesis to my sister and my parents, without whose love and constant support none of this would have been possible.

List of symbols

Symbol	Units	Description
A_i	1	asphere coefficients
b	1	phenomenological parameter
c_p	$J \cdot kg^{-1} \cdot K^{-1}$	specific heat
E	MPa	elastic modulus
G	MPa	shear modulus
H	$J \cdot mol^{-1}$	activation energy
k	$W \cdot m^{-1} \cdot K^{-1}$	thermal conductivity
K	1	conic constant
M_v	1	response function
r	m	radius
R	$J \cdot mol^{-1} \cdot K^{-1}$	gas constant
T	°C	temperature
T_g	°C	transition temperature
T_f	°C	fictive temperature
T_{ref}	°C	reference temperature
t	sec	time
v	m^3	volume
w_g	1	weights
x	1	fraction parameter
α	K^{-1}	coefficient of thermal expansion
α_1	K^{-1}	liquid coefficient of thermal expansion
α_g	K^{-1}	solid coefficient of thermal expansion
ε	1	strain
η	Pa·s	viscosity
σ	MPa	stress
σ_V	MPa	viscous stress
σ_∞	MPa	stress acting on spring
ν	1	Poisson's ratio
ρ	$kg \cdot m^{-3}$	density
τ	sec	relaxation time
τ_s	sec	stress relaxation time
τ_v	sec	structural relaxation time

1. Introduction

In the recent years, aspherical glass optics is widely chosen because of their superior optical properties, such as lesser aberration and lower birefringence, over spherical optics. The traditional lens manufacturing process is a multi-step process which requires a series of material removal processes. Although, there have been recent advances in optical fabrication techniques such as magnetorheological finishing and ion beam polishing, the complexity of these processes is such that the overall costs are high for medium to high volume production of aspheric optics. Furthermore, the process incurs environmental issues because of the use of grinding fluids and polishing slurries.

A potential low-cost and fast method to produce precision glass optics is a compression molding process. In a lens molding process a glass gob is heated to a temperature above the glass transition temperature and is pressed between two molds having the required aspheric profile. The formed lens is then either cooled naturally or by forced convection to a room temperature resulting in its final geometry. If this entire process is designed correctly, it can be easily adopted for high volume production of precision aspherical glass lenses.

Precision glass molding process is an attractive approach to manufacture small precision optical lenses in large volume over traditional manufacturing techniques because of its advantages such as low cost, fast time to market and being environment friendly. [9]

A lens in the most fundamental terms can be defined as an optical device which transmits and refracts the light incident on it, resulting in the convergence or the divergence of the light beam. The surface profile of the lens is a crucial characteristic that governs the performance of an optical lens. The surface accuracy and finish should be precise. These kinds of lenses which require highly precise surface profiles and finish are known as precision lenses.

Conventional lenses generally have either cylindrical or spherical profiles. These lenses are relatively easy to fabricate and design. However, these lenses have major drawbacks in their optical properties such as spherical aberration, coma astigmatism etc. Aspherical lenses, on the other hand, have one or both surfaces that do not conform to a sphere and provide greater advantage over spherical lenses because of reduced light losses and aberrations, better image quality, and compact lens assemblies. Aspherical glass lenses are increasingly being used in consumer products like high power laser generators, digital cameras, projectors and scientific instruments. Manufacturing of standard quality spherical elements is cheap. On the other hand, mass production of aspherical elements using grinding and polishing is 3 to 10 times more expensive.

1.1. Glass versus plastics as lens materials

Glass has been and continues to be a material of choice for imaging optics. Different polymers, including acrylic, polystyrene and polycarbonate have been used for years to produce consumer level semi-precision optical system. Table 1.1 compares some of the relevant physical and optical properties of glass and plastics for use as lens materials.

Table 1.1 Comparison of glass and plastic properties

Property	**Glass/Plastics**
Transparency	Glass superior
Impact strength	Glass brittle
Specific gravity	Plastics≈$1/3^{rd}$of the glass
Scratch resistance	Glass higher
Moisture resistance	Glass unaffected/Plastics low
Thermal stability	Thermal expansion coefficient of plastics ≈ 10 times higher than glass
Processing	Plastics easier: can be mass produced

The main advantages of plastics are their light weight and ease of mass production. Glass on the other hand has higher transparency and scratch resistance. The thermal expansion coefficient (α) of a typical glass is approximately $7.1 \cdot\ 10^{-6}K^{-1}$ whereas for a thermoplastic and thermosetting plastic it lies in the range of $60 - 120 \cdot\ 10^{-6}K^{-1}$ [11]. In the design of high optical assemblies, such temperature dependent properties pose problems for the optical designer. Furthermore plastics offer a limited range of refractive index (η), have a large negative change in refractive index with temperature $(T)(dn/dT)$, show coating instabilities and sometimes excessive surface irregularities which makes them unsuitable for precision applications.

1.2. Advantages and benefits

Lens that are produced by process of compression molding have many desirable advantages over conventional manufacturing process. By using this method, lens that is produced has near the final shape and does not require any further finishing. It is a faster method because of the minimal amount of processes required as compared to the conventional machining process. For the same reason, compression glass molding approach is much cheaper than the conventional manufacturing process which uses techniques like magnetorheological finishing, ion beam polishing etc. which are very expensive.

Compression molding process is also environment friendly as it doesn’t require any polishing fluids or grinding slurries and doesn’t leave any glass debris that needs to be disposed off with care. Some asphere glass lenses contain hazardous elements like lead and arsenic; hence the disposal of the manufacturing glass debris needs to be done with care.

2. Research objectives

The glass molding process can press glass perform into a shape of finished lens under high pressure and temperature conditions, and it is easy to achieve mass production. So, it has emerged as a promising alternative way to produce complex shape lens. However, there are inherent technical issues associated with the process that has prevented it from being widely used in the industry. The aim of this thesis is to understand the basic underlying physics of the glass molding process. It was also desired to develop a reliable process simulation model that can be utilized for making process predictions and accordingly design, optimize and improve its performance.

More specific research objective of this work is to develop a relatively simple physics- based numerical method but yet accurate enough to model a compression glass molding process for manufacturing process, predict the final shape of the glass element at the end of the molding process, and to predict the critically important residual stresses at the end of the molding process.

The specific objectives of the proposed research are to:

1. Conduct experiments on a commercial machine to study process feasibility to mold a precision aspherical glass lens with the desired surface finish and curve accuracy as well as determine process repeatability.
2. Perform a parametric experimental study to investigate the influence of different molding parameters on process performance.
3. Develop a 2D FEM model of lens molding by incorporating viscoelastic stress and structural relaxation phenomenon of glass into the simulation.

The fundamental purpose of the research is to understand the glass molding process and develop a relatively simple computational model to predict the same.

The implications of developing such a tool would be prediction of the glass molding process and help in designing the process in a way that would result in the final desired optical element. It would help in prediction of the residual stresses and hence in the optimum design of the process parameters of the molding process.

3. Literature overview

Increasing demand for high quality optical glass components such as aspherical lenses, make the need to develop an efficient and economic production process which is significant to the optics industry. High precision glass molding technologies have tremendous potential to fulfill the needs of economic complex shaped optical components.

Because of the complexities involved in a glass molding process and the precision that needs to be achieved, the glass molding process chain is driven by iterative cycles between mold designs, lens profile, residual stresses etc. Multiple cycles are necessary to reach the final accuracy of the lens profile and to determine the optimum cooling rate to have residual stresses within acceptable limits. Numerical simulation of the glass molding process can help to predict the final profile of the lens and most importantly predict the residual stresses at the end of the process.

Although technologies for designing machines that perform the glass molding process have been developed significantly, limited work has been established in the field of numerical modeling of the glass molding process. This can be attributed to some major challenges such as modeling the material model of glass which is dependent on both time and temperature, time and temperature dependent boundary conditions, large deformations and contact phenomena, which in totality make the analysis highly nonlinear. It is possible to model all these characteristics using commercial software, but it would be an expensive alternative – monetarily and computationally.

Jiwang Yan et al. [6] model the high temperature glass molding process by coupling heat transfer and viscous deformation analysis. He proposed two-step pressing process according to the non-linear thermal expansion characteristics of glass. The phenomenon of heat transfer was modeled by considering the temperature dependence of specific heat and thermal conductivity of glass. The author carried out experiments on an ultraprecision glass molding machine GMP211. Computer simulation of the glass molding process were carried out using a commercially available FEM program DEFORM^{TM}-3D, the program which is capable of simulating large deformation of material flow under isothermal and non-isothermal conditions. The author concluded that incomplete heating of glass not only causes sharp increase in pressing load at the beginning of the pressing, but also leads to non-uniformity in viscous deformation and geometrical error of the glass component. The high-temperature material flow of glass was simulated by a modified Newtonian fluid model, and the predicted pressing loads agree well with the experimental results.

A. Jain et al. [3] dealt with some scientific issues associated with the glass lens molding process and the application of the technology for making optical elements for different application. Finite Element Method approach for studying and predicting has been described. Numerical simulations of the lens molding process were performed using a commercial FEM code MSC Marc by modeling glass as a Newtonian fluid during the molding stage. Authors simulated annealing stage of molding process by implementing to different methods: 1) thermal expansion coefficient of glass and 2) characteristic structural relaxation model of glass as described by the Narayanaswamy theory. They also develop a new method of making micro lens arrays. This method is based on heating the glass to a temperature above its transition temperature and is then pressed into a micro-hole array located on the mold surface. Authors were able to obtain excellent results in comparing the predicted lens cure and actual lens geometry.

Anurag Jain et al. [5] based his research on fundamental understanding of the lens molding process by adopting a combined experimental, analytical and numerical Finite Element Method approach. Author performed experiments which involved molding of a test aspherical glass lens on a commercial lens molding machine, and determined the effect of different molding parameters. Results from the experiments have showed that molding process is capable of producing precision glass lenses with shape and form accuracy comparable to lenses manufactured using conventional abrasive techniques. Numerical simulation was able to predict, residual stress in the glass lens as a function of process parameters, and proved that FEM can be used to predict, optimize and improve the performance of a lens molding process.

Jiři Málek et al. [10] explored the evolution of As_2Se_3 glass volume below the glass transition temperature measuring it by dilatometry under isothermal and non-isothermal conditions. Experimental data were described by Tool-Narayanaswamy-Moynihan model for a single set of kinetic parameters. Experimental data for volume relaxation of Ae_2Se_3 glass were annealed sufficiently long time to achieve equilibrium at temperatures below T_g. They measured structural relaxation far below T_g and tested the evolution of volume based fictive temperature as a function of time.

Shriram Palanthandalam Madapusi [8] based his research in developing physic-based computation tool to treat and quantify each individual process that occurs in the molding process such as heating, compressing and cooling and hence be able to predict the residual stresses and the final geometry of the glass element. He developed numerical method to model glass press molding process, and predicted the final shape of the glass at the end of process.

4. About the process

The glass molding process is essentially performed in five cycles. The five cycles involved in the glass molding process are:

1. Heating Cycle
2. Soaking Cycle
3. Pressing Cycle
4. Gradual Cooling Cycle
5. Rapid Cooling Cycle

A typical glass press molding cycle is composed from the above five cycles sequentially; heating the glass and mold, soaking the glass to achieve uniform temperature, pressing the glass to obtain the deformed lens shape, gradually cool the lens to ensure uniform cooling and finally rapid cooling to room temperature.

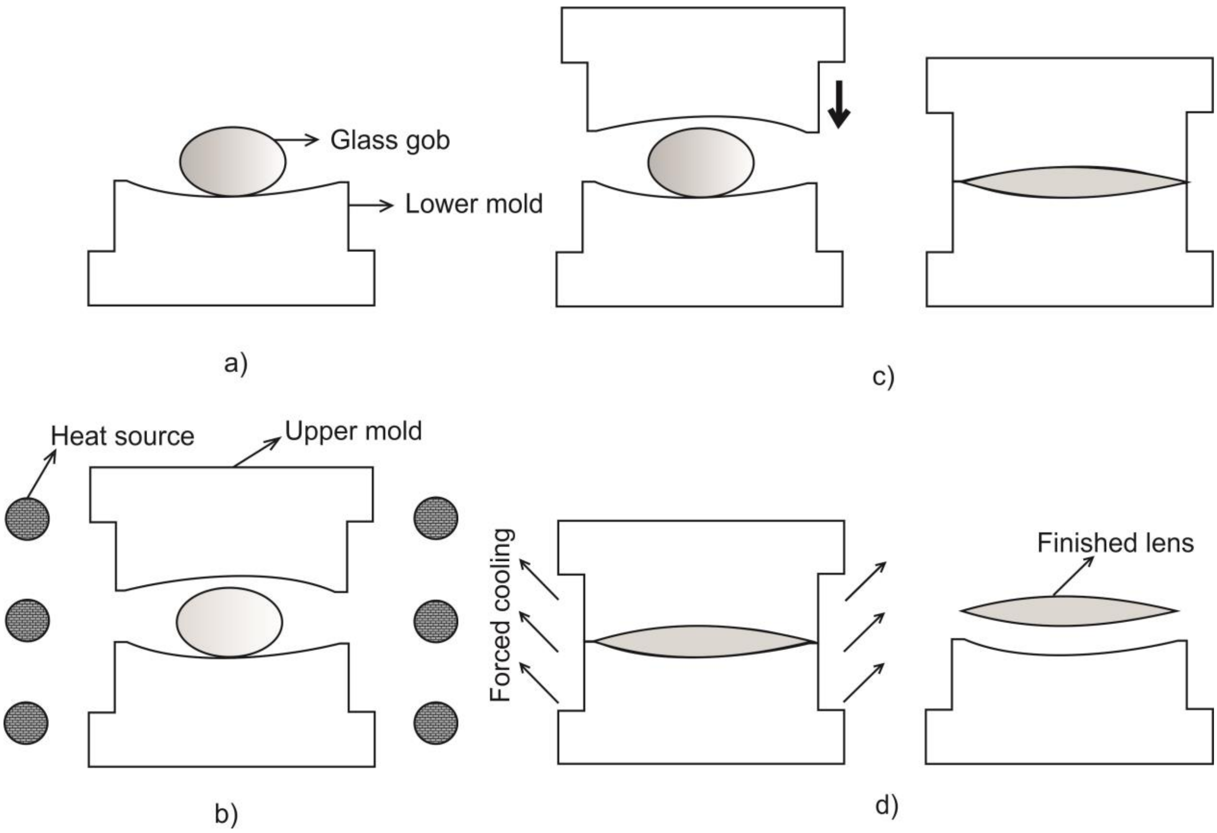


Figure 4.1 Placing of raw glass gob/ blank material on the lower mold, (b) Heating of the glass and mold assembly to the molding temperature, (c) Pressing (molding) of the glass material between the mold halves and (d) Forced cooling of the lens and mold assembly to near room temperature and lens release

4.1. Heating cycle

The heating is the first step in glass press molding. During this process, the molds and the glass gob are heated above the glass transition temperature. During the heating process the system is continuously purged with Nitrogen to prevent oxidation on the molds. The molds are heated to the commanded temperature by an induction heating system around the molds.

Usually the molds do not undergo any compression during this cycle. Any compression will most likely destroy the glass sample. Typically, the commanded temperature is slightly above the glass transition temperature where the glass is soft enough for pressing. Typical values range from 5-10% above T_g. The molds and the glass sample expand during this cycle due to the thermal effects.

4.2. Soaking cycle

The soaking cycle is necessary for the temperature of the glass and the molds to reach a steady state, where all the components are at a uniform temperature distribution. The controller maintains the commanded temperature for the duration of soaking cycle time. On large size molds and glass samples the soaking time can be on the order of few minutes to ensure that the temperature is uniform.

4.3. Pressing cycle

The pressing cycle commences at the end of the soaking cycle. During this cycle the controller maintains the commanded temperature and will start moving the pressing axis to compress the glass sample. In the cycle, the controller can be either operated in position or force control. If operating in position control, the user must ensure that the expansion of the molds and glass material will not create excessive forces on the molds and glass. Since molds are highly rigid, even a slight inaccuracy in specifying the displacement or position can result in very high reaction forces. Hence the pressing process is generally performed under the force control mode where the amount of force to be applied is specified. Under force control mode, the expansion compensation is not necessary because the press will automatically move to maintain the commanded force. The molding area is enclosed with metal bellows to enable molding in a vacuum or inert gas environment. This will help to prevent oxidation damage to the mold surfaces at the elevated temperatures, and will help to prevent dust and other contaminants from collecting on the mold surfaces. The fully enclosed molding chamber with vacuum will help to minimize the convective and radiation heat losses.

4.4. Gradual cooling cycle

The gradual cooling is the fourth step in the glass press molding process. In this step the temperature of the molds and glass is gradually decreased to a desired temperature. Usually additional heat is required to ensure that the molds do not cool too fast. The gradual cooling is done by continuously injecting heat and Nitrogen gas to follow the specified temperature profile. During this phase it is possible to press again to give the glass a final shape and alignment.

