Systematic Influence Investigation of Key Parameters for Precision Glass Moulding Process Based on Self-developed Simulation Tool - SimPGM

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Abstract

Recently, precision glass moulding is becoming a very important manufacturing technology for precise glass optical components. The quality of moulded optical components is strongly related to process parameters, such as temperature, load and cooling rate. The influence of these parameters is still unclear due to the complexity of precision glass moulding process. In this study, sensitivity analysis of process key parameters is carried out based on self-developed simulation tool SimPGM, as a preparation step for further study of glass moulding process optimization.

1 Precision glass moulding process and simulation tool

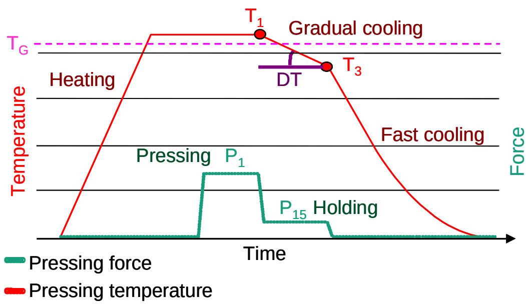
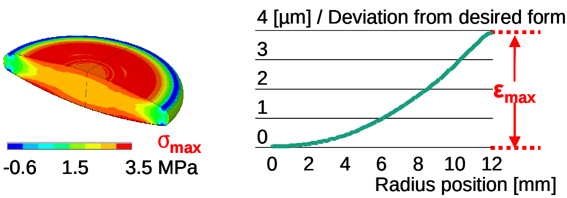


Figure 1: Process and key parameters of precision glass moulding

In a precision glass moulding process (Fig. 1), preformed glass raw material is firstly heated to forming temperature T_1, which is above its transition temperature T_g. Then the pressing force P_1 is applied to form the glass into lens shape. When the predefined pressing time is reached, the cooling process starts. Under specified cooling rate DT, the system is gradually cooled down to T_3 (around T_g). Meanwhile, the pressing force is switched to holding force P_{15} to maintain the lens shape. Then the fast cooling phase is carried out to cool down the system to room temperature. In this phase, no holding force is applied.

From previous experience, the crack of moulded lens mostly happens at the end of the gradual cooling stage, because the holding force is applied on the solid like glass. Therefore the maximum principal stress (σ_{max}) (Fig. 2) is introduced to evaluate this problem. After the moulding process, the form of the optical surface of the moulded lens will be measured and compared with the design form (Fig. 2). The maximum form deviation is indicated by ε_{max}. To ensure the high quality of the moulded lens, both σ_{max} and ε_{max} should be minimized.



(1) (2)

Figure 2: Lens quality evaluation parameters (1) Maximum principal stress distribution at T_3, (2) Maximum form deviation of the moulded lens

Generally, the measurement of ε_{max} takes a lot of manpower, and the in-process measurement of σ_{max} is impossible. Thus, an FEM simulation software SimPGM, developed by Fraunhofer IPT was used to predict the maximum principal stress distribution and form deviation of the moulded lenses[1].

2 Investigation for single parameter influence

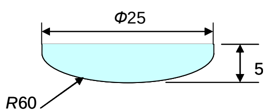


Figure 3: Dimensions of moulded lens

The demonstrator of this study is a flat-convex lens with 60 mm radius (Fig. 3). The values of key parameters are defined by experience (Table 1), where status 0 and 2 indicate lower and upper borders for each parameter and their middle value is used as the standard status. For each simulation, the status of only one parameter is changed, which generates a simulation group with 11 variations (Table 1).

Status		0	1	2
T1	°C	560	565	570
T_3	°C	503	493	483
P_1	N	500	2000	4000
P_{15}	N	400	1600	3200
DT	°C/s	0.5	0.9	1.9

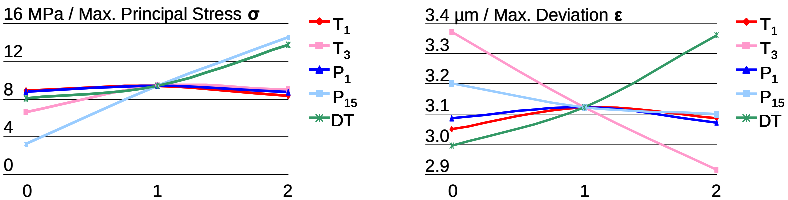
(1)

Grp.	T_1	T_3	P_1	P_{15}	DT
1	1	1	1	1	1
2	0	1	1	1	1
3	2	1	1	1	1
4	1	0	1	1	1
5	1	2	1	1	1
6	1	1	0	1	1
7	1	1	2	1	1
8	1	1	1	0	1
9	1	1	1	2	1
10	1	1	1	1	0
11	1	1	1	1	2

(2)

Table 1: Definition of key parameters (1) the range of value (2) status matrix for single parameter influence

Fig. 4 shows simulation results of all 11 variations. The maximum principal stress strongly depends on P_{15} and DT, while the maximum deviation is sensitive to T_3, P_{15} and DT.



