Cooling Optimization Simulation with Finite Element Method Used for Manufacturing of Polycarbonate Lens

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Abstract

The topic of this research work was to demonstrate the feasibility of the Rapid Heat Cycle Molding (RHCM) for lenses injection in which the cooling time accounts for approximately half of the cycle. Thermal structural analysis of FEA transient (Moldex3D) was used to determine the effects of RHCM to optimize the cooling cycle time. However it is impossible with standard cooling channel to reach a lower cooling time. To solve this problem, the additional cooling channels were made to interact with the inserts closer to the injection part. The hotspot issue was addressed by laser sintering method. The standard cooling channel geometry and cooling insert geometry were both analyzed for comparison of cooling time. The results showed that the cooling time decreased by 30-70 percent compared to previous process with no effect on the lenses' quality.

Keywords: Injection molding, Simulation, Moldex3D, Laser sintering, Rapid heat cycle molding (RHCM)

Introduction

The ophthalmic lenses find use in the medical prescription business in order to solve vision disorders and provide better vision to people suffering from presbyopia, myopia, or both. These lenses are produced by injection molding of polycarbonate plastic (PC) which has the properties of good transparency and toughness matching with the requirements.

The injection molding cycle consists of many component processes shown in Figure 1.

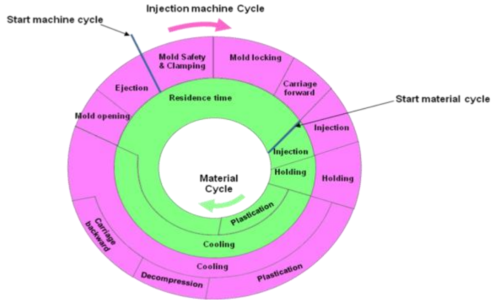

Figure 1 An injection molding cycle.

In figure 1, there are three important phases which are the injection phase, holding phase and cooling phase. However, the cooling time is the most critical component of a cycle are part of cooling time which accounts for approximately half of the cycle. The cooling time affects the entire molding cycle and therefore must be optimized to achieve a cycle time reduction.

Due to the fact that a large amount of injection molding machine hours are spent each year for making products, any reduction in this number of machine hours (required to make a certain number of parts) would result in substantial cost savings [1]. The Rapid Heat Cycle Molding (RHCM) process is introduced to achieve a reduced residual stress free condition and reduced cooling time as well. The RHCM process is used to increase the mold temperature during filling phase, and rapidly reduce the mold temperature at the beginning of packing.

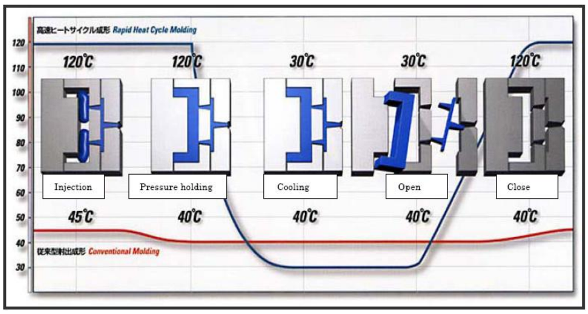

Figure 2 Rapid heat cycle Molding Method compared to conventional Molding

Therefore with high temperature in filling phase, residual stress could be reduced and as cooling process starts at a low temperature, it could shorten the required cycle time. Due to its excellent balance in product performance and production cost, RHCM has gained a lot of attention in plastic injection molding industry recently [2]. The goal of this paper was to demonstrate the feasibility of the Rapid Heat Cycle Molding (RHCM) for lenses' injection of polycarbonate (PC) type.

Theory Background

An injection molding method is a plastic casting method by transforming a "solid" (pellet) , via heating and shearing effect, into a "liquid" or molten state followed by injection of this liquid mass in a mold block for a shape formation and eventual solidification. Thereafter, the mold block is opened to extract the molded pieces, once polymer is solidified (cooled).

Simulation is the process of creating and experimenting with a computerized mathematical model of a physical system.

Moldex3D is the commercial finite element software for finding the ability of three-dimensional (3D) flow of complex injection molding processes.