This cycle is the most critical cycle in the glass molding process. During the cooling, the outer surface of the glass cools faster than the inner surface which results in a non-uniform temperature distribution. During the temperature range where the phase changes, the outer surface approaches the elastic state while the inner core is still viscous. This non-uniform temperature distribution and the phase change results in residual stresses, which are detrimental to the performance of the optical element. Hence, the cooling has to be carefully controlled to minimize the non-uniform temperature distribution. This allows enough time for the stresses to relax and attain equilibrium with every step change in temperature.

4.5. Rapid cooling cycle

Rapid cooling is the last cycle in the process and it takes the molds and glass temperature to ambient temperature. The cooling is accomplished using a high flow of nitrogen gas. After this cycle is completed the glass in unloaded from the molds and a new glass gob is loaded. The rapid cooling generally is started from the lower range of the glass transition range where the glass can be considered to be frozen into a solid.

5. Fundamental of glass rheology

5.1. Glass terminology

Strain point: Temperature above which glass relieves stresses over time. It marks the low-temperature end of the glass transition region. If a glass sample is cooled below the strain point, any remaining stress would be locked, i.e., stress would not relax.

Annealing point: Temperature above which stresses rapidly relax. Annealing is generally carried out at a viscosity of $1012\ Pa \cdot s$.

Significance of annealing: Variations in cooling rates between the inside and outside regions of the glass induce thermal stresses. The inside region is comparatively at a higher temperature leading to expansion while the outside region contracts due to faster cooling. If the glass is cooled too fast, this expansion and contraction are locked into place leading to residual stresses. Thus, glass will eventually crack to relieve this built up stress.

Softening point: Temperature above which glass extends/deforms due to its own weight.

Viscosity: Viscosity is a measure of the materials resistance to deformation. Usually viscosity varies with temperature following the Arrhenius law, given by

$$\frac{1}{\eta} = Ae^{\frac{H}{RT}}, \tag{5.1.1}$$

where A is a constant, H is the activation energy, R is the gas constant and T is the absolute temperature.

5.2. Glass transition temperature and its significance

Before understanding the meaning of glass transition, it is important to know about crystalline, amorphous and semi-crystalline solids. Crystalline solids have long range atomic order with respect to their position of atoms whereas amorphous solids have no long range atomic order of their position of atoms. However they can have local arrangement of atoms at atomic length scale due to the nature of chemical bonding. Semi crystalline solids are a combination of both crystalline and amorphous parts. It is well known that glass is an amorphous solid. As shown in Figure 5.1, amorphous solids can be either in glassy or rubbery state based on the temperature. The temperature at which the transition from glassy state to rubbery state takes place in an amorphous solid is called the transition temperature [2]. Glass transition temperature is not a fixed parameter since glass phase in not in equilibrium. Important factors that affect the transition temperature value, T_g, are: (1) thermal history, i.e., rate of cooling and heating, (2) age, (3) molecular weight, and (4) method employed to measure T_g. Figure 5.1 shows the definition of the transition temperature as the point of intersection of the tangents to the glassy and rubbery curves. Note that the transition temperature is different from the melting temperature, which is a characteristic of crystals while transition temperature is a characteristic of amorphous solids.

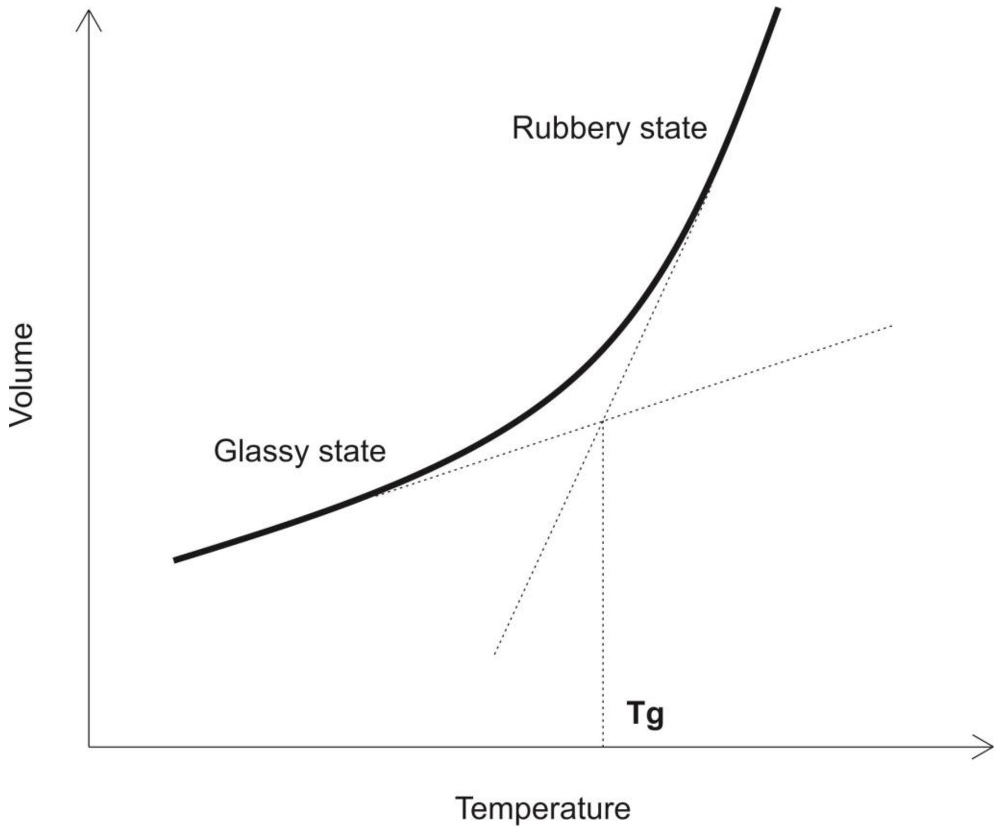


Figure 5.1 Glass transition region

The glass transition is a region of temperature in which the rearrangements occur at a molecular level to attain equilibrium on a scale of perceivable time of the order of minutes or hours and hence the change of properties occur at a rate that is easily observed. When subjected to mechanical load in the region, time dependent change in dimensions results. If a glass in the transition region is subjected to a sudden change in temperature, time dependent change in properties (like volume, density etc.) occurs which is known as structural relaxation.

5.3. Viscoelasticity

Viscoelasticity is a property of the material that exhibit both elastic and viscous behavior while undergoing deformation. These materials can be graphically and mathematically modeled by combining elements that represent these characteristics i.e. they can be represented as a combination of springs and dashpots. Many such models have been developed, for instance the Kelvin model, Voight model, Maxwell model etc.

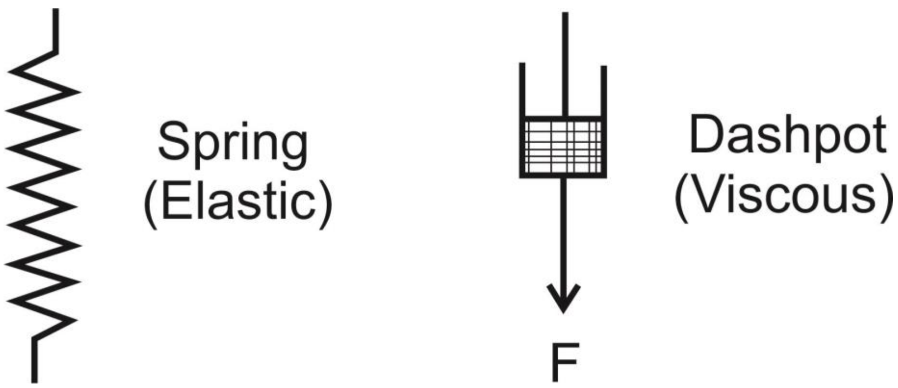


Figure 5.2 Spring and dashpot

Mathematically, a spring demonstrates Hookean behavior for solids and dashpot demonstrates Newtonian law for liquids. According to Hooke's law of solids,

$$\varepsilon = \frac{\sigma}{E}, \tag{5.1.2}$$

where ε is the strain, σ is the stress and E is Young's modulus of elasticity of the material at room temperature.

The delayed version of the viscoelastic material demonstrates non-Hookean behavior and resembles Newtonian material where stress is proportional to the first derivative of strain.

For an ideal Newtonian fluid, the shear stress is related to the rate of application of strain

$$\sigma = \eta \frac{d\varepsilon}{dt}, \tag{5.1.3}$$

where η is viscosity of the fluid.

A viscoelastic material exhibits a response which is a combination of elastic response and viscous response. Hence there is an instantaneous response of a viscoelastic material to an applied mechanical load, followed by a time dependent viscous response. At molecular level, when stress is applied to a viscoelastic material like glass or polymer, part of the long material chain change composition. This movement or rearrangement is known as creep. The material still remains as a solid material while these rearrangements happen in order to accompany the applied stress. This generates a back stress in the solid, and when the applied stress is taken away the back stress causes the material to return to its original form. Hence, the material creeps due to its viscosity (hence the prefix viscous) and as it eventually returns to its original form, the suffix elasticity. [8]

Viscoelastic behavior of glass as already mentioned can be theoretically expressed using a suitable series/parallel configuration of springs and dashpots. Instantaneous elongation is represented using springs, which are meant to describe Hookean elastic behavior, and dashpots, comprising of piston, cylinder and the viscous fluid describing Newtonian behavior. Maxwell's Model is proposed by James Clerk Maxwell in 1867, and it is a model that combines a purely elastic spring and a purely viscous damper connected in series.

The standard linear model can be easily generalized to include an arbitrary number of Maxwell elements arranged in parallel – which is known as the generalized Maxwell model. A real viscoelastic material does not conform to the response as predicted by the standard linear model but instead conforms to the generalized Maxwell model which leads to a distribution of relaxation times. This in turn produces a relaxation spread over a much longer time than can be modeled accurately with a single relaxation time. [8]

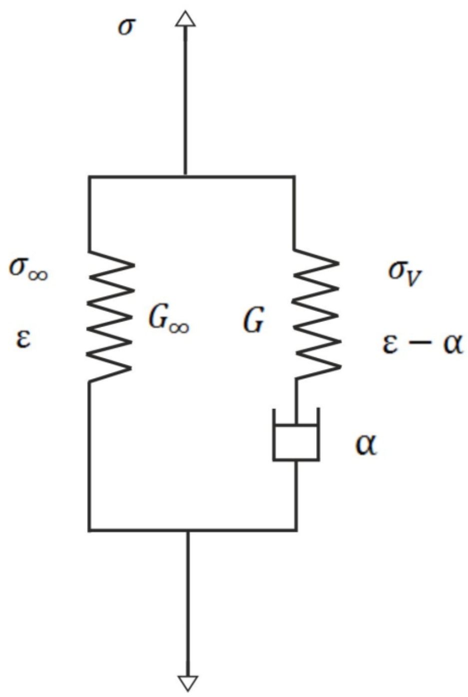


Figure 5.3 Standard Maxwell linear model for viscoelasticity

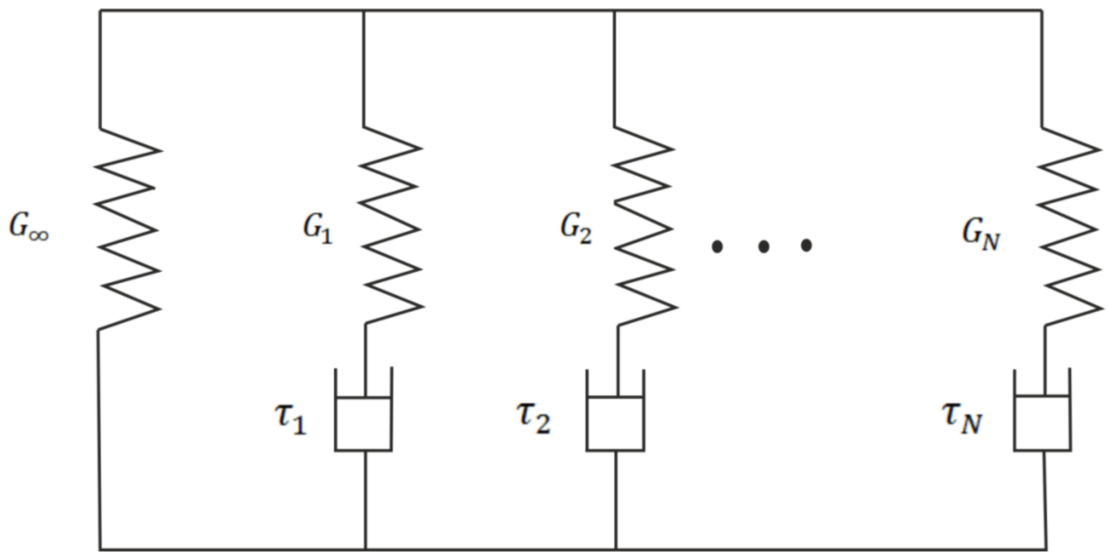


Figure 5.4 Generalized Maxwell model for viscoelasticity

In this arrangement, the Maxwell arm and the parallel spring G_∞ experience the same strain, and the total stress σ is the sum of the stresses in each arm as in Equation

$$\sigma = \sigma_V + \sigma_\infty, \tag{5.1.4}$$

where σ_V denotes the viscous stress in the Maxwell arm and σ_∞ is the stress acting on the spring with constant G_∞. If the total strain is ε, by equilibrium we have:

$$\sigma = G_\infty \varepsilon + \sigma_V \tag{5.1.5}$$

For detailed explanation of general Maxwell model and accompanying equations, see [8].

5.4.Stress relaxation and creep

The property of viscoelasticity induces non-linearity into the behavior of material. This non-linearity can be defined by both stress relaxation and creep. Stress relaxation can be defined as time dependent decrease in stress under a constant strain or deformation in the viscoelastic region. In other words, it is the stress decay during creep in transition region. Stress relaxation is shown on Figure 5.5.

Contrary to stress relaxation, creep refers to the study of strain behavior on application of constant stress. Creep-recovery experiments are comparatively easier than perform stress relaxation experiments. Creep recovery experiments are considered advantageous over stress relaxation experiments due to the fact that it is possible to extract high sensitive creep-recovery data when compared to low sensitive stress decay measurement from stress relaxation tests. Stress relaxation and creep are complimentary. Creep is shown on Figure 5.6.

When a body is subjected to a constant strain, there is a gradual decay in the stress known as stress relaxation. This is achieved through position control, i.e., the specimen is compressed or extended by a known distance resulting in a predetermined stress. Now the stress due to applied strain followed by the decayed stress is estimated from the load and position at the desired temperature in the glass transition region. Strain is maintained constant by keeping the displacement/position constant. [2]

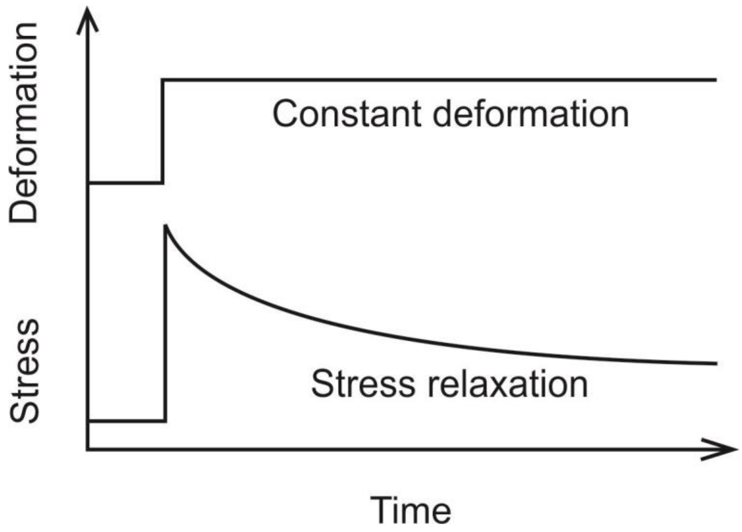


Figure 5.5 Stress relaxation vs. time

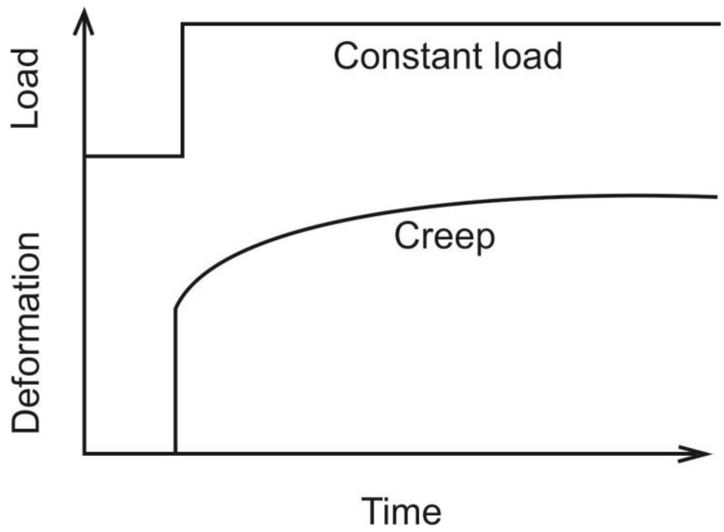


Figure 5.6 Creep vs. time

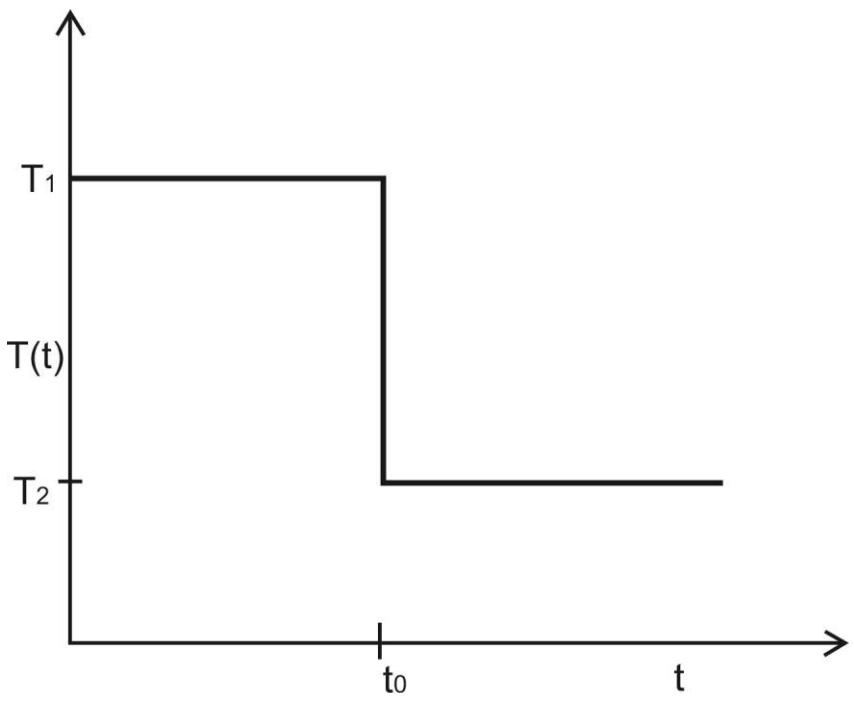
5.5.Structural relaxation

Structural relaxation is the phenomenon of time dependent change of a property, like a volume, when a viscoelastic material, like glass, is subjected to a sudden step change in temperature.

