Effect of injection compression process parameters on residual stress of products based on numerical simulation

Junjie Zhu, Yanfang Chen, Wenhan Huang, Qiurong Zhang, Xiaoming Liao, Yizhi Huang and Zhiwen Qiu
School of Electro-mechanical Engineering, Heyuan Polytechnic, Heyuan, Guangdong517000, China
Author: zhujunjie2006mmxy@163.com

Abstract. With the maximum residual stress of Mises-Hencky as the index, a numerical model for injection compression molding of the disc was established by CAE software. The process parameters of 7 factors including mold temperature, melt temperature, pressure holding time were analyzed by orthogonal experiment. Effect of key process parameters on residual stress was studied by single factor method finally. The results show that effect of mold temperature on residual stress was greatest, followed by melt temperature, compression delay time and compression speed, the residual stress decreases with the increase of mold temperature and melt temperature, increases with the increase of compression delay time, and the effect of compression speed on residual stress is not obvious.

1. Introduction
With the wide application of optical components, higher requirements are put forward for the quality of transparent products. Compared with traditional injection molding technology, injection compression molding has unique advantages in shaping transparent products. Injection compression molding can achieve uniform packing pressure effect, so that the physical properties are more uniform and the residual stress is lower, the warpage and birefringence of product are improved finally. The size and residual stress distribution of products are mainly determined by the history of time, temperature and pressure during the forming process. Therefore, the process conditions such as mold temperature, melt temperature, compression speed and compression time have important effect on the final residual stress and warping deformation[1]. Wang Kejian[2] and others investigated the birefringence distribution of optical products by different injection process parameters through a single variable experiment, calculated the residual stress value on the symmetry axis through the stress-photoelastic law, and optimized it. Liu Wenjuan[3] and others used the kriging agent model and the sequence optimization method of EI point criteria to optimize the process parameters of polycarbonate products to reduce the residual stress. Bushko[4-5] had studied the solidification mechanism of large plate forming process and analyzed effect of residual stress on the warpage of plastic parts during solidification process.

This paper takes a disk as an example, injection compression molding process were simulated by CAE numerical simulation software, the quantitative effect of key process parameters on the residual stress of Mises-Hencky after product release was analyzed by orthogonal experiment, in order to study effect of injection compression process parameters on residual stress.
2. Numerical calculation theory of residual stress

Residual stress of injection molding parts refers to the sum of all kinds of stresses that are not relaxed in the products after products are unformed and free to contract and deform without external constraints[6]. Generally, the residual stress of product is considered as inclusion residual stress and thermal residual stress. In the filling and packing stage, the viscous flow of melt produces flow residual stress, which is related to the molecular orientation of the material. On the other hand, because of the temperature and pressure history of each part of the product in the molding process are different, that lead to uneven cooling contraction and thermal residual stress, which is the main source of product residual stress [1].

Thermal residual stress is mainly determined by temperature distribution, solid-liquid interface location and pressure history, according to the Bolzmann principle, a mathematical model based on the distribution of residual stress induced by thermal stress and compression pressure is used, when residual stress calculated by Moldflow numerical software[8]:

\[
\sigma_{ij} = \int_{-\infty}^{t} C_{ijkl} \left( \xi(t) - \xi(t') \right) \partial \varepsilon_{kl} \partial t' \, dt' - \int_{-\infty}^{t} B_{ij} \left( \xi(t) - \xi(t') \right) dT(t')
\] (1)

In this formula, \( \sigma_{ij} \) — Stress tensor; \( C_{ijkl} \) — Material mechanical properties tensor; \( B_{ij} \) — Material thermal properties tensor; \( T \) — Thermodynamic temperature; \( \partial \varepsilon_{kl} \partial t' \) — Coefficient of thermal expansion tensor; \( \xi(t) \) — Change function of material temperature over time

\[
\xi(t) = \int_{0}^{1} a_{t} dt'
\] (2)

3. Numerical example simulation

3.1 Finite element analysis model and material selection

This paper takes a disk as the analysis model, the diameter of the disc is 120mm, the thickness is 0.8mm, the number of finite element mesh elements in the analysis model is 6014, and the number of nodes is 3025, the finite element model is shown in figure 1. Molding material is PMMA with the brand of CP61, the main properties of materials were shown in table 1.

| Table 1. Main properties of PMMA |
|---------------------------------|
| Melt temperature/°C             | 200~280          |
| Mold temperature/°C             | 20~80            |
| Maximum allowable shear stress/MPa | 0.26            |
Shear modulus/MPa  
Elasticity modulus/MPa  
Poisson's ratio  

3.2 Orthogonal experiment

Combined with actual production experience, the maximum Mises-Hencky residual stress after the mold release was selected as the index, 7 injection compression process parameters including mold temperature, melt temperature, pressure packing time, compression delay time, compression force, compression distance and compression speed were taken as experimental factors, denoted A, B, C, D, E, F and G respectively. According to the parameters of the injector and recommended parameters range of materials, 3 levels were uniformly taken within the range of values, and the specific experimental factors and levels were shown in table 2.

