Warpage analysis and optimization of thin-walled injection molding parts based on numerical simulation and orthogonal experiment

Yanfang Chen, Junjie Zhu
Heyuan Ploytechnic, Heyuan, Guangdong, 517000, China
Author’s e-mail: yfanfangchen2018@sina.com

Abstract. With the warpage of a mobile phone case as the index, a numerical model for injection molding was established by CAE software. The process parameters of 5 factors including injection time, mold temperature, melt temperature, packing time and packing pressure were analyzed by orthogonal experiment, the effect of injection process parameters on warpage was studied and the minimum combination of process parameters was obtained. The simulation results show that the warpage was reduced by 6.98% after optimization, and higher quality plastic parts were obtained, which has important guiding significance for the production practice of thin-wall parts.

1. Introduction
With the 3C product shell, medical and health products continue to move towards the ultra-thin field, higher requirements are put forward for thin-wall injection molding technology. Due to the thin wall thickness of the parts, the plastic melt into the mold cavity, easy to form a less liquid condensation layer. Therefore, it leads to the increase of melt flow resistance, the increase of pressure loss, uneven shrinkage and residual stress during cooling, which makes the thin wall prone to warping deformation. Warping deformation not only affects the appearance of plastic parts, but also affects the performance, precision and assembly of plastic parts. Therefore, the optimization of warping deformation of thin-walled parts has become a research hotspot. Lin Youwen and others [1] used CAE and neural network technology to analyze and optimize the welding lines and warping deformation of the automobile intake grille, thus improving the molding quality of plastic parts. Gao [2]and others used Kriging model to conduct an in-depth study on warping deformation and put forward an optimization scheme. Jiang Qingsong [3]and others conducted joint simulation by using Moldflow and Abaqus based on coupled finite element analysis method, and investigated the influence of main process parameters and wall thickness on warping deformation.

This paper takes a mobile phone case as an example, the warpage of thin-walled parts was predicted by using CAE numerical simulation platform. With the method of orthogonal experiment design, the influence of injection molding process parameters on the warpage of plastic parts was studied, and the forming process conditions were optimized. This has important feasibility reference significance to the production practice of thin-wall parts.

2. Establishment of CAE numerical model
The CAE numerical simulation technology of injection molding mainly uses the basic theories of polymer material science and rheology to establish the physical and mathematical models of melt flow
in mold cavity, and uses the numerical calculation theory to simulate and analyze the injection molding process. The dynamic filling, packing and cooling process of melt in actual molding were simulated intuitively, the computer simulation process of the state parameters (such as pressure, temperature, time, etc) in the forming process can be given quantitatively. The melt of polymer plastic was assumed to be viscoelastic fluid, the non constant temperature three dimensional flow mathematical equation can be expressed as follows [4-5].

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0
\]

(1)

\[
\frac{\partial}{\partial t} \left( \rho \mathbf{u} \right) + \nabla \left( \rho \mathbf{u} \mathbf{u} - \sigma \right) = \rho \mathbf{g}
\]

(2)

\[
\rho C_p \left( \frac{\partial T}{\partial t} + u \cdot \nabla T \right) = \nabla \cdot \left( \lambda \nabla T \right) + \eta \dot{\gamma}^2
\]

(3)

In this formula, \( \mathbf{u} \) - Velocity vector, \( T \) - Melt temperature, \( t \) - time, \( \sigma \) - Total stress tensor, \( \mathbf{g} \) - Acceleration of gravity, \( \rho \) - melt density, \( \gamma \) - Shear rate, \( \lambda \) - Coefficient of thermal conductivity, \( C_p \) - Specific heat capacity, \( \eta \) - Shear viscosity.

This paper takes a mobile phone shell as a numerical analysis model, the length of the plastic part is 100mm, the width is 48mm, and the average thickness is 1.1mm. The number of finite element mesh elements and nodes in the analysis model is 8936 and 4464 respectively. The finite element model was shown in figure 1. Molding material is ABS+PC with the brand of Cycoloy C1200HF, the main properties of materials was shown in table 1.