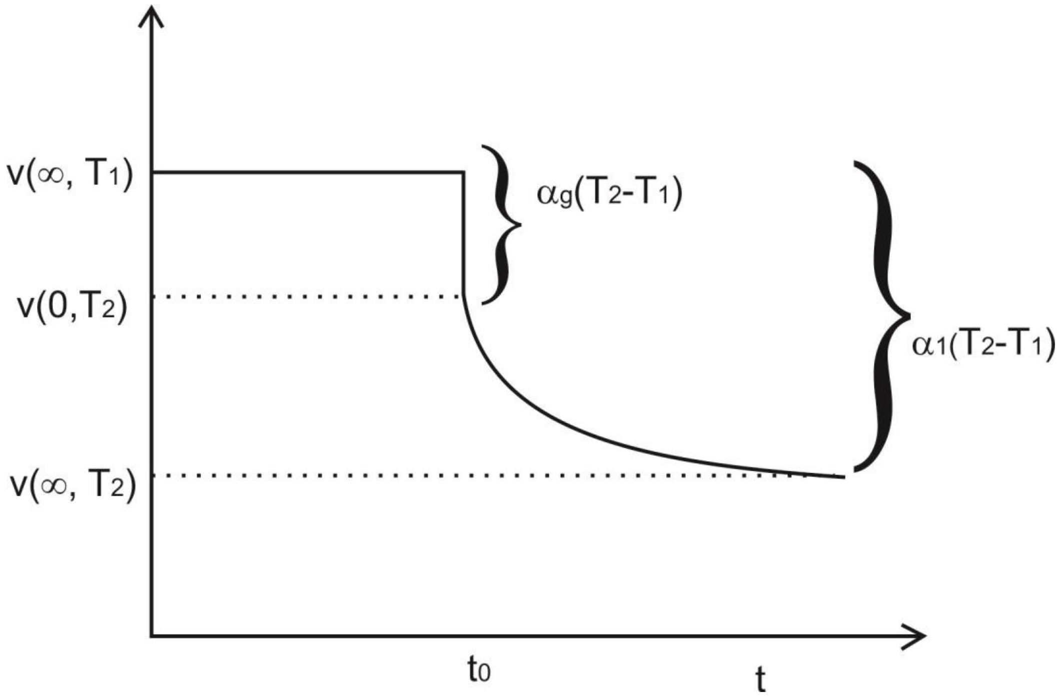
The process of structural relaxation is more complex than the process of viscoelastic stresses relaxation, because in the first case there is a variation of temperature and so, there is a change in the viscosity value that affects the relaxation times of the process. So, there are many cases where the viscoelastic relaxation process is linear, but the structural relaxation process is inherently non-linear due to the variation of viscosity with temperature.

Narayanaswamy and Moynihan [12] proposed a model for predicting the heating and cooling differential scanning calorimetry (DSC) curves which represent the structural relaxation phenomena in the proximity of the glass transition temperature.

Suppose a viscoelastic material is at equilibrium at temperature T_1 which is suddenly cooled to temperature T_2, then the properties will change as shown in Figure 5.7. The instantaneous change in volume is characterized by α_g which is the coefficient of thermal expansion at the glassy state and the total change after equilibrium corresponds to α_1 which is the coefficient of thermal expansion at the liquid state [8].



a)



b)

Figure 5.7 Phenomenon of structural relaxation a) Viscoelastic material subjected to a step change in temperature b) Corresponding response of a property like volume for e.g. with time when subjected to a step change in temperature

In the transition region, the response of a property to a small change in temperature from T_1 to T_2 is defined by the response function $M_v(t)$ given in Equation 5.1.6.

$$M_v(t) = \frac{V(t) - V_2(\infty)}{V_2(0) - V_2(\infty)} = \frac{T_f(t) - T_2}{T_1 - T_2}, \tag{5.1.6}$$

where the subscripts 0 and ∞ represent the instantaneous and long term values of volume (V), following the step temperature change. This function represents the fraction of the volume change that has not yet occurred.

The quantity T_f is defined as fictive temperature – the actual temperature of an equilibrium state that corresponds to the given non-equilibrium state. Hence if a liquid were equilibrated at T_f (T_1) and then instantaneously cooled to T_1, it would change along the line with slope α_g as no structural rearrangement would occur. The fictive temperature T_f is found by extrapolating a line from $V(T_i)$ with a slope α_g to intersect a line from $V(T_0)$ with slope α_1 as illustrated in Figure 5.8.

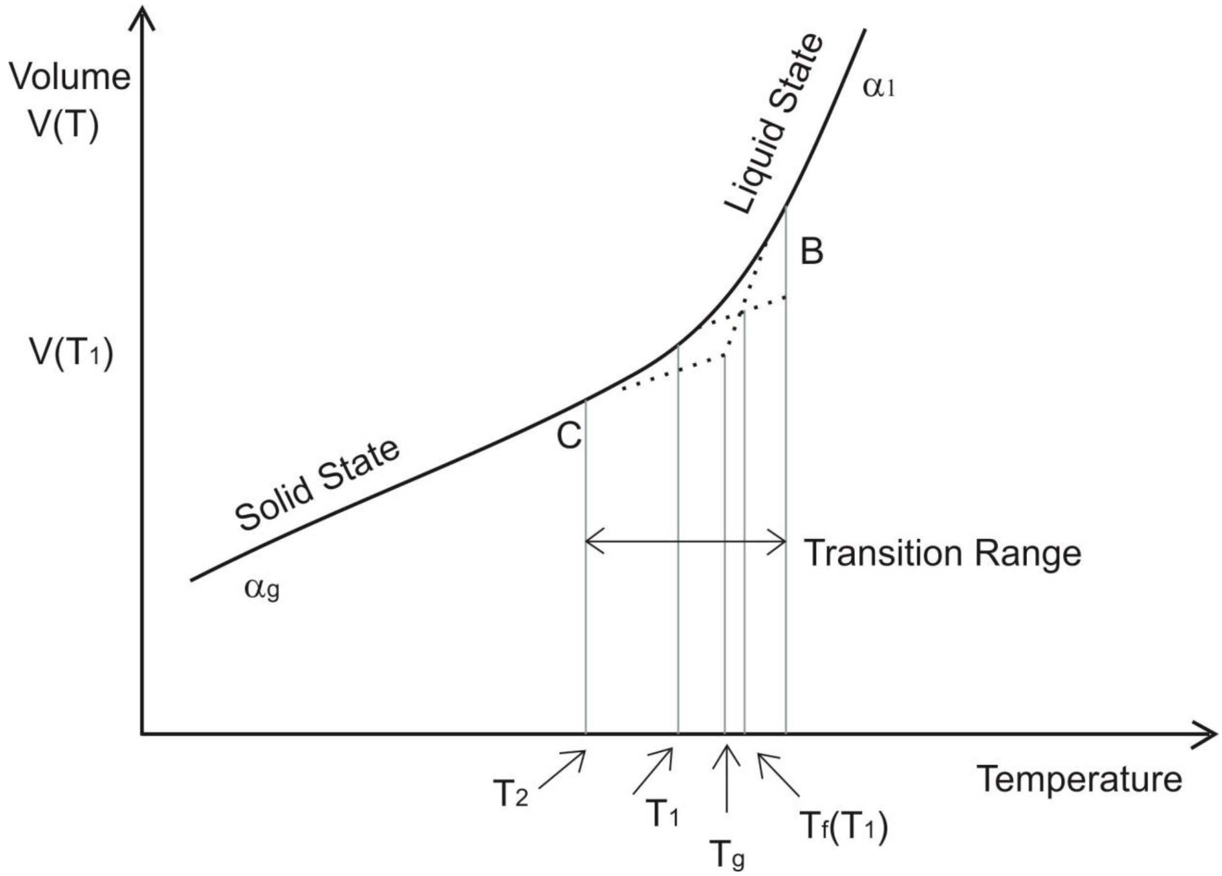


Figure 5.8 Volume vs. temperature behavior for a viscoelastic material like glass

The experimentally measured shape of the response function is described by Equation 5.1.7.

$$M_v(t) = exp[-(t/\tau_v)^b], \tag{5.1.7}$$

where b is a phenomenological parameter whose value lies between 0 and 1 and is typically equal to 0.5 [8] and τ_v is structural relaxation time. Alternatively, the experimental data can be fitted more accurately by using a spectrum of relaxation times and weights as expressed in Equation 5.1.8.

$$M_v(t) = \sum_{i=1}^{N} w_i \exp(-t/\tau_{vi}), \tag{5.1.8}$$

where w_i corresponds to the weight associated with each i^{th} component and $\sum w_i = 1$.

Structural relaxation times and stress relaxation times are strongly temperature dependent. In order to estimate the variation of these quantities with temperature, we assume glasses to exhibit thermorheologically simple behavior.

5.6. Linearity and thermorheological simplicity

Linearity is the property of instantaneous and delayed elastic responses being linearly proportional to the applied stress. Linearity is manifested in all glasses as long as the applied stresses are sufficiently low, i.e., creep curves are independent of applied stresses. This concept is also applicable to complicated glasses such as borosilicate glass. [2]

By thermo-rheological simplicity we mean that the effect of temperature leads to a shift of the relaxation curve on the log scale without change in shape, i.e., the curves are parallel to each other as shown in Figure 5.9 and equation 5.1.9.

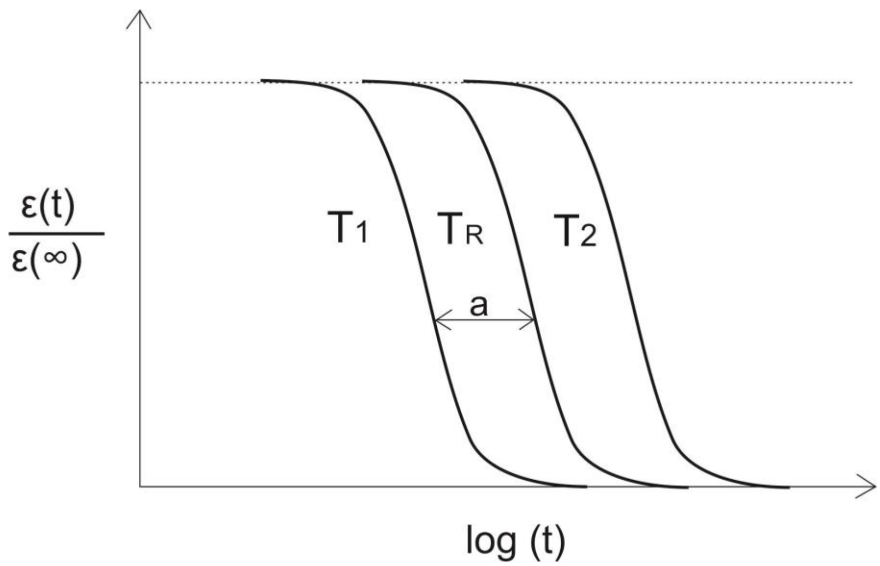


Figure 5.9 Thermo-rheological simple behavior

$$-\log a = A + \frac{B}{T}, \quad (5.1.9)$$

where A and B are given by

$$A = -log\frac{\tau_r}{\tau_0} \quad (5.1.10)$$

$$B = \frac{\Delta H}{R}, \quad (5.1.11)$$

where, ΔH is the activation energy, R is the gas constant, τ is relaxation time and T is the absolute temperature. If stress relaxation time follows the Arrhenius equation for viscosity, then viscosity is proportional to relaxation times and is given by:

$$\tau = \tau_0 exp\left(\frac{\Delta H_i}{RT}\right) \tag{5.1.12}$$

In this case the curves demonstrate thermorheologically simple behavior.

6. Lens molding experiments

This chapter describes the experimental lens molding work that was performed on a commercial lens molding machine (Model No. 140 GPM, Nanotech, USA) presented on Figure 6.1.

The Nanotech 140GPM is a glass press molding machine designed for precision glass optic applications. This machine compliments the Nanotech 450UPL or 350FG which can be configured for ultra-precision grinding of WC (tungsten carbide) and SiC (silicon carbide) mold components.

Figure 6.1 Nanotech 140GPM

Lens molding experiments were performed to study the capability of the molding process to make a precision lens to the desired figure accuracy and surface finish as well as process repeatability. Preliminary simulations were performed using a commercially available nonlinear FEM program MARC, which is suitable for viscoelastic modeling of materials.

Geometry of parts used in press molding is shown on the next figure. It consists of ring, bottom and top guides (molds) and inserts.

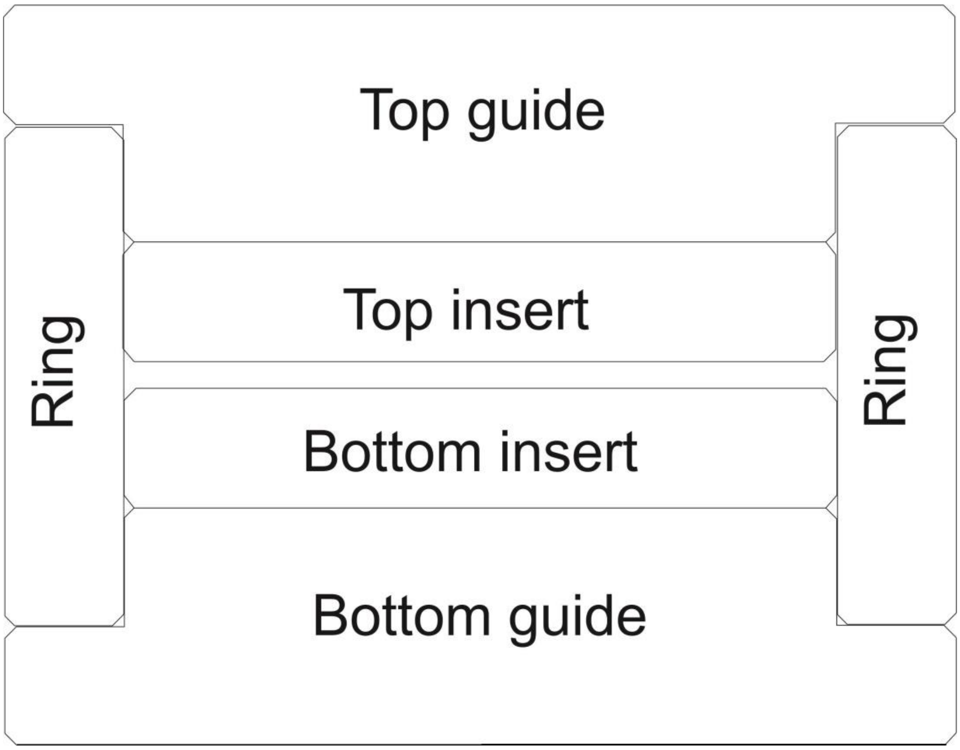


Figure 6.2 Geometry of parts used in press molding

6.1. Material of glass

Type of glass used in experiments is chalcogenide glass. Chalcogenide glass is a glass containing one or more chalcogenide elements sulfur, selenium and tellurium, but excluding oxygen. Such glasses are covalently bonded materials and may be classified as covalent network solids. Polonium is a chalcogenide but is not used because of its strong radioactivity and high price. Chalcogenides materials behave rather differently from oxides, in particular their lower band gaps contribute to very dissimilar optical and electrical properties.