Finite element method is a numerical technique that makes the domain of a continuous structure discrete, thus errors are inevitable.

Laser sintering method uses laser beam to melt the powder metal layer by layer to solidify it which also can have cooling channel inside.

Rapid heat cycle molding (RHCM) is a method for heating up, before start of injection phase, to make the surface of part and/or core quickly heated-up for reducing residual stress in final product and bringing temperature down during the cooling phase.

An important benefit of rapid heat cycle molding (RHCM) is the improvement of the filling ability of the polymer melt. This novel injection molding technique, using RHCM, involves heating-up rapidly to a high temperature, usually higher than the glass transition temperature of the polymer material, before melt-injection, followed by rapidly cooling down to solidify the shaped polymer melt in mold cavity for ejection.

Minimum Cooling Time

Cooling time is a function of polymer material properties, part thickness and molding temperatures. The relationship between these variables is given by the following equation.

$$t_c = \frac{h^2}{\alpha\pi^2}\ln\left|\frac{4}{\pi}\left(\frac{T_M}{T_E}-\frac{T_W}{T_W}\right)\right| \qquad (1)$$

Where t_c is minimum cooling time, α is the thermal diffusivity of the material, h, is the wall thickness, T_w is the mold wall temperature, T_m is the melt temperature, capital T_e is the ejection temperature

Energy Conservation

During the molding cooling process, a three-dimensional, cyclic, transient heat conduction problem with convective boundary conditions on the cooling channel and mold base surfaces is involved. The overall heat transfer phenomenon is governed by a three-dimensional Poisson equation,

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \qquad (2)$$

Where T is the temperature, t is the time, x, y, and z are the Cartesian coordinates, ρ is the density, C_p is the specific heat, k is the thermal conductivity. Equation (1) holds for both mold base and plastic part with modification on thermal properties.

Initial Condition

The mold temperature is initially assumed to be equal to the coolant temperature. The initial part temperature distribution is obtained from the analysis results at the end of filling and packing stages.

$$T(0,\vec{r}) = \begin{cases} T_c, \ for\ \vec{r} \in \Omega_p \\ T_p(\vec{r}), for\ \vec{r} \in \Omega_p \end{cases} \qquad (3)$$

Boundary Conditions

Heat of the molten plastic part is removed by the coolant flowing through the cooling channel as well as the ambient air surrounding the exterior surfaces of the mold base via a heat convection mechanism. In this work, the effect of thermal radiation is ignored. The conditions defined over the boundary surfaces and interfaces of the mold are specified as,

$$for, t \geq 0, -k_m \frac{\partial T}{\partial n} = h(T - T_0) \quad (4)$$

Where n is the normal direction of mold boundary. On the exterior surfaces of the mold base Γ_m:

$$h = h_{air}, T_0 = T_{air} \quad for\ \vec{r} \in \Gamma_m \quad (5)$$

On the cooling channel surfaces Γ_c:

$$h = h_c, T_0 = T_c \quad for\ \vec{r} \in \Gamma_c \quad (6)$$

The heat transfer coefficients h_c and h_{air} are obtained from the empirical equations cited in the standard text of transport phenomena.

Numerical Discretization Method

In this work, a numerical solution based on Finite Volume Method (FVM) is developed to solve the governing equations. The solution has been successfully applied in injection molding filling simulation [3]. Numerical experiments confirm its reliability and efficiency. Currently the proposed solution can handle tetra, hexa, prism, pyramid, and mixing elements. Prism layer element can also be used for analysis to improve thermal boundary resolution while without extensive refining of mesh. This is valuable in mold cooling analysis that may involve millions of elements.

Results and Discussions

Conventional Molding Process

Figure 3 shows the geometry of mold part and the layout of conventional cooling channels are adopted as the CAE simulation model. In the first analysis of the running process the whole mold was considered as used by following the actual process in production. It was analyzed for reference that can be compared with conformal cooling design simulation.