(1) (2)

Figure 4: Influence of key parameters: (1) Maximum principal stress at the end of the gradual cooling stage, (2) Maximum form error after moulding

3 Sensitivity analysis of key parameters – Latin Hypercube method

The sensitivity analysis of key parameters is carried out based on Latin Hypercube (LH) method[2]. T_1, T_3, P_1, P_{15} and DT are considered as design variables, while simulation outputs $\sigma_{\max}$ and $\varepsilon_{\max}$ are used to construct objective function:

$$\begin{cases} f_{obj} = \delta_1 \sigma^* + \delta_2 \varepsilon^* \\ \delta_1 + \delta_2 = 1 \\ \sigma^* = \sigma_{\max} / \sigma_{ov} \\ \varepsilon^* = \varepsilon_{\max} / \varepsilon_{tol} \end{cases} \qquad 3.1$$

where δ_1 and δ_2 are weights, σ^* is non-dimensional maximum principal stress (σ_{ov} is critical Weibull stress, used for fracture probability calculation), and ε^* is non-dimensional form deviation (ε_{tol} is the tolerance of form deviation).

Grp.	T_1	T_3	P_1	P_{15}	DT	σ_{max}[MPa]	ε_{max}[μm]	σ_{max}/σ_{ov}	$\varepsilon_{max}/\varepsilon_{tol}$	$\delta_1(\sigma)$	$\delta_2(\varepsilon)$
1	0	0	2	0	1	7.89	3.03	0.079	3.029	-	-
2	0	1	1	1	2	9.49	3.22	0.095	3.221	1.091	-0.091
3	0	2	0	2	0	2.87	3.38	0.029	3.382	0.709	0.291
4	0	0	0	2	0	9.12	2.87	0.091	2.872	0.891	0.109
5	0	0	1	2	1	1.04	2.93	0.104	2.934	1.273	-0.273
6	1	0	1	0	1	8.05	3.01	0.080	3.014	0.771	0.229
7	1	1	0	2	0	5.87	3.09	0.059	3.093	0.783	0.217
8	1	2	2	1	2	5.03	3.46	0.050	3.462	0.978	0.022
9	1	1	0	1	2	8.70	3.22	0.087	3.218	0.869	0.131
10	1	1	1	1	2	9.41	3.21	0.094	3.209	0.553	0.447
11	2	0	1	1	2	8.83	3.03	0.088	3.028	1.033	-0.033
12	2	1	2	0	0	6.48	3.13	0.065	3.129	0.811	0.189
13	2	2	0	2	1	3.93	3.43	0.039	3.429	0.922	0.078
14	2	2	2	0	1	3.57	3.41	0.036	3.413	1.298	-0.298
15	2	2	2	0	0	6.24	3.37	0.062	3.374	0.598	0.402

Figure 5: Latin Hypercube design with 15 simulations, 5 parameters, 3 levels

Under previous definition, a 15*5 LH design on 3 levels was built (Fig. 5). The weights of objective function are calculated by

$$\begin{cases} \delta_1^i \sigma^*_i + \delta_2^i \varepsilon^*_i = \delta_1^{i+1} \sigma^*_{i+1} + \delta_2^{i+1} \varepsilon^*_{i+1}, & i = 1,2,\ldots,14 \\ \delta_j = \sum_{i=1}^{14} \delta_j^i \Big/ 14, & j = 1,2 \end{cases} \qquad 3.2$$

The final objective function is

$$f_{obj} = 0.899\sigma^* + 0.101\varepsilon^* \qquad 3.3$$

4 Conclusion

In this study, systematic investigation of the influences by key parameters for precision glass moulding process was carried out using a self-developed simulation tool-SimPGM.

In single parameter influence investigation, the dependency of simulation outputs $\sigma_{\max}$ and $\varepsilon_{\max}$ on 5 key process parameters T_1, T_3, P_1, P_{15} and DT are studied.

By means of sensitivity analysis via LH method, an objective function was determined, which will be used for further study of glass moulding process optimization.

References:

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[2] A. Saltelli, etc, “Global Sensitivity Analysis - The Primer”, Wiley, (2008).