The classical chalcogenide glasses (mainly sulfur-based ones such as As-S or Ge-S) are strong glass-formers and possess glasses within large concentration regions. Glass-forming abilities decrease with increasing molar weight of constituent elements; i.e., S > Se > Te.

Chalcogenide compounds such as AgInSbTe and GeSbTe are used in rewritable optical disks and phase-change memory devices -they are fragile glass-formers; by controlling heating and annealing (cooling), they can be switched between an amorphous (glassy) and a crystalline state, thereby changing their optical and electrical properties and allowing the storage of information.

These types of glasses have received particular attention because of their transmission in the middle-infrared. Due to this ability, they have been used in infrared cameras optics and optical fiber in order to carry signals emitted by thermal sources or by a laser such as CO_2 laser. Chalcogenide glasses, in particular TAS glass (ternary system $Te_2As_3Se_5$), are used in evanescent wave spectroscopy of biomolecules in human lung cells, IR signatures being recorded in order to measure the impact of toxic agents on cell health for example. But most of chalcogenide glasses such as Ge_xSe_{1-x} or $Te - As - Se$ exhibit poor mechanical properties. Moreover, due to their low glass transition temperature (T_g), they behave viscoelastically at room temperature.

The exact type of chalcogenide glass used for experiments is IG6- $As_{40}Se_{60}$. IG-6 features excellent transmittance and low thermal change in refractive index and dispersion. IG-6 is ideal for applications in combination with other IR material for color corrected designs and infrared optical systems without thermal defocusing in the 2-12 µm spectrum. Molding, classical polishing or Single-Point-Diamond-Machining permits the production of optical components with flat, spherical and/or aspherical shaped surfaces for the infra-red and optoelectronics industries. Antireflection coatings further improve transmission by reducing the reflection at the air-glass interfaces.

Table 6.1 Material properties

	IG-6	
Density	4630	$kg \cdot m^{-3}$
Thermal expansion [20°C-100°C]	20.7	$10^{-6} \cdot K^{-1}$
Specific heat capacity	360	$Jkg^{-1} \cdot K^{-1}$
Thermal conductivity	0.24	$W \cdot m^{-1} \cdot K^{-1}$
Transition temperature	185	°C
Softening point	236	°C
Young’s Modulus	18.3	GPa
Poisson’s ratio	0.3	(1)

The lens before experiment had diameter of 25 mm with a thickness of 1.3 mm.

Table 6.2 shows typical glasses used for glass press molding.

Table 6.2 Typical glasses used for glass press molding

Manufacturer	Glass	T_g [°C]
Hoya	BACD5	620
Hoya	TAF1	663
Hoya	TAF3	638
Hoya	BAFD8	610
Schott	N-BK7	525
Schott	N-FK5	446
Schott	N-FK51	420
Schott	N-PSK57	497
Schott	N-LAF33	600
Ohara	S-LAL12	652
Ohara	S-NPH1	552
Ohara	S-LAL18	685

6.2. Molds and ring

Form base (ring, bottom and top guide) are made from stainless steel 1.4305. The ring is made in several height variants, due to different glass height. EN 1.4305 is a free-machining austenitic stainless steel. The excellent machinability is due to its sulphur content of between 0,15 - 0,30 %. It has good resistance to atmospheric corrosion and many organic and inorganic chemicals. It is non-magnetic in the annealed condition but may become slightly magnetic due to the introduction of martensite or ferrite at the cold working or welding stages.

Table 6.3 Material properties of stainless steel 1.4305

Stainless steel 1.4305						
Temperature $[°C]$	20	100	200	400	600	800
Density $[kg \cdot m^{-3}]$	7900					
Modulus of elasticity $[GPa]$	200	195	185	175	155	135
Mean coeff. of thermal expansion $[x\ 10^{-6} \cdot K^{-1}]$	-	17.0	17.5	18.5	19.0	19.5
Specific heat $[J \cdot kg^{-1} \cdot K^{-1}]$	440	480	520	560	590	630

6.3.Inserts

There are three different types of inserts (same dimensions - diameter 30 mm, height 5 mm), that provides shape and surface for molding. All three are coated by Al_2O_3 in nm thickness as an anti-sticking surface.

1. NiP coated (cca. 20 µm) stainless steel 1.4305
2. Classic brass for automatic machining CW607N (CuZnPb)
3. Alloy Elmendur X (CuCrZr)

Table 6.4 Material properties of Elmendur X

Elmendur X			
Chemical composition (reference values in %)	Cr	Zr	Cu
	0.8	0.08	balance
Material properties	Precipitation hardened copper alloy with excellent hardness and high electrical and thermal conductivity.		
Density $[kg \cdot m^{-3}]$	8900		
Modulus of elasticity $[GPa]$	108		
Specific heat $[J \cdot kg^{-1}K^{-1}]$	0.376		
Thermal conductivity $[W \cdot m^{-1} \cdot K^{-1}]$	320		

Table 6.5 Material properties of brass

CW607N								
Chemical composition (reference values in %)	Cu	Al	Fe	Ni	Pb	Sn	Zn	Others
	60.0-60.1	max. 0.05	max. 0.20	max. 0.30	0.80-1.60	max. 0.20	rest	max. 0.20
Material properties	Highly suitable for hot formed parts, e.g. profiles.							
Density $[kg \cdot m^{-3}]$	8400							
Modulus of elasticity $[GPa]$	102							
Heat capacity $[J \cdot kg^{-1}K^{-1}]$	377							
Thermal conductivity $[W \cdot m^{-1} \cdot K^{-1}]$	109							

Figure 6.3 Ring, guide and insert

6.4. Experiment

Experiments were done with chalcogenide glass IG6. The heating is the first step in glass press molding. Before the heating process starts the system is purged with Nitrogen to remove any oxygen from the environment. Nitrogen purge is set in seconds. At the end of the purge cycle the heating cycle commences. Usually there is no compression of the molds during this cycle. Typically, the commanded temperature is slightly above the glass transition temperature where the glass is soft enough for pressing. The molds and the glass sample expand during this cycle due to the thermal effects. After heating the molds and glass to predefined temperature, pressing cycle starts, where upper and lower mold are moved in order to obtain desired shape. The gradual cooling is next step in the glass press molding process. In this step the temperature of the molds and glass is gradually decreased to a desired temperature. As mentioned earlier, usually additional heat is required to ensure that the molds do not cool too fast. The gradual cooling is done by continuously injecting heat and Nitrogen gas to follow the specified temperature profile. During this phase it is possible to press again to give the glass a final shape and alignment. Last step of glass molding process is rapid cooling cycle where glass and molds are cooled to the room temperature.

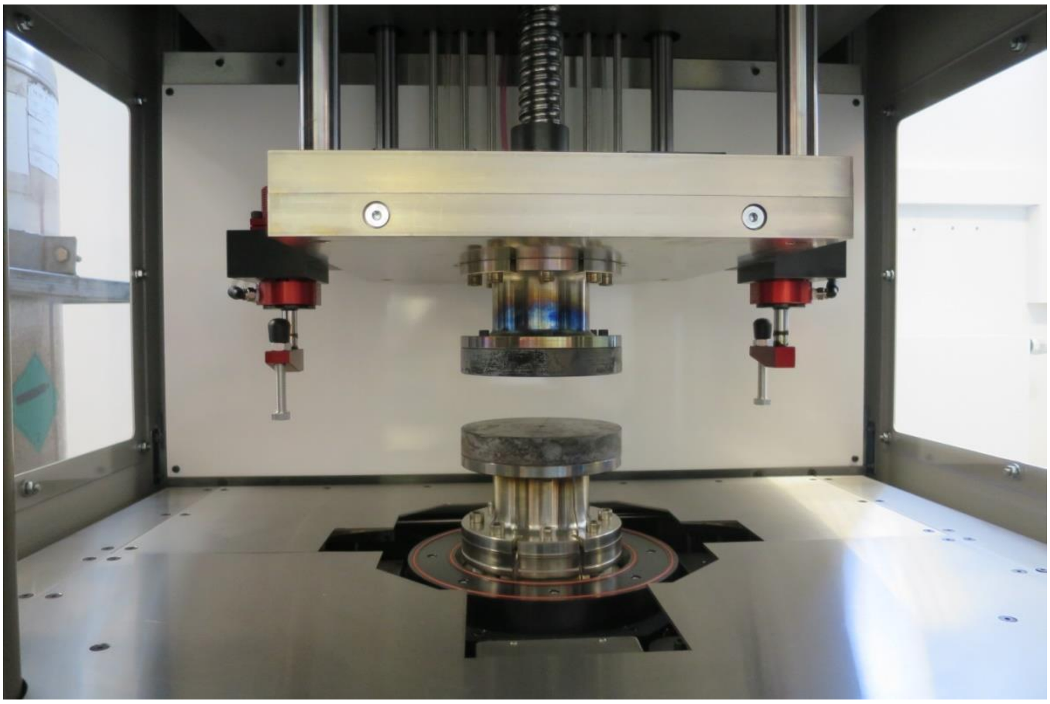


Figure 6.4 Molding setup

Figure 6.5 shows a variation of the molding temperature, mold position and molding force with time during the experiment.

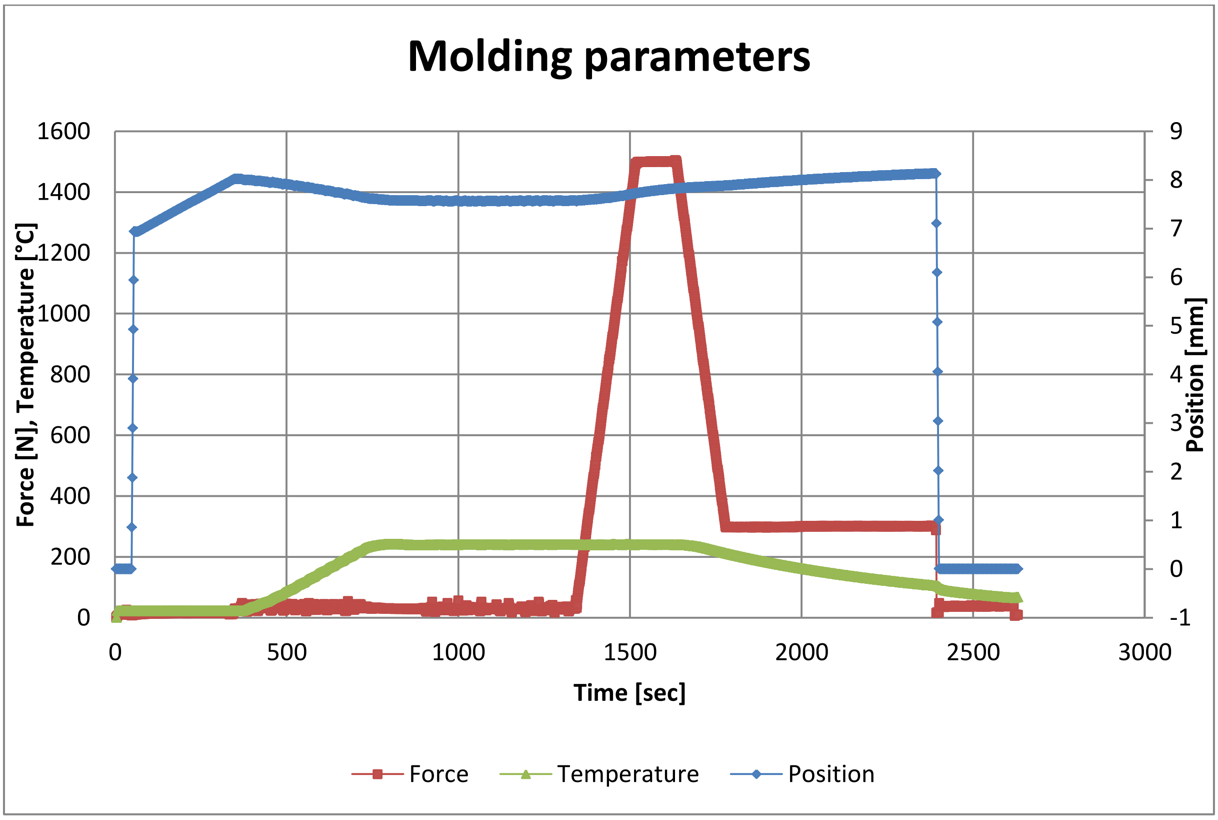


Figure 6.5 Process sheet showing the variation of mold temperature, position and molding force as a function of time during the experiment

On the previous diagram it is visible that the force is applied after sufficient amount of time, when it is assumed that the temperature is evenly distributed in the molds and glass.

Figure 6.6 is made according to the Figure 6.5 and cycles described at Chapter 4 to show different cycles of glass press molding. T_1 represents heating time, T_2 soaking time, T_3 pressing time, T_4 gradual cooling time and T_5 rapid cooling time.

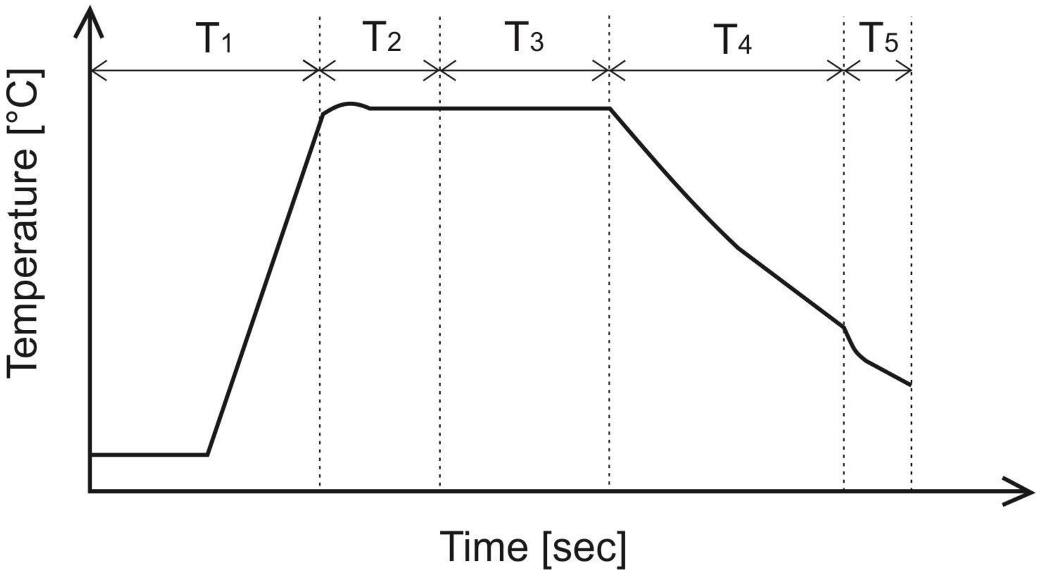


Figure 6.6 Different cycles in glass molding process

The process parameters used in the molding process were also used in the FE simulation.

Determination of a suitable temperature for pressing is an essential issue for glass molding. If pressing is performed above yielding point [6] and held on to keep the shape of the lens during cooling, the volume expansion around yielding point will lead to a sharp increase in pressing load, and in turn, adhesion of glass to molds. On the contrary, if pressing is done below yielding point of glass, a high pressing load will be required because glass is not sufficiently softened at this temperature range. In this case, significant residual stresses will occur in the glass lens, and the high pressing load may also shorten service life of the molds.

Heating time determines the uniformity of temperature in glass, and affects the pressing load too. One of the phenomenon caused by non-uniformity of temperature in glass is that the initially cylindrical glass preform, after pressing, will be deformed to be an isosceles trapezoid where the diameter of the bottom surface is bigger than the top surface. Choosing a suitable heating time is not only an important issue for prolonging the service life of molds, but also an essential step for improving accuracy and optical property of the molded lenses.

6.5. Light white interferometry

Shape of inserts and glass used in molding is measured by light white interferometry. White light interferometry is an extremely powerful tool for optical measurements. It is a non-contact optical method for surface height measurement on 3-D structures with surface profiles varying between tens of nanometers and a few centimeters. While white light interferometry is certainly not new, combining rather old white light interferometry techniques with modem electronics, computers, and software has produced extremely powerful measurement tools.