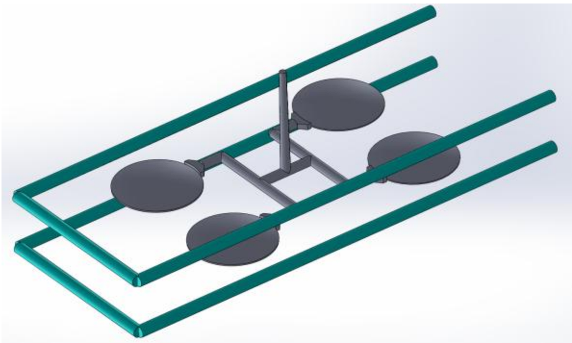

Figure 3 The geometry of the molded part with conventional cooling channels.

Figure 4 The simulated results of mold temperature distribution at lens for conventional cooling design.

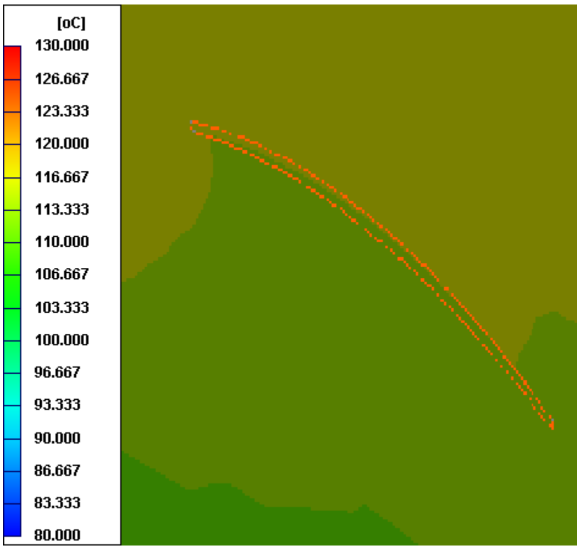

Figure 4 Mold temperature distribution for conventional cooling design

Figure 5 displays the simulated results of shear rate behavior. The distribution of shear rate of part cavity is shown in different colors at current instance. Since shear rate is the rate of shear deformation of the material during the polymer processing, it can be observed in figure 5 that the shear rate is homogeneously distributed on the part. Slightly increased shear rate can be observed only at the brink. Shear rate distribution is not related to the variation of velocity gradient and molecular weight and monomolecular entanglement of polymer chains. High shear rate tends to drastically deform molecular chains, breaking and then lowering the strength of product. From the picture, maximum shear rate was less than 300/sec.

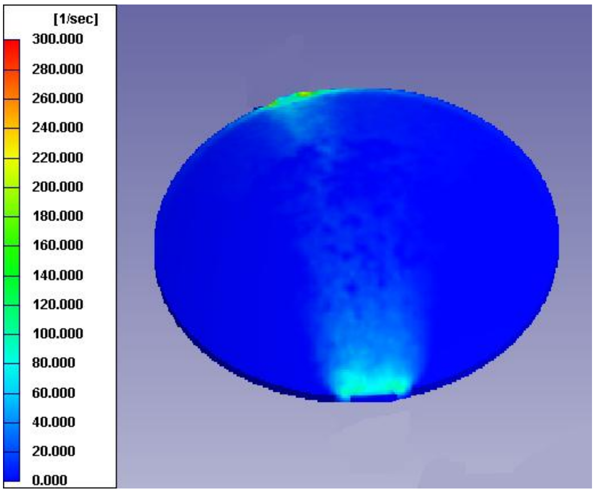

Figure 5 Shear rate behavior for conventional cooling design

Shear stress behavior is demonstrated in figure 6. The shear stress at current instance is shown in different color according to different stress levels. Shear stress is one of sources of the molded-in residual stress in molded parts. If the shear stress is not distributed evenly, it will cause some dimensional problems. Too high the shear stress level will result in stress-induced problems in the molded part. From the picture, shear stress maximum was less than 10 MPa.