According to the experimental factors and level in table 2, L18(3^7) orthogonal table is selected for numerical simulation on the CAE software platform, the maximum Mises-Hencky residual stress (denoted R) was obtained after simulation, the test results were shown in table 3.

| Factors and levels table |
|--------------------------|
| Factors | A/℃ | B/℃ | C/s | D/s | E/t | F/mm | G/cm/s |
| 1 | 50 | 220 | 8 | 0.5 | 150 | 1 | 0.1 |
| 2 | 60 | 230 | 10 | 1 | 170 | 2 | 0.2 |
| 3 | 70 | 240 | 12 | 1.5 | 190 | 3 | 0.3 |

| Table3. Orthogonal experimental results |
|----------------------------------------|
| Experiment number | A | B | C | D | E | F | G | R /MPa |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 30.52 |
| 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 27.84 |
| 3 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 26.61 |
| 4 | 2 | 1 | 1 | 2 | 2 | 3 | 3 | 26.22 |
| 5 | 2 | 2 | 2 | 3 | 3 | 1 | 1 | 26.17 |
| 6 | 2 | 3 | 3 | 1 | 1 | 2 | 2 | 25.87 |
| 7 | 3 | 1 | 2 | 1 | 3 | 2 | 3 | 24.75 |
| 8 | 3 | 2 | 3 | 2 | 1 | 3 | 1 | 22.72 |
| 9 | 3 | 3 | 1 | 3 | 2 | 1 | 2 | 23.57 |
| 10 | 1 | 1 | 3 | 3 | 2 | 2 | 1 | 30.49 |
| 11 | 1 | 2 | 1 | 1 | 3 | 3 | 2 | 27.83 |
| 12 | 1 | 3 | 2 | 2 | 1 | 1 | 3 | 26.61 |
| 13 | 2 | 1 | 2 | 3 | 1 | 3 | 2 | 26.26 |
| 14 | 2 | 2 | 3 | 1 | 2 | 1 | 3 | 26.08 |
| 15 | 2 | 3 | 1 | 2 | 3 | 2 | 1 | 25.94 |
| 16 | 3 | 1 | 3 | 2 | 3 | 1 | 2 | 24.81 |
| 17 | 3 | 2 | 1 | 3 | 1 | 2 | 3 | 22.65 |
| 18 | 3 | 3 | 2 | 1 | 2 | 3 | 1 | 23.51 |
3.3 Data processing and analysis
Orthogonal experiment is try to find the optimal parameter horizontal combination and experimental factors with a few experiments, so the weight of the experimental index should be investigated, However, results have deviation because of the unstable factors, Therefore, S/N ration (Signal /Noise) is adopted to measure the robustness of output characteristics.S/N is the ratio of noise to signal, it has three types: small feature, large feature and visual feature[9-10]. Due to small residual stress characteristics, the smaller the test results, the larger the S /N.The formula for calculating the S/N of small features is shown in (3).

\[
\frac{S}{N} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)
\]

(3)

S/N — Signal to noise ratio(dB), \(y_i\)—Results of experiment \(i\), \(n\)—Number of repetitions per trial, \(n=1\).

In order to observe the effect of various experimental factors on the quality index at different levels, average analysis and range analysis of Mises-Hencky residual stress after S/N ratio transformation of the test results are required, the results are shown in table 4.

| Levels   | Factors |
|----------|---------|
|          | A       | B       | C       | D       | E       | F       | G       |
| Average 1| -28.591 | -28.650 | -28.297 | -28.410 | -28.178 | -28.369 | -28.427 |
| Average 2| -28.329 | -28.116 | -28.239 | -28.078 | -28.356 | -28.347 | -28.294 |
| Average 3| -27.476 | -28.068 | -28.298 | -28.246 | -28.299 | -28.120 | -28.112 |
| Range k  | 1.115   | 0.582   | 0.059   | 0.332   | 0.178   | 0.249   | 0.315   |

According to the calculation formula of S/N ratio of small feature (3), it is a minus function, the higher the S/N, the smaller the corresponding quality index. When mold temperature is at level 3(70℃), melt temperature is at level 3(240℃), pressure packing is at level 2(6s), compression delay time is at level 2(1s), compression force is at level 1(150MPa), compression distance is at level 3(3mm), compression speed is at level 3(0.3cm/s), the Mises-Hencky residual stress of product is minimal, it indicates that \(A_3B_3C_2D_2E_1F_3G_3\) is the best process parameter combination to control residual stress. The residual stress distribution of \(A_3B_3C_2D_2E_1F_3G_3\) process parameters are shown in Figure 2, the maximum residual stress is 21.24MPa, which is 30.41% lower than the maximum residual stress (30.52MPa) in the experiment scheme.