Currently most interferometry is performed using a laser as the light source. The primary reason for this is that the long coherence length of laser light makes it easy to obtain interference fringes and interferometer path lengths no longer have to be matched as they do if a short coherence length white light source is used. The ease with which interference fringes are obtained when a white light source is used is both good and bad. It is good that it is easy to find laser light interference fringes, but it can be bad in that it can be too easy to obtain interference fringes and any stray reflections will give spurious interference fringes. Spurious interference fringes can result in incorrect measurements.

Optical profilers from ZYGO are white light interferometer systems, offering fast, non-contact, high-precision 3D metrology of surface features. All optical profilers include proprietary data analysis and system control software. Choosing the right surface measurement system depends on the application's requirements, including precision, speed, automation, configuration flexibility, and vertical range.

The performance and capability of any optical profiler is largely dependent on the lens objectives it uses. Objectives determine the magnification, working distance, slope capability, and field of view of the profiler, so choosing the right objective(s) is very important in achieving metrology goals.

Following figures are the result of shape measurement with light white interferometry of inserts before and after molding and shape of the glass after molding.

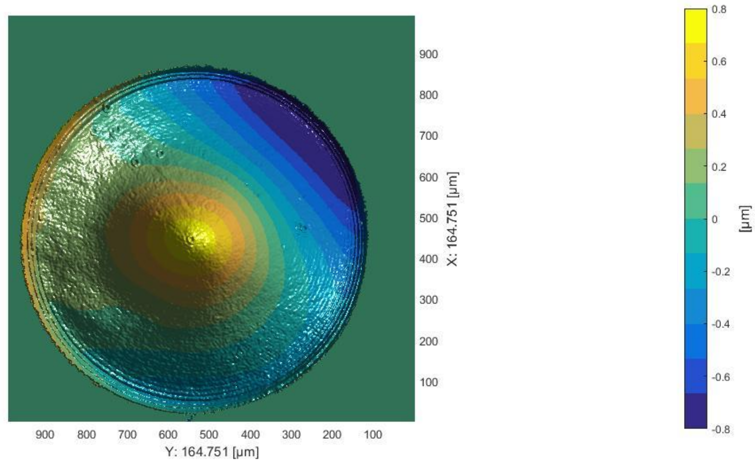
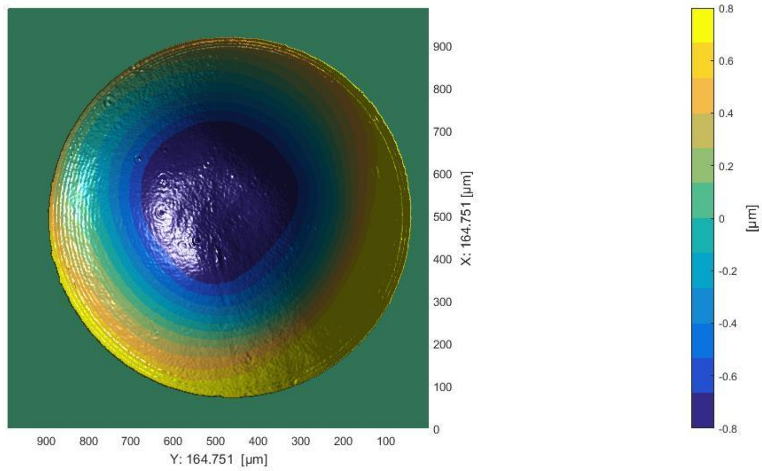


Figure 6.7 Shape of the CuZnPb insert (coated with Al_2O_3) before molding



b)

Figure 6.8 Shape of the CuZnPb insert (coated with Al_2O_3) after molding

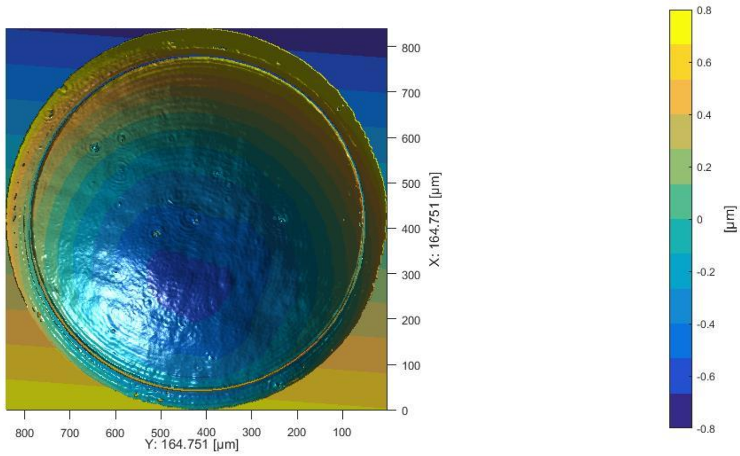


Figure 6.9 Shape of the NiP coated stainless steel insert before molding

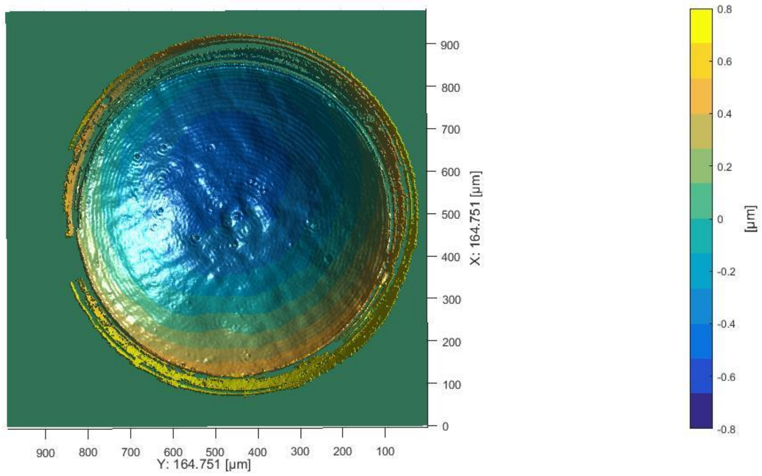


Figure 6.10 Shape of the NiP coated stainless steel insert after molding

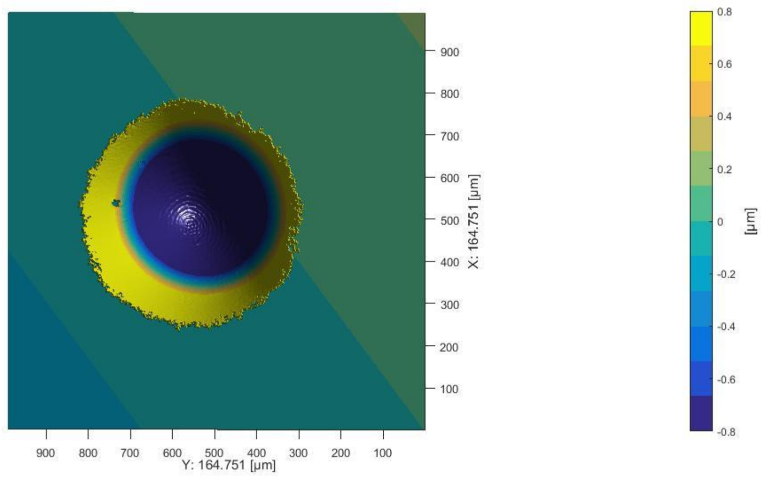


Figure 6.11 Shape of the glass (CuZnPb side) after molding

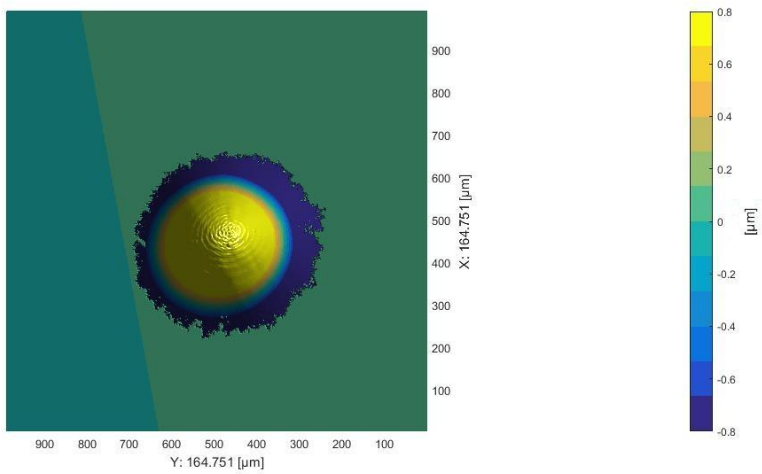


Figure 6.12 Shape of the glass (NiP side) after molding

7. Numerical simulation

Numerical Finite Element Method (FEM) has routinely been used in the manufacturing industry to study, analyze, develop, improve and optimize, manufacturing process performance. With the advent of the advanced commercial FEM codes and computing hardware it is possible to realistically simulate and observe process variables that are difficult or even impossible to measure from experiments, for example in case of lens molding it includes among others: glass flow behavior/ flow front position with time, temperature distribution in glass, residual stress distribution, glass-mold contact behavior, lens shape change during cooling, etc. [5]

Computer simulations of the glass molding process were carried out using a commercially available nonlinear FEM program MARC, which is suitable for viscoelastic modeling of materials. The main objective of performing these simulations was to implement the viscoelastic material model of glass with stress and structural relaxation into FEM. The implementation of the structural relaxation model would enable the prediction of residual stresses in the lens at the end of cooling. Figure 7.1 shows the 2D-axysymmetric numerical simulation model of lens and molds in Marc.

Four node quadrilateral elements have been used all throughout the simulation. Because of rotational symmetry of most of the optical devices, the entire simulation was modeled as an axisymmetric formulation for computational simplicity. This simplification can help by greatly reducing the number of calculations required, saving computational space and time. Molds, each, are meshed with 600 elements, while glass is meshed with 100 elements.

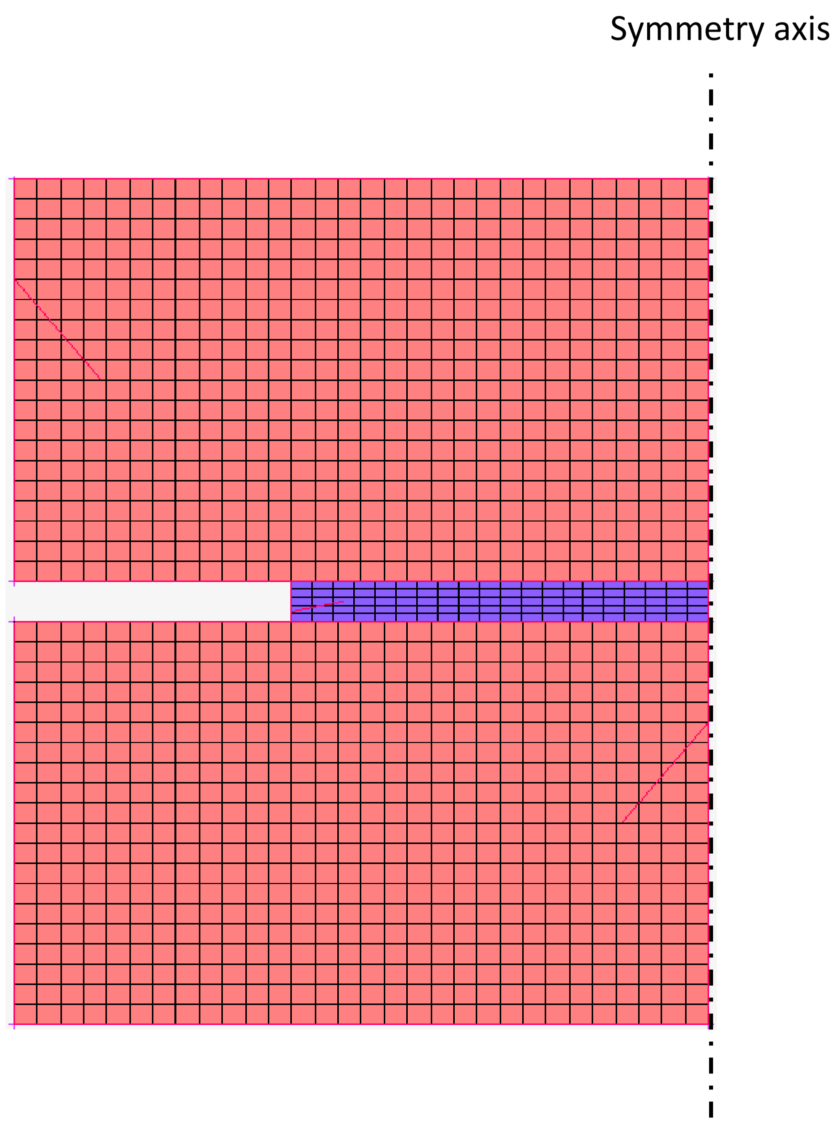


Figure 7.1 Geometry of glass and molds modeled in MSC Marc

7.1. Inputs

7.1.1. Materials

First step was to choose correct material model for simulation. This part is one of the most important parts, since inadequate parameters of the material can lead to complete incorrect results. Modeling the material model of glass is quite complicated since it is dependent on both time and temperature, has time and temperature dependent boundary conditions, large deformations and contact phenomena, which in totality make the analysis highly nonlinear.

There are several methods to evaluate the viscoelastic properties of glass. The most common method is to fit the experimental data with analytical or mathematical constitutive model using method of nonlinear regression analysis or be the method of least squares [8]. Creep and stress relaxation tests are the most commonly used methods to determine the viscoelastic properties of materials like glass etc. In these tests, instantaneous strain (or displacement) or stress (or force) is applied and the corresponding decay of the other quantity is noted.

Time should be invested in studying and implementing these methods which can be used for obtaining correct viscoelastic values of material in question [5]. Using and implementing those kind of methods, goes beyond the scope of this thesis.

From viscosity data for chalcogenide glass in [10] we were able to calculate necessary viscoelastic parameters by fitting the viscosity curve with Equation 5.1.1. Presenting mentioned viscosity data in excel, and connecting the points with linear trend line we get equation 7.1.1.

$$y = 15.317x - 22.902 \tag{7.1.1}$$

By fitting Equation 7.1.1 and Equation 5.1.1 we obtain value for gas activation energy H listed in the Table 7.3.

Shear modulus was calculated using following equation

$$G = \frac{E}{2 \cdot (1 + \nu)}, \tag{7.1.2}$$

where E is Young's modulus, and ν is Poisson's coefficient. Value of the share modulus obtained is $G = 7038\ MPa$.

Number of Maxwell arms used in simulation is 3, and according to that number in Table 7.1 are listed values of relaxation times and shear constants. The sum of shear constants must be equal to shear modulus calculated with equation 7.1.2. Ratios for shear constants and values for relaxation times are obtained from molding software provided by the manufacturer of glass press molding machine.

Table 7.1 Relaxation times and shear constants

Relaxation times [sec]	Ratios	Shear constants [MPa]
$1 \cdot 10^{-6}$	0.3	2111.4
$1 \cdot 10^{-4}$	0.25	1759.5
$1 \cdot 10^{-1}$	0.45	3167.1

Weighting factors and time constants were obtained by using a special program utilizing a Lavenberg-Marquardt optimization for the viscosity data mentioned above. Values are listed in the Table 7.2.

Table 7.2 Weighting factors and time constants

Weights w_i	Time constants
$8.4127 \cdot 10^{-3}$	$1.3749 \cdot 10^{-4}$
$3.9607 \cdot 10^{-2}$	$2.4389 \cdot 10^{-3}$
$1.4337 \cdot 10^{-1}$	$1.7462 \cdot 10^{-2}$
$4.1893 \cdot 10^{-1}$	$7.8545 \cdot 10^{-2}$
$3.8916 \cdot 10^{-1}$	$2.2631 \cdot 10^{-1}$
$5.0304 \cdot 10^{-4}$	22.7299

Table 7.3 shows viscoelastic parameters used in simulation. It should be noted that the parameters from Table 6.1 were also used in simulation.

Table 7.3 Viscoelastic properties of IG-6

Viscoelastic properties of IG-6		
Number of Maxwell elements	3	(1)
Shear Modulus	7038	MPa
Reference temperature	175	°C
Gas activation energy	38	kK
Fraction parameter [10]	0.71	(1)

7.1.2. Boundary conditions

In order to have a working simulation, boundary conditions need to be applied. Boundary conditions applied in our model, are according to the done experiment. Figure 7.2 shows applied B.C.

Displacement of the nodes of lower mold is fixed in x direction. Position, which is obtained from experiment, is applied on the upper mold, so when the mold moves it presses the glass. Finally nodal temperature that corresponds to temperature from experiment is applied to all nodes of the model.