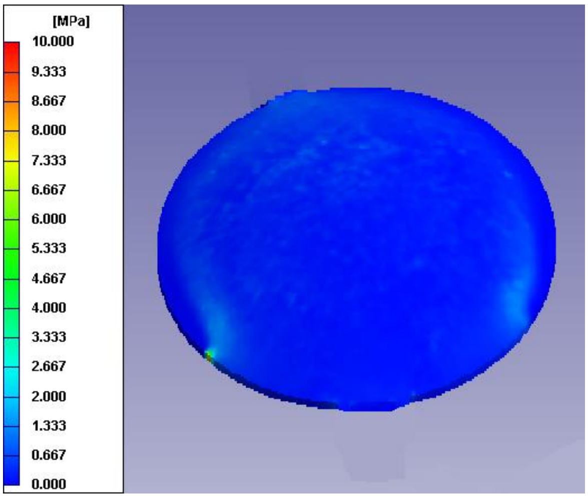

Figure 6 Shear stress behavior for conventional cooling design

Figure 7 shows residual stress behavior. It was a scalar form of the components of the stress tensor and represented the overall magnitude of the residual stress tensor. One can see that the residual stress maximum is less than 20 MPa.

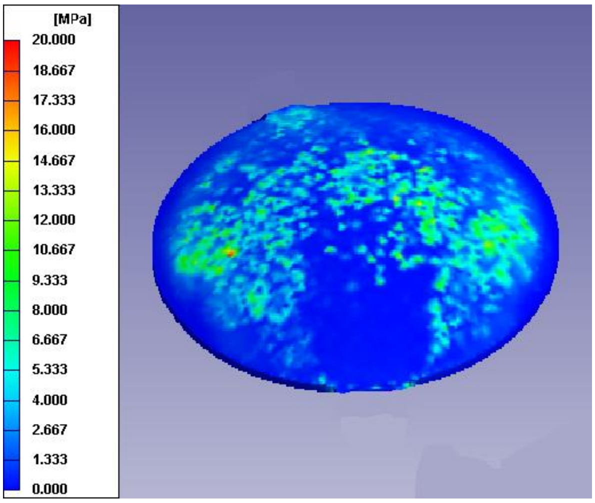

Figure 7 Residual stress behavior for conventional cooling design

Figure 8 displays the lens displacement behavior. The length of the total displacement vector after the parts were ejected and cooled down to room temperature is relative to the model coordinate. From the picture, maximum lens displacement is less than 2 mm.

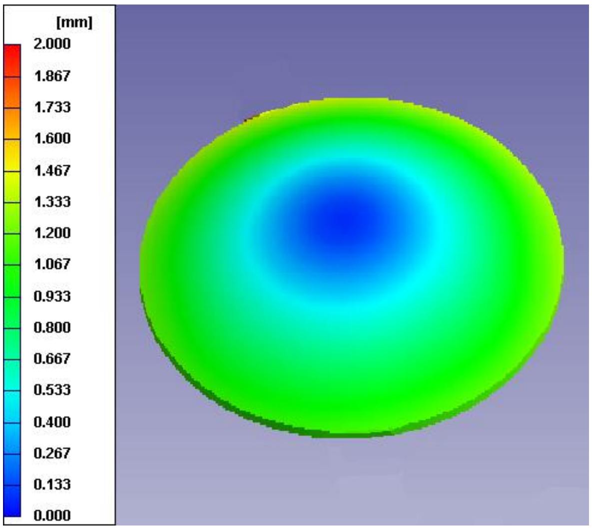

Figure 8 Lens displacement behavior for conventional cooling design

From the above five figures, we can see that is a reference from conventional process to achieve good lenses quality.

The RHCM Process with Conformal Cooling Channel

Figure 9 shows the layout of conformal cooling channels which had been added on both sides of optical surface. In order to demonstrate the advantage of RHCM process, the cycle-average approach was used to simulate the conventional molding process, whereas the fully transient true 3D approach was used to simulate the RHCM process. The process settings during filling and packing analysis were used as actual process parameters. But in conventional molding process, the temperature of coolant is constant. In RHCM process, the cooling channels (carrying high temperature steam) behave as heating rods during filling phase and as low temperature coolant during packing and cooling phases. The simulation results are discussed in the following description

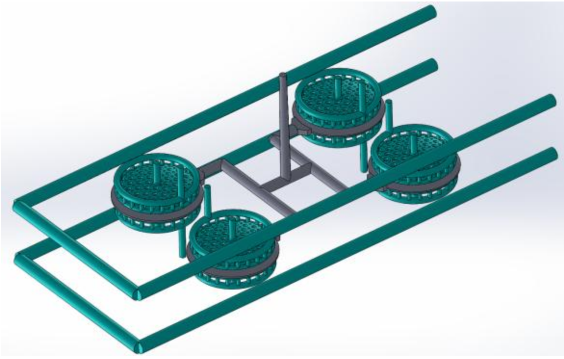

Figure 9 The geometry of the molded part with additional conformal cooling channels.