![Figure1. Numerical analysis model](image)

| Table 1. Main process of material |
|----------------------------------|
| Melt temperature/°C | 274-301 |
| Mold temperature/°C | 60-87 |
| Maximum allowable shear stress/MPa | 0.4 |
| Maximum permissible shear rate/\(s^{-1}\) | 40000 |

3. Orthogonal experiment

3.1. Determination of experiment factors and levels

Combined with the actual production experience, the warpage of plastic parts was selected as the quality index. 5 injection process parameters, such as injection time, mold temperature, melt temperature, pressure packing time and pressure packing pressure, were selected as the test factors (represented by A, B, C, D and E respectively). According to molding requirements of plastic parts, parameters of injection machine and recommended parameters range of raw materials, three levels were uniformly selected within the value range of each process parameter. The specific factors and levels were shown in table 2.
Table 2. Factors and levels

| Levels | A/s | B/℃ | C/℃ | D/s | E/MPa |
|--------|-----|------|------|------|-------|
| 1      | 0.6 | 63   | 277  | 4    | 44    |
| 2      | 0.8 | 70   | 284  | 6    | 52    |
| 3      | 1.0 | 77   | 291  | 8    | 58    |
| 4      | 1.2 | 84   | 298  | 10   | 64    |

3.2. Orthogonal experimental results

According to the experimental factors and levels values in table 2, L₁₆(4⁵) orthogonal table was selected for numerical simulation. The warpage of the mobile phone shell was obtained through simulation, which was represented by $W$, the results of orthogonal experiment were shown in table 3.

Table 3. Orthogonal experimental results

| Test NO. | A  | B  | C  | D  | E  | W/mm |
|----------|----|----|----|----|----|------|
| 1        | 1  | 1  | 1  | 1  | 1  | 0.8256 |
| 2        | 1  | 2  | 2  | 2  | 2  | 0.7806 |
| 3        | 1  | 3  | 3  | 3  | 3  | 0.7466 |
| 4        | 1  | 4  | 4  | 4  | 4  | 0.6938 |
| 5        | 2  | 1  | 2  | 3  | 4  | 0.7469 |
| 6        | 2  | 2  | 1  | 4  | 3  | 0.7680 |
| 7        | 2  | 3  | 4  | 1  | 2  | 0.7460 |
| 8        | 2  | 4  | 3  | 2  | 1  | 0.7802 |
| 9        | 3  | 1  | 3  | 4  | 2  | 0.7669 |
| 10       | 3  | 2  | 4  | 3  | 1  | 0.7732 |
| 11       | 3  | 3  | 1  | 2  | 4  | 0.7465 |
| 12       | 3  | 4  | 2  | 1  | 3  | 0.7430 |
| 13       | 4  | 1  | 4  | 2  | 3  | 0.7239 |
| 14       | 4  | 2  | 3  | 1  | 4  | 0.7166 |
| 15       | 4  | 3  | 2  | 4  | 1  | 0.9990 |
| 16       | 4  | 4  | 1  | 3  | 2  | 0.9541 |

4. Results analysis and discussion

4.1. Data processing and analysis

In order to study the effects of injection process parameters on the warpage of mobile phone shell, the warpage in table 3 was analyzed by average analysis and range analysis. Explore the rule of warpage change with injection process parameters, and find out the best combination of process parameters. The average analysis and range analysis data were shown in table 4.

Table 4. Average analysis and range analysis table

| Levels       | A     | B     | C     | D     | E     |
|--------------|-------|-------|-------|-------|-------|
| Average 1    | 0.7616| 0.7658| 0.8235| 0.7578| 0.8445|
| Average 2    | 0.7603| 0.7596| 0.8174| 0.7578| 0.8119|
| Average 3    | 0.7574| 0.8095| 0.7526| 0.8052| 0.7454|
| Average 4    | 0.8484| 0.7928| 0.7342| 0.8069| 0.7260|
| Range $R$    | 0.091 | 0.0499| 0.0893| 0.0491| 0.1185|
As can be seen from table 4, when injection time (A) was at level 3 (1 s), mold temperature (B) was at level 2 (70°C), melt temperature (C) was at level 3 (298°C), pressure packing time (D) was at level 1 (4 s), pressure packing pressure (E) was at level 4 (64 MPa), the mobile phone shell of warpage was the minimum. It indicates that the combination of A3B2C4D1E4 is the best combination of technological parameters to control the warpage. In addition, according to the range R of different factors, the order in which the effect of injection process parameters on the warpage of the product can be obtained from large to small is: Pressure packing pressure > Injection time > Melt temperature > Mold temperature > Pressure packing time.

4.2. Effect of injection process parameters on warpage of mobile phone shell

In order to further analyze the effect of injection process parameters on warpage, according to the analysis data in table 4, the effect curve of main injection process parameters (injection time, mold temperature, melt temperature and pressure packing pressure) on the warpage of mobile phone shell was made (The effect of pressure packing time on warpage was not considered because the effect of holding time was the least). The results were shown in figure 2, figure 3, figure 4, and figure 5.

It can be seen from figure 2, Injection time