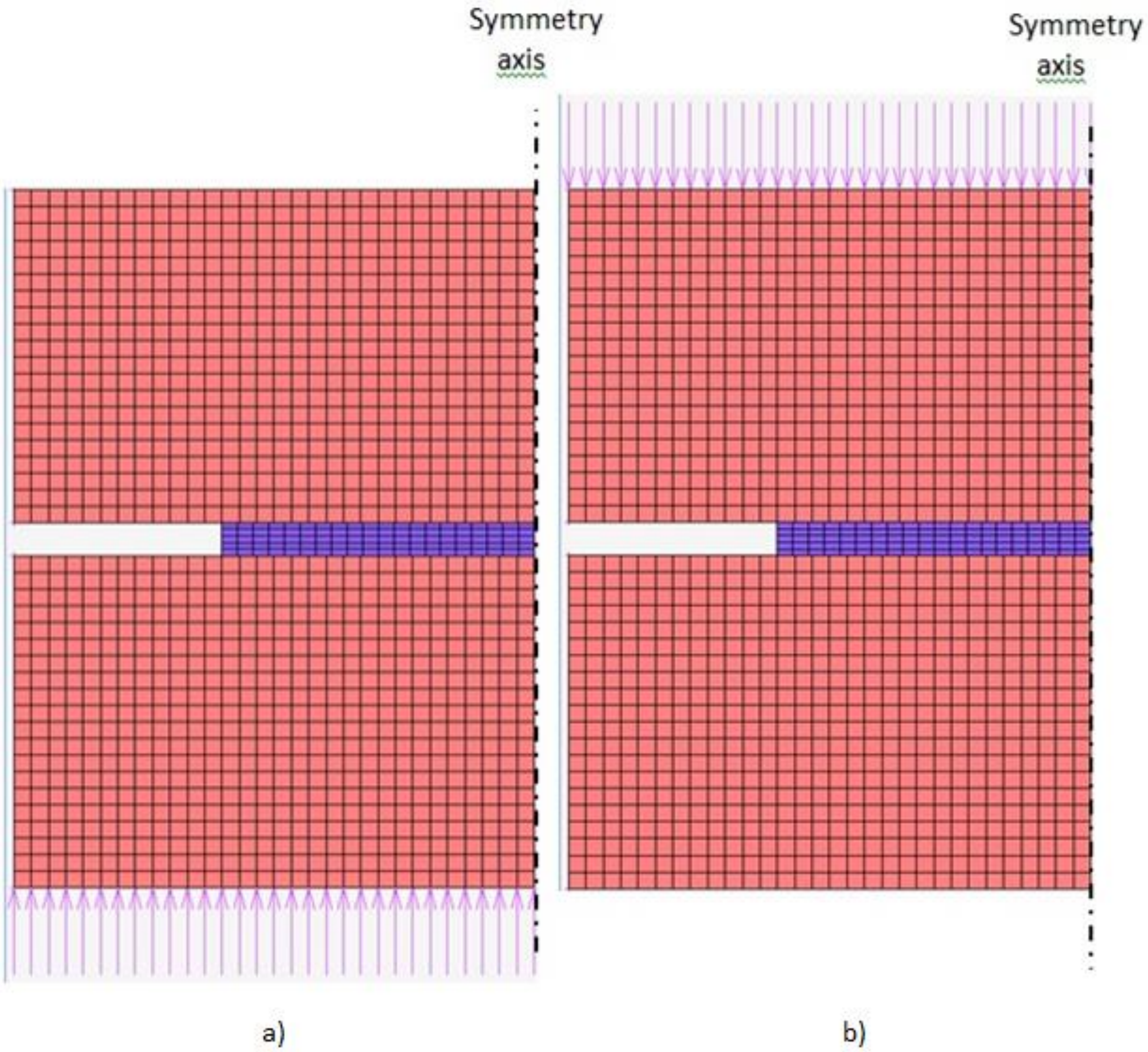
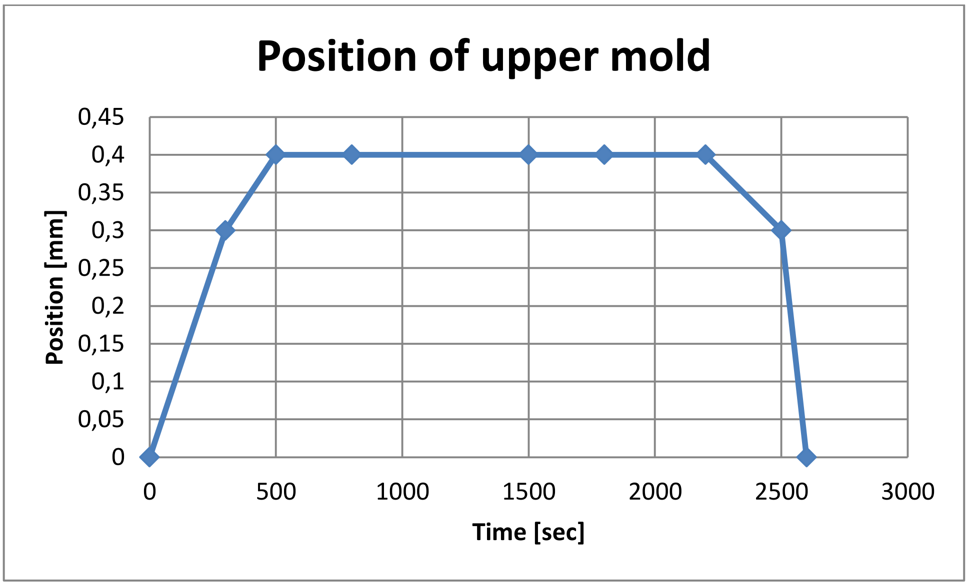


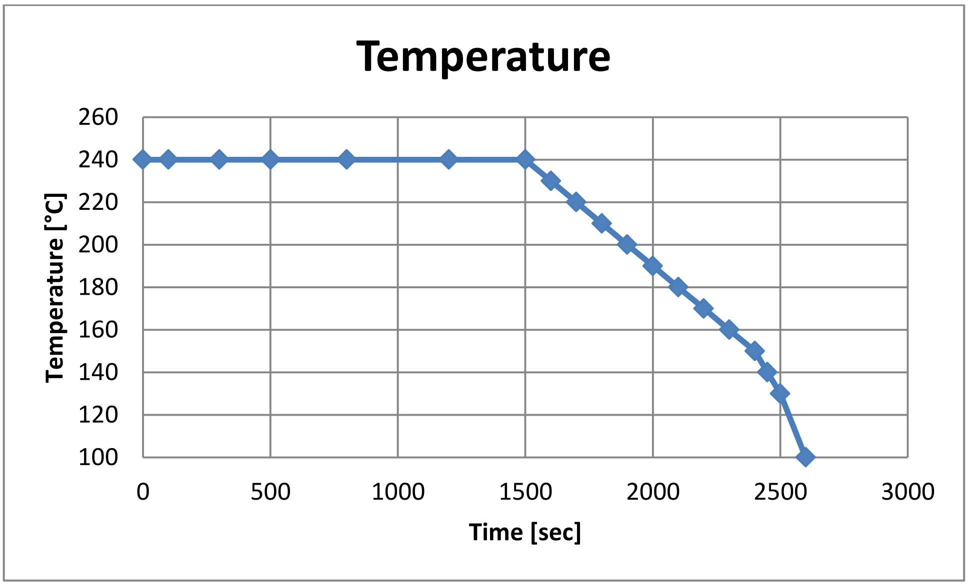
Figure 7.2 a) Fixed displacement in x-direction applied on lower mold b) Change in position applied on upper mold

On the Figure 7.3 are presented values of temperature and position implemented in the simulation. It should be noted that, both of these conditions are simplified, but yet are good approximation of values obtained in the experiment.

Both molds and glass are heated up to a temperature of 240°C (well above glass transition temperature) during experiment. Here in the simulation, initial temperature is set to be 240°C in order to simplify the process, so the pressing starts almost immediately.



a)



b)

Figure 7.3 Boundary conditions applied on the geometry in the simulation a) Position of upper mold b) temperature of glass and molds

7.2.Cycles in simulation

Heating cycle

Due to thermal expansion that takes place during the heating cycle, the profile of glass and the mold changes. It is important to quantify the change in mold profile so as to obtain the accurate pressing surface for the molding. The objective at the end of this cycle was to capture the thermal expansion of the mold profile and the expansion of glass

Pressing cycle

During the pressing cycle, the upper mold is pressed over the soft glass to achieve the desired imprint of the lower and upper molds. Molding temperature is achieved for this cycle, and that temperature is held constant while pressing i.e. the pressing process is essentially isothermal.

Cooling Cycle

Objectives

During the cooling or annealing of the formed glass lens from the pressing temperature to the room temperature it is important to make sure that the residual stresses that result are minimum due to the non-uniform cooling and phase change of glass from the pressing temperature to the room temperature. The presence of residual stresses leads to an inhomogeneous refractive index which will deteriorate the optical performance of the lens.

Hence the objective of this cycle is to capture the residual stresses that arise during the cooling of the glass and also estimate the shrinkage of the glass that would give the final profile of the glass at the end of the molding process. As a consequence we will also be able to predict the temperature distribution during the rapid and at the end of the gradual cooling phases.

Figure 7.4 shows the different stages of the lens molding process simulation in Marc. Figure 7.4 a) shows the initial glass and molds configuration during the heating stage, Figure 7.4 b) shows the molding stage in which the glass is pressed between upper and lower molds. Figure 7.4 c) shows the stage where glass is already cooled below its transition temperature and gained its molded shape. It should be noted that the geometry of both molds and glass is simplified for this simulation. Inserts were not taken into account, and molds are presented as two rectangles.

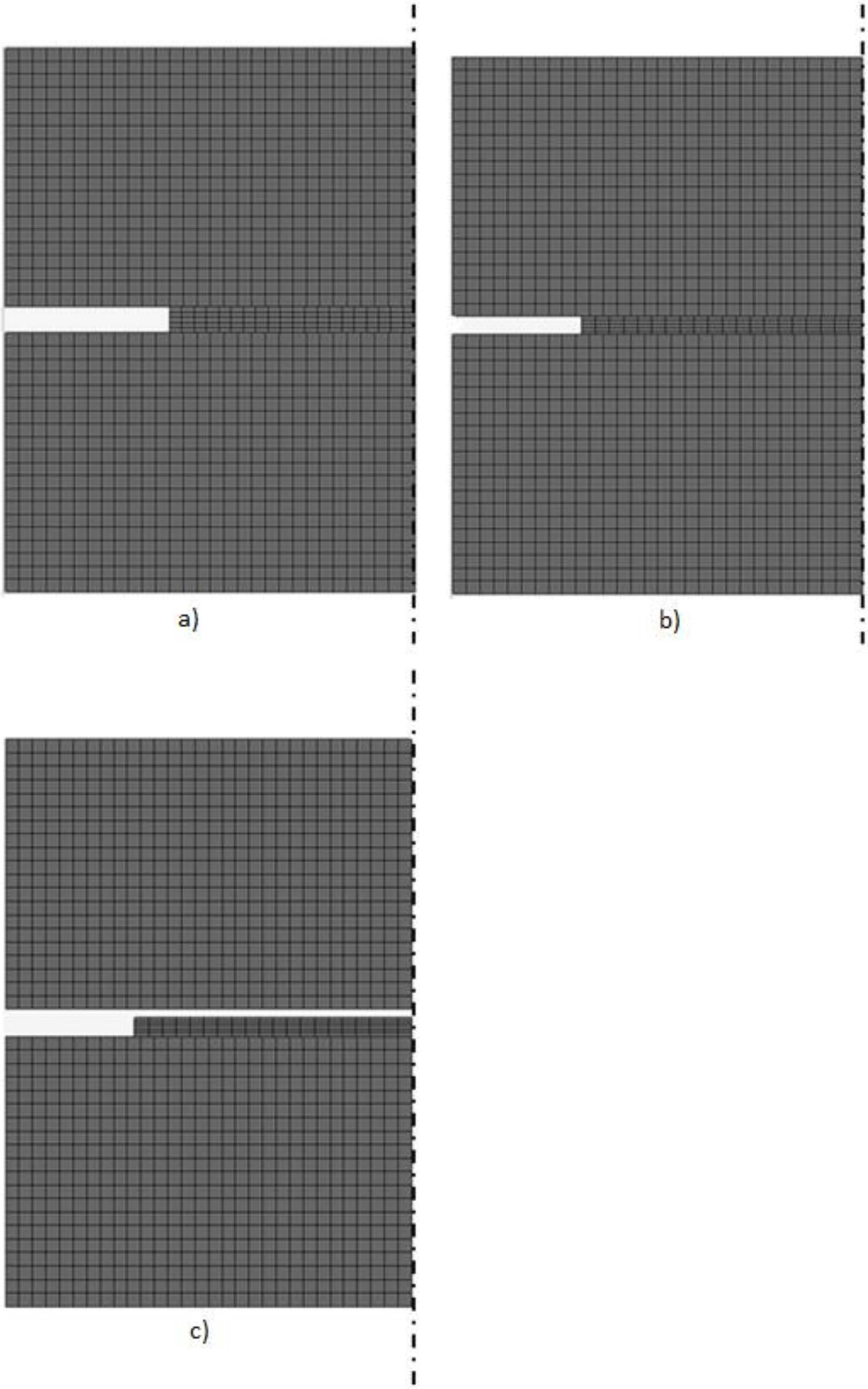


Figure 7.4 Different stages during MARC lens molding simulation (a) heating stage, (b) pressing stage, (c) cooling and lens release

7.3. Results

This part will be dealing with the results obtained from simulation with the geometry presented earlier. Focus is set on residual stresses and shape change influenced by most important part of press molding process, cooling.

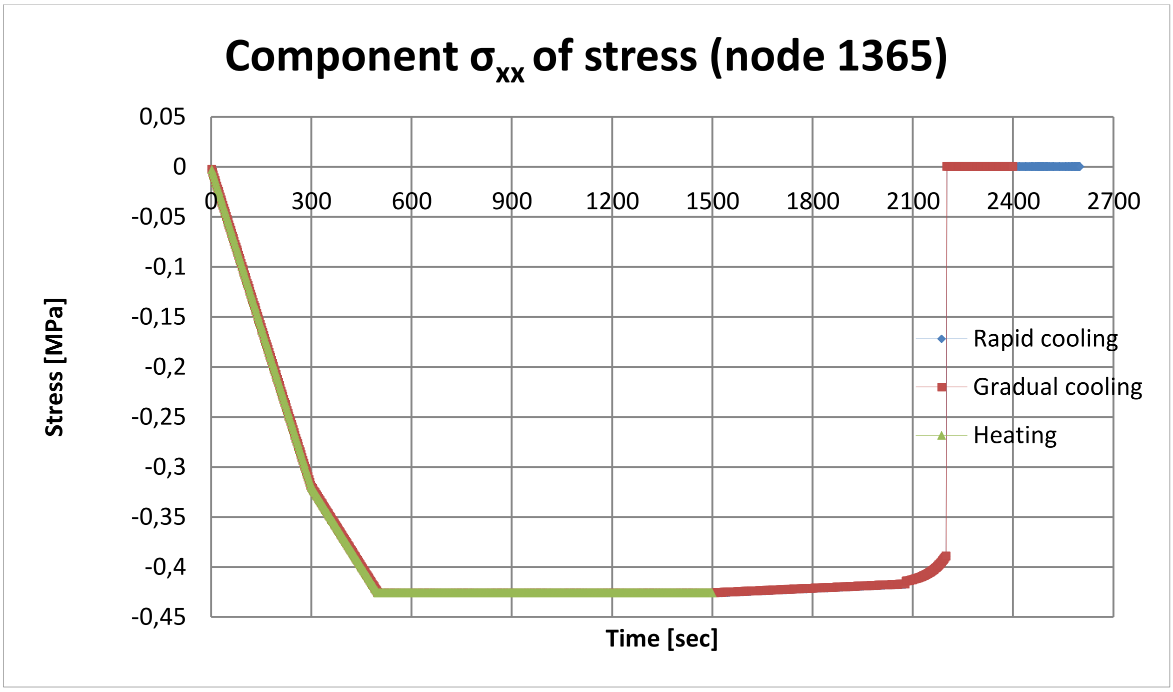


Figure 7.5 Component σ_{xx} of stress during heating, gradual cooling and rapid cooling stage

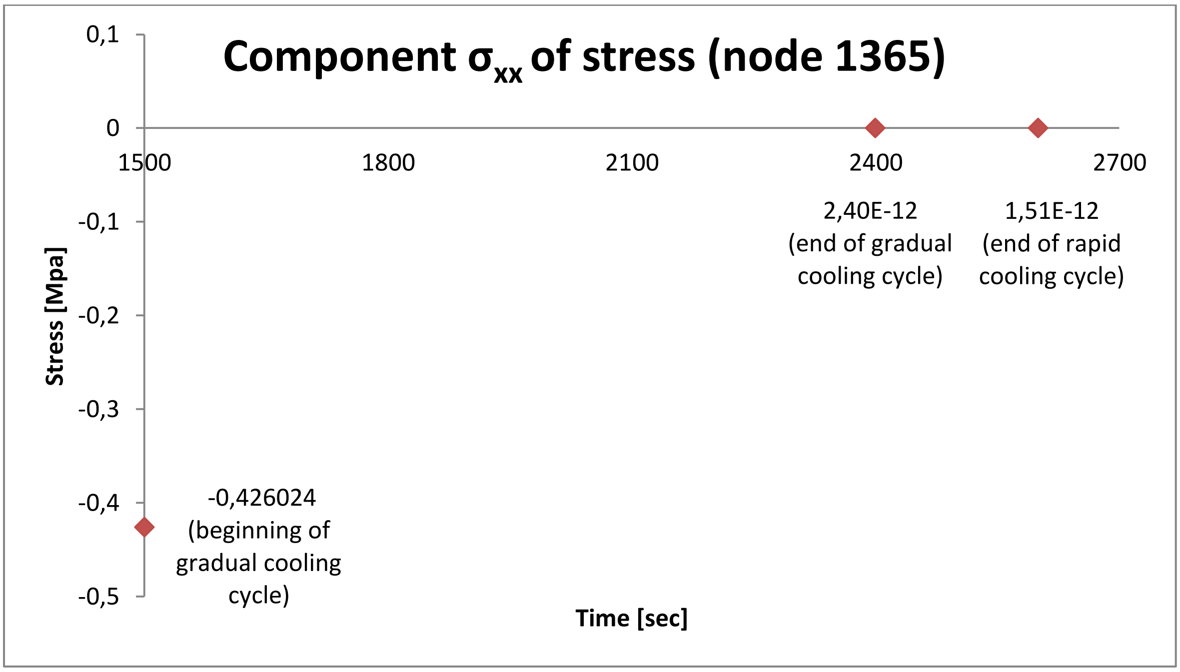


Figure 7.6 Component σ_{xx} of stress at the beginning of gradual cooling. end of gradual cooling and end of rapid cooling cycle

Figure 7.5 is representing how the value of σ_{xx} component of stress, measured at node 1365, changes during the glass press molding cycles. As it is visible from Figure 7.5, stress at the end of the rapid cooling cycle approaches the value of 0, which is the aim of this process. Gradual cooling cycle is the most critical part, because if we cool the glass too fast, the value of residual stress would be much higher.