The simulated results of mold temperature distribution at lens for conformal cooling design with RHCM process in heating and cooling phases are given in figures 10 and 11 respectively. One can notice that the mold temperature distribution rises at the beginning of filling phase (cf. figure 10), whereas the mold temperature of cooling phase is much lower than before.

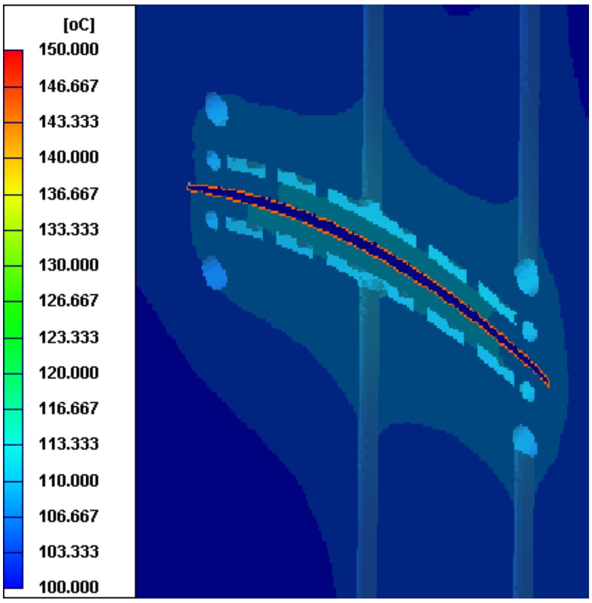

Figure 10 Mold temperature distribution for conformal cooling design with RHCM process in heating phase

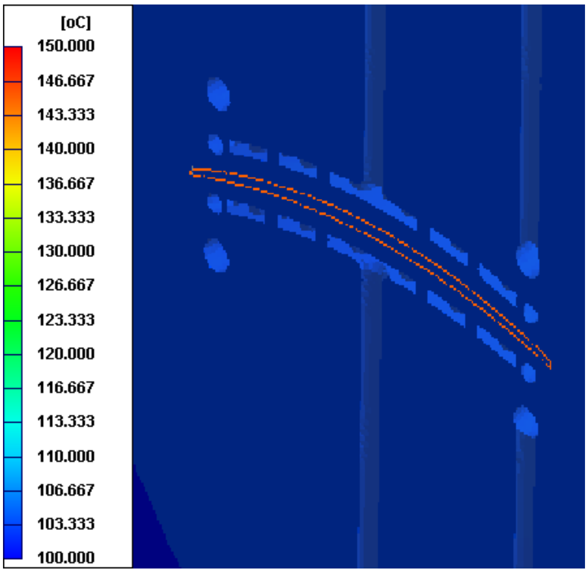

Figure 11 Mold temperature distribution at lens for conformal cooling design with RHCM process in cooling phase

For lenses manufacturing the part displacement is very importance. Because if the lenses geometry was different. It can be also created the different optic and power which will not correct with wearer. Therefore the criterion for determine cooling time in simulation is using trial and error method which increasing cooling time step by step. Start from the conventional process ejection temperature. Until the result of lens displacement reach same as conventional process lenses displacement. Figure 12 shows lens displacement vs. cooling time. Note that X is the reference of conventional displacement. The intersection point of lenses displacement between conventional process and conformal cooling design with RHCM process was showed optimize cooling time was around 94.62 second.

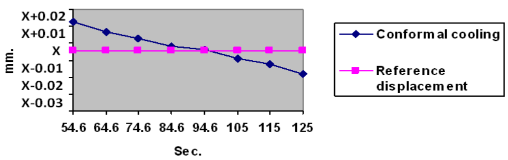

Figure 12 show lens displacement vs. cooling time for cooling time estimation

Optimize cooling time at 94.62 was put in simulation to analyze another lenses defect. Figure 13 show shear rate behavior. From the picture shear rate maximum is less than 300 1/sec.