![Figure2. Residual stress after optimization](image)

In addition, according to the range \(k\) of different factors, the order in which the effect of injection compression process parameters on the residual stress of the product can be obtained from large to small is: Mold temperature > Melt temperature > Compression delay time > Compression speed >
Compression distance > Compression force > Pressure packing time.

3.4 Single factor numerical simulation analysis

According to the results of S/N analysis, four key injection-compression process parameters effect on residual stress more obviously were selected (mold temperature, melt temperature, compression delay time, compression speed), the effect of each key technological parameter on the residual stress of products was studied by single factor experiment, according to the range of parameters of the injection machine and the range of molding materials, the level of each process parameter is set as shown in table 5.

| Level | Mold temperature/°C | Melt temperature/°C | Compression delay time/s | Compression speed/cm/s |
|-------|----------------------|---------------------|-------------------------|------------------------|
| 1     | 30                   | 220                 | 0                       | 0.1                    |
| 2     | 40                   | 230                 | 0.5                     | 0.2                    |
| Reference | 50               | 240                 | 1                       | 0.3                    |
| 3     | 60                   | 250                 | 1.5                     | 0.4                    |
| 4     | 70                   | 260                 | 2                       | 0.5                    |

4. Results and discussion

Effect law of the key injection compression process parameters (mold temperature, melt temperature, compression delay time and compression speed) on the residual stress of the product was obtained based on the above numerical simulation and orthogonal experiment.

4.1 Effect of mold temperature on residual stress

Residual stress of product at different mold temperatures is shown in figure 3, residual stress of disk is decreasing gradually. When the temperature from 30°C to 70°C, the residual stress decreased from 29.12 MPa to 22.70 MPa, was reduced by 22.05%. This is mainly because the high temperature melt enters the low temperature mold cavity, the plastic melt will rapidly undergo condensation and hardening. With the increase of mold temperature, the condensation layer will become thinner, cooling efficiency will decrease, and the cooling and solidification time of melt will be longer, which can release the internal stress on the surface of the product more fully, thus the residual stress of the product will decrease. Residual stress distribution with mold temperature of 30°C and 70°C were shown in figure 4 (a) and (b).

![Figure 3. Effect of mold temperature on residual stress](image-url)
4.2 Effect of melt temperature on residual stress
Residual stress of product at different melt temperatures is shown in figure 5. The residual stress of the disk is decreasing gradually. When the temperature from 220°C to 260°C, the residual stress decreased from 28.34 MPa to 22.47 MPa, was reduced by 20.71%. According to the PVT property of the material (PMMA), melt temperature rises and thermal contraction is obvious under certain other conditions. On the other hand, the increase of melt temperature improves the fluidity of the melt, so that the solidification time of the melt is prolonged, which results in the increase of feeding amount in the pressure maintaining stage, the decrease of volume contraction and the decrease of residual stress.

4.3 Effect of compression delay time on residual stress
Residual stress of product at different compression delay time was shown in figure 6. The residual stress of the disk shows a gradual upward trend, increasing from 24.17MPa at 0s to 39.28MPa at 2.0s. With the extension of compression delay time, the molecular orientation increases, and the thickness of the condensate layer at the cavity interface increases. In the secondary compression process, the compression mechanism in the cavity affected the equilibrium distribution of stress, the residual stress increased finally[8]. In addition, when the compression delay time is too long, defects such as short shot will be produced due to the gradual condensation of melt, thus affecting the forming quality. Residual stress distribution with compression delay time of 0 s and 3 s are shown in figure 7 (a) and (b), there is obvious short shot defect in the gray area of (b).
4.4 Effect of compression speed on residual stress
Residual stress of product at different compression speeds is shown in figure 6. Generally, the residual stress of the disc is increased, but the change is not obvious, 25.38MPa at 0.1cm/s increased by 25.50MPa at 0.5cm/s, the main reason is that compression speed affects the speed and time of secondary flow of plastic melt in mold cavity, with the reduction of compression speed, there are more melts near the gate, the melt is more compact and the internal stress of the product is less, when the compression speed increases, the amount of plastic melt flowing into the end from the gate changes little, so it has little effect on the residual stress of products.

5. Conclusions
Effect of different injection compression process parameters on the residual stress of the disc were
analyzed in detail through numerical simulation analysis, and the following results were obtained finally:

(1) The degree of effect of injection compression process parameters on the residual stress of the product is from large to small: Mold temperature > Melt temperature > Compression delay time > Compression speed > Compression distance > Compression force > Pressure packing time, mold temperature, melt temperature, compression delay time and compression speed are the main factors affecting the residual stress of products.

(2) The effect of four key process parameters on the residual stress of products was studied by using the single factor method, the residual stress decreases with the increase of mold temperature and melt temperature, increases with the increase of compression delay time, and the effect of compression speed on residual stress is not obvious.

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