Figure 7.7 and Figure 7.8 represent component σ_{yy} component of stress, measured at the same node as σ_{xx} component of stress, during the cycles of glass press molding. Similar like in previous case, from these it is visible that at the end of the process value of residual stress approaches zero.

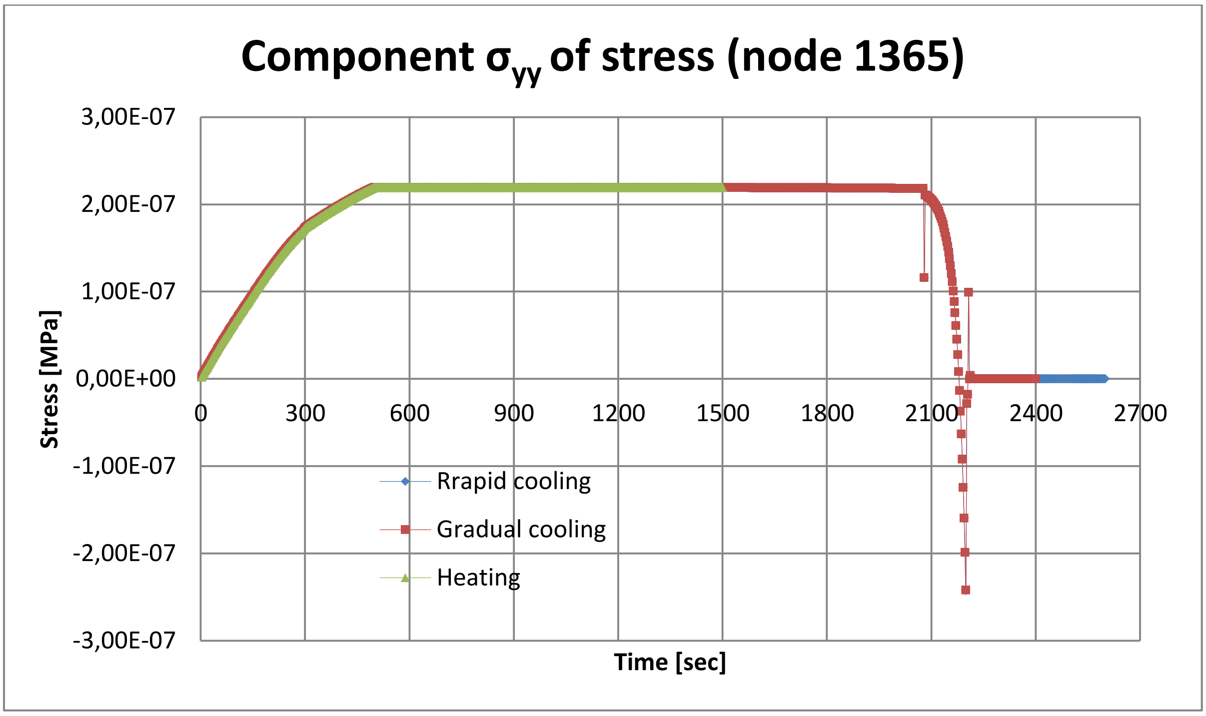


Figure 7.7 Component σ_{yy} of stress during heating, gradual cooling and rapid cooling stage

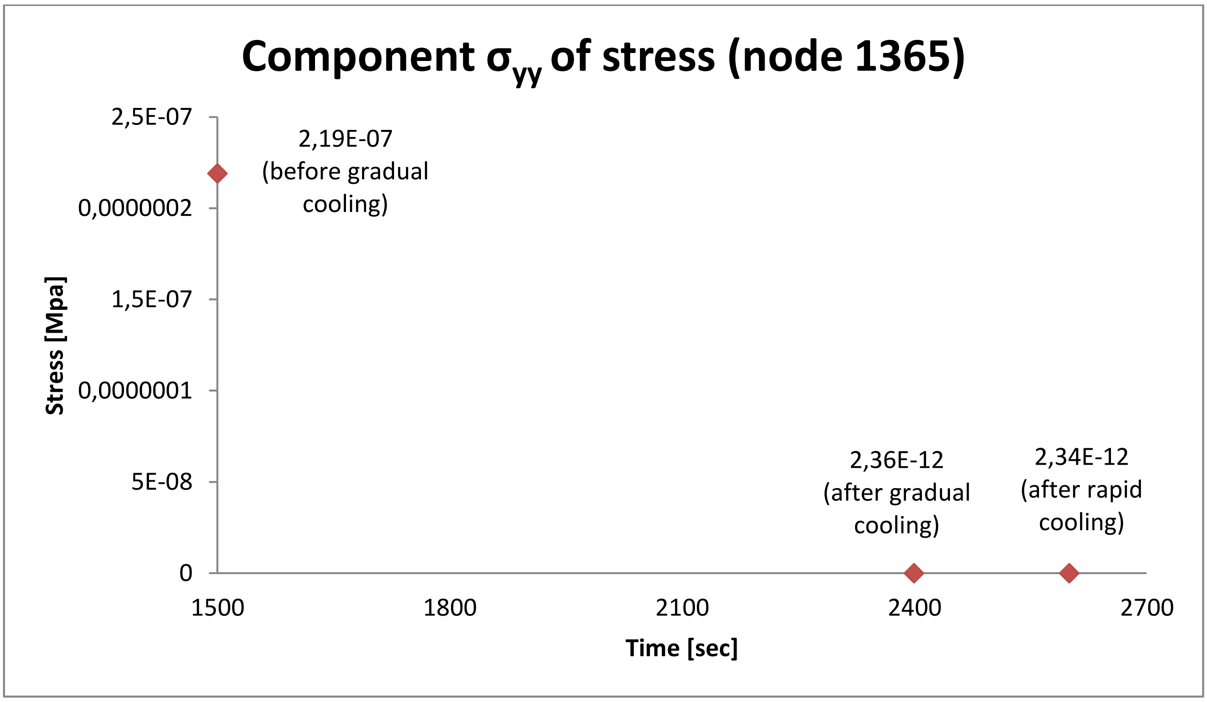


Figure 7.8 Component σ_{yy} of stress at the beginning of gradual cooling, end of gradual cooling and end of rapid cooling cycle

Figure 7.9 shows the change of the shape, measured at arc length of upper part of the glass, at the end of process of glass press molding.

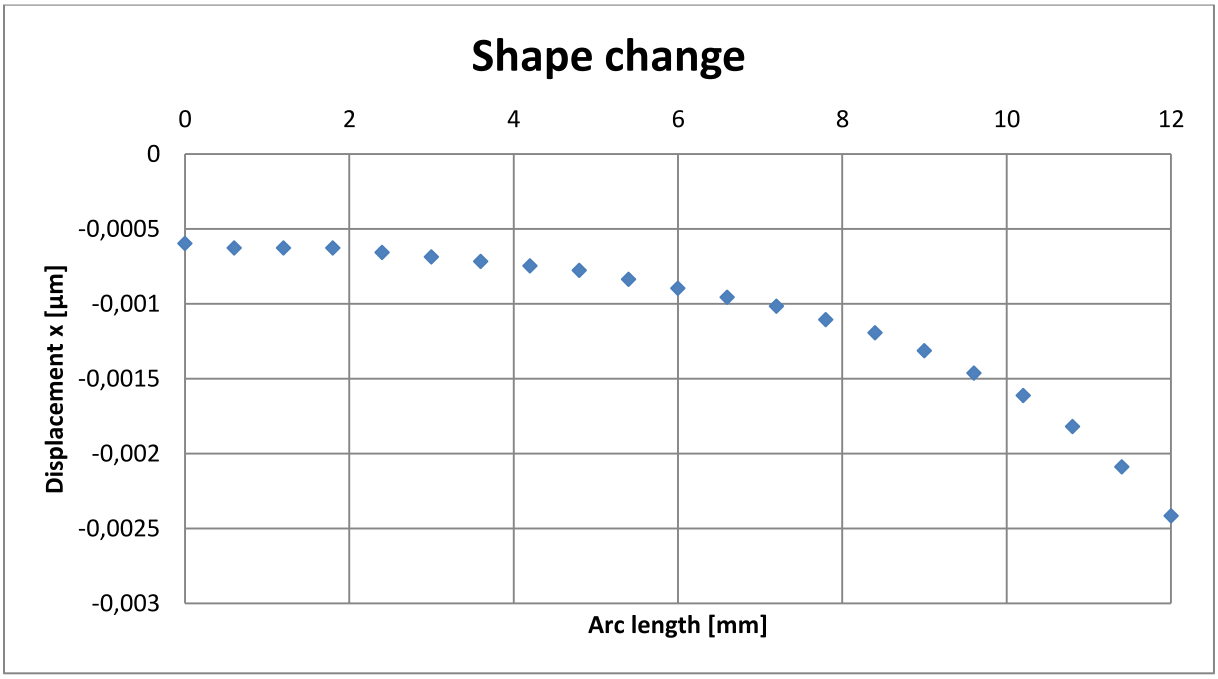


Figure 7.9 Change of the shape at the end of process of the upper part of glass

7.4.Numerical simulation of molding of aspheric lens

The most notable benefit of aspheric lenses is their ability to correct for spherical aberration. Spherical aberration results from using a spherical surface to focus or collimate light. In other words, all spherical surfaces suffer from spherical aberration independent of alignment or manufacturing errors; therefore, a non-spherical, or aspheric surface, is needed to correct for it.

7.4.1. Aspheric geometry

Conventional lenses generally have either cylindrical or spherical profiles. These lenses are relatively easy to fabricate and design. Asphere lenses have a profile which is neither completely cylindrical nor spherical. Aspherical lenses have one or both surfaces that do not conform to a sphere and can theoretically focus all the incoming monochromatic light rays on to a single point on the lens axis. Aspherical lenses are therefore more efficient since they do not need additional error-correcting lenses. Fewer lenses help make the device lighter, smaller and even cheaper.

Its profile is mathematically expressed by what is known as the asphere equation. An asphere lens can consist of multiple segments hence giving more flexibility to design the lens profile. The segments can be asphere, flat, spherical etc.

The profile of the upper mold used in simulation is described by an asphere shape. Equation 7.1.3 describes the asphere curve of the upper mold profile.

$$Z = \frac{Y^2}{r(1+\sqrt{1-(1+K)Y^2/r^2})} + A_2Y^2 + A_4Y^4 + A_6Y^6 + A_8Y^8 + A_{10}Y^{10} \quad (7.1.3)$$

where r is the radius, K is the conic constant, and A_2, A_4, A_6, A_8 and A_{10} are the asphere coefficients.

Parameters for the equation 7.1.3 are given in the Table 7.4

Table 7.4 Aspheric coefficients

	r	K	A_2	A_4	A_6	A_8	A_{10}
S_1	PLANO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
S_2	1.586014	-2.062694	0.000000	4.968263E-2	-6.116114E-3	1.717442E-3	-4.643557E-4

7.4.2. Materials

Type of glass used in this simulation is D-ZLaF52LA. Parameters of glass used in this simulation are represented in Table 7.5. Molds are modeled with the same material like in numerical simulation for test lens described in Chapter 6.2. Parameters for stainless steel 1.4305 from Table 6.3 were used in simulation.

Table 7.5 Properties of glass

	D-ZLaF52LA	
Density	4560	$kg \cdot m^{-3}$
Young's modulus	11506	MPa
Poisson's ratio	0.3	(1)
Glass transition temperature	546	°C
Shear modulus	4427	MPa

In Table 7.6 are shown glasses equivalent with glass used in this simulation, and their manufacturer.

Table 7.6 Equivalent glasses

Manufacturer	Glass
Hoya	M-NBFD130
Ohara	L-LAH53
Sumita	K-VC89

Advanced solution feature, global remeshing, is used in this simulation in order to improve accuracy of the results. Type of remeshing used here is global remeshing, which is used for problems exhibiting very large strains and mesh distortion.

On the Figure 7.10 is shown geometry made in Marc, for molding the aspheric lens.

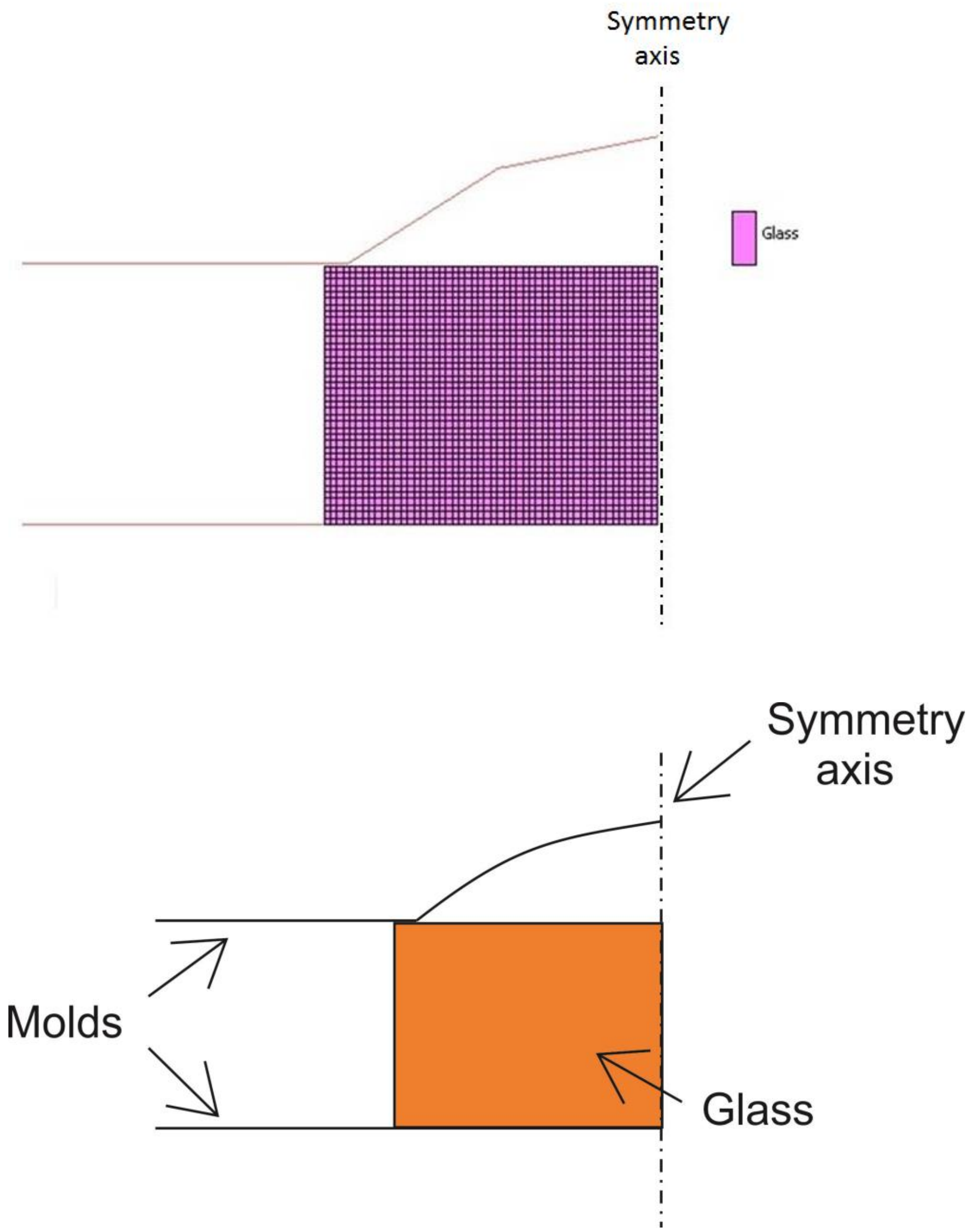


Figure 7.10 Geometry of molds and glass

7.4.3. Results

In this part the results obtained by simulation will be presented. On Figure 7.11 it is shown the value of σ_{xx} component of stress, measured at node 1111. As it is visible from the graph, value of residual stress towards the end of process approaches zero. Similarly, on Figure 7.12 it is shown the value of σ_{yy} component of stress, measured at the same node.