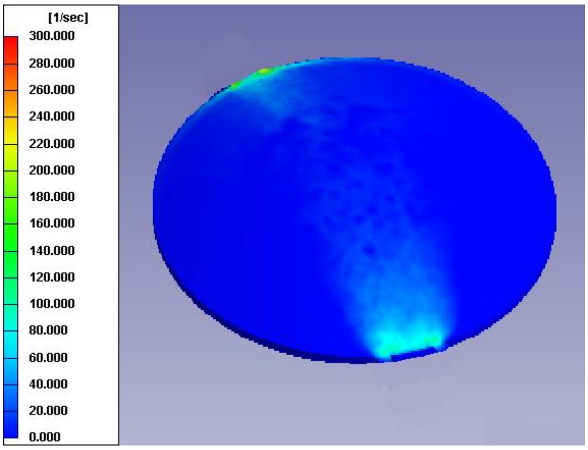

Figure 13 Shear rate behavior for conformal cooling design with RHCM process

Figure 14 show shear stress behavior. From the picture maximum shear stress is less than 10 MPa.

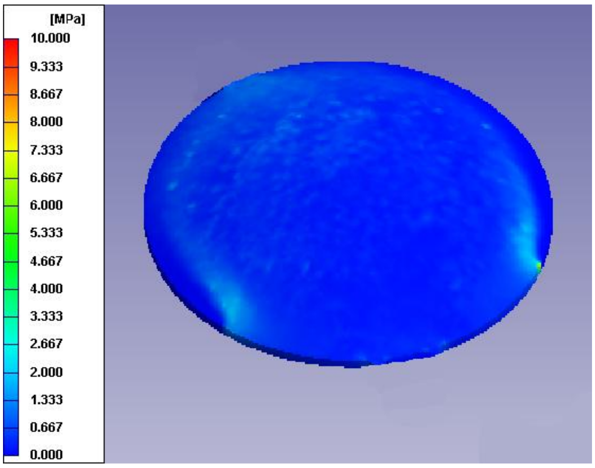

Figure 14 Shear stress behavior for conformal cooling design with RHCM process

Figure 15 shows residual stress behavior. From the picture residual stress maximum is less than 20 MPa.

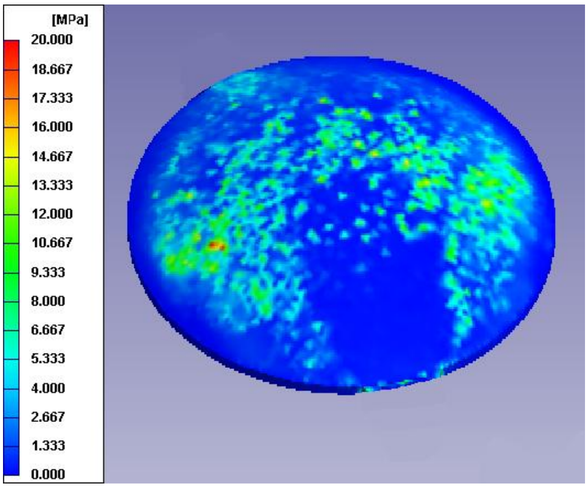

Figure 15 Residual stress behavior for conformal cooling design with RHCM process

From the above three figures, shear rate, shear stress and residual stress were considered for lenses quality of conformal cooling design with HRCM process for comparison with conventional cooling design. The results of both processes are similar, which means conformal cooling design with RHCM does not have much influence on lenses quality. Note that RHCM process enhanced the cooling time remarkably compared to conventional molding process.

Conclusion

In this research, an integrated fully transient true 3D approach was proposed by considering the interplay between filling/pack and cooling phases. A further application of RHCM process was discussed and the use of RHCM process in lenses injection molding was taken into consideration. The results of thermal analysis correlated closely to theoretical values. An important observation of thermal analysis is that the cooling time of the lenses geometry approach the theoretical minimum cooling time. We could see that by optimizing the design and process we were able to achieve a reduced cooling time of 94.62 second, which is around 30-70 percent of that in conventional process with no effect on the lenses' quality.

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