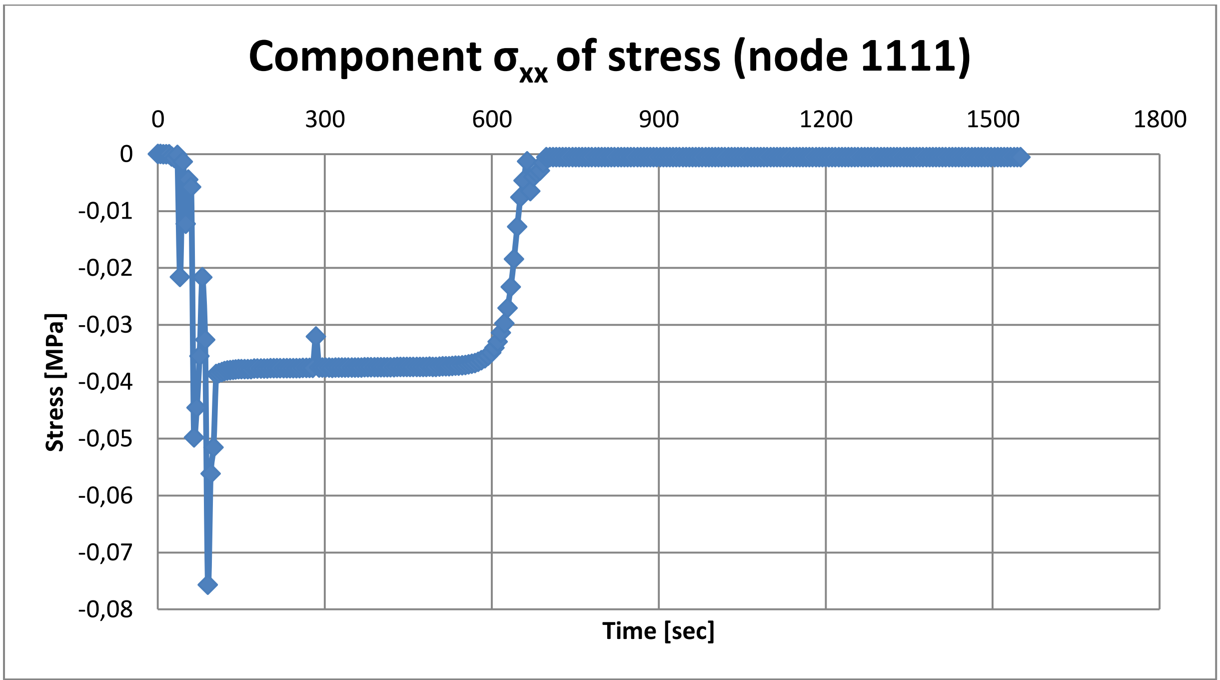


Figure 7.11 Value of σ_{xx} component of stress

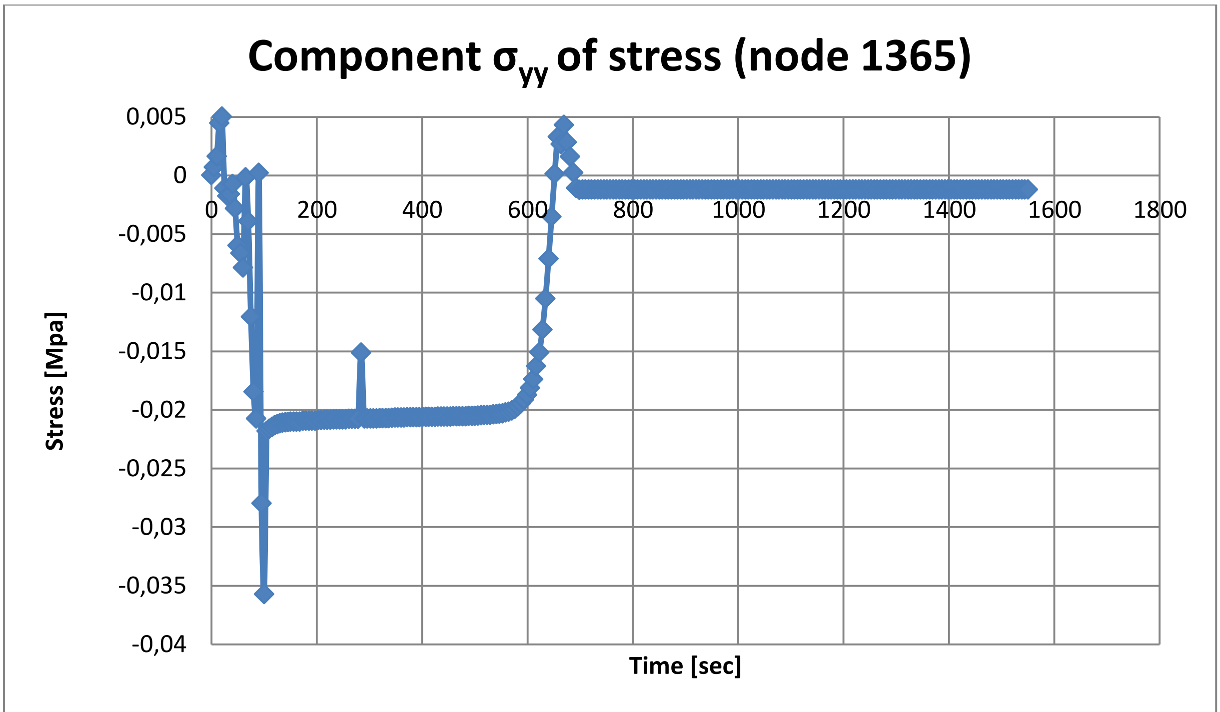


Figure 7.12 Value of σ_{yy} component of stress

It should be noted that the peaks that are showing up on figures Figure 7.11 and Figure 7.12 are due to the remeshing used in simulation, which was mentioned earlier in this chapter.

On Figure 7.13 it is represented the final shape of the glass, obtained by simulation, with the mold that has aspheric profile.

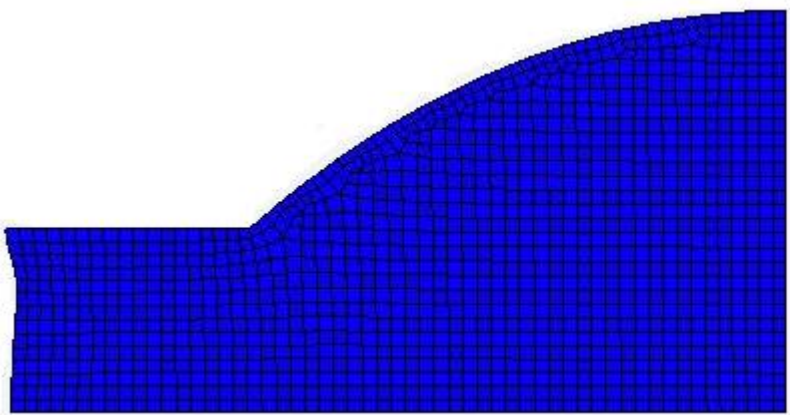


Figure 7.13 Final shape of the glass at the end of simulation

On Figure 7.14 it is represented the comparison between the aspheric profile of the glass at the end of the simulation, and the initial shape of the aspheric surface of the mold. As it is visible from the figure, these two profiles are in a good agreement with each other.

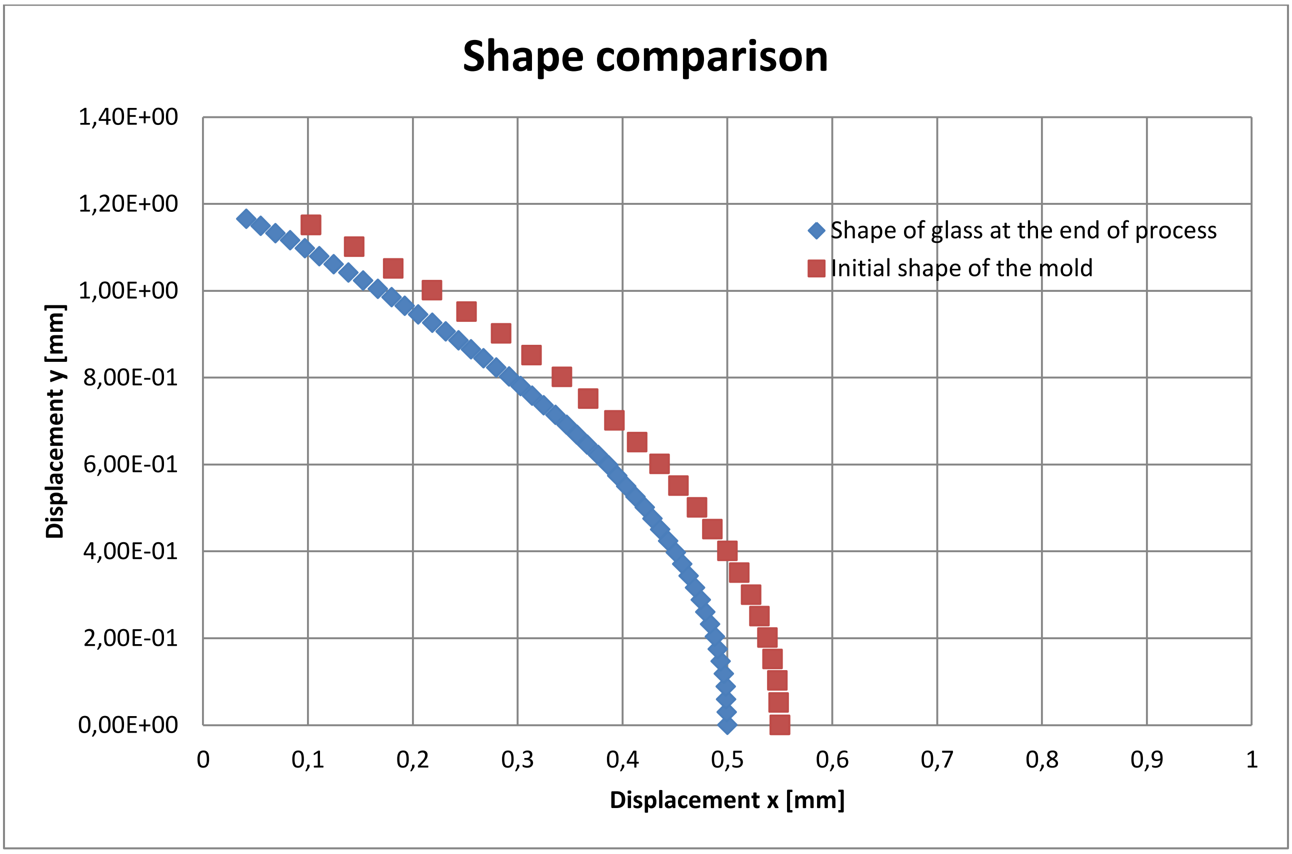


Figure 7.14 Comparison of the aspheric shape of glass and mold

8. Conclusion and future work

This research was used to show possibility of numerical modeling of glass press molding process. We were able to develop material model for simulation that shows good agreement with experimental results.

Experiments were performed on commercial glass press molding machine, and parameters from experiments were used to run the simulation. FEM model was developed firstly for test element, and then it was used to perform simulation on real element. Results from simulations are in a good agreement with the theory of process of glass press molding.

The progress in numerical prediction of the glass molding process opened doors to the volume production of precision asphere lenses. This method replaces expensive and time consuming traditional methods. The main goal of glass molding process is to manufacture precise aspherical optics for reasonable price. This goal could not be achieved without deep knowledge of the thermomechanical processes, without detailed data of thermomechanical properties of used materials and without possibility to perform numerical simulation. Advantage is also that numerical simulations save time and costs of inserts which can be pretty expensive if they are made from hard stiff materials like WC (wolfram carbide) or SiSiC (siliconized silicon carbide).

FEM approach can be used to study different process phenomenon which are difficult or sometimes impossible to observe from real experiments such as glass material flow behavior, stress variation in glass during the molding cycle and residual stress distribution in a molded lens for a given set of conditions. It is important to minimize residual stresses as much as possible, because they influence optical properties and are detrimental to proper function of the lens.

In order to obtain more accurate results as mentioned earlier, experiments for obtaining exact material parameters should be conducted. Without correct parameters for material model, simulation will not show good results. Because of that, emphasis should be put on experiments such as compression tests, beam bending test etc.

Special attention should be put on things which we can improve in the future. Among them are:

1. We need to be able to measure material properties, and to determine material parameters.
2. We need to be able to manufacture inserts from CW.
3. We need to develop coatings.
4. For large elements it is necessary to manufacture pre-molds; usually by classical technology.
5. We need to focus in reducing the time of the cycle, and by using numerical simulation we can obtain optimal parameters for our experiments.

9. Literature

1. Gaylord Scott, 2008. *Thermal and structural properties of candidate moldable glass types*, Master thesis, Clemson University, 114 p.
2. Hemanth Kadali, 2009. *Experimental characterization of stress relaxation in glass*, Master thesis, Clemson University, 91 p.
3. Jain A., L. Li, and A. Y. Yi, Columbus, F. Klocke, G. Pongs, and F. Wang, 2005. A collaborative research in experimental study and numerical simulation of compression molding of precision glass optical elements, *20th Annual ASPE Conference on Precision Engineering*, Norfolk, VA.
4. Jain, A., Firestone, G. C. and Yi, A. Y., 2005. Viscosity Measurement by Cylindrical Compression for Numerical Modeling of Precision Lens Molding Process. In *Journal of the American Ceramic Society*, Vol. 88, No. 9, pp. 2409-2414.
5. Jain Anurag, 2006. *Experimental study and numerical analysis of compression molding process for manufacturing precision aspherical glass lenses*, Dissertation, The Ohio State University, 175p.
6. Jiwang Y., Tianfeng Z., Jun M. and Tsunemoto K., 2008. Modeling high-temperature glass molding process by coupling heat transfer and viscous deformation analysis. In *Journal of the International Societies for Precision Engineering and Nanotechnology*, Volume 33, Issue 2, pp. 150-159.
7. Koontz Erick, 2015. *Characterization of structural relaxation in inorganic glasses using length dilatometr,* Dissertation, Clemson University, 213p.
8. Madapusi Shriram Palanthandalam, 2009. *A computational tool for numerical prediction of precision glass molding process*, Master thesis, University of Florida, 95 p.
9. Madapusi Shiriram, Nam-Ho Kim, Yazid Tomhe, 2009. Predictive molding of precision glass optics, SAE World Congress, Detroit, MI, 7 p.
10. Málek Jiří, Shánělová Jana, 2005. Structural relaxation of As2Se3 glass and viscosity of supercooled liquid. In *Journal of Non-crystalline Solids*, Vol. 351, pp. 3458-3467.
11. Osswald, T.A., 1998, Properties Table, Polymer Processing Fundamentals, Hanser Publishers, Cincinnati, USA, pp. 217-226.
12. P.E. Viollaz, S.M. Alzamora, A.B. Nieto, 2002. Structural relaxation in glasses: nuemrical exploration of variables of Narayanaswamy and Moynihan’s model. In *Journal of food and engineering,* Vol. 56, pp. 393-399.
13. Schott Glass Inc, ‘’Products and Applications’’. Accessible from: http://www.schott.de
14. Zhang Xiaobing, Yin Shaohui, 2015. Study on high-temperature glass lens molding process using FEM simulation. In *Journal of the open materials science,* Vol. 9, pp. 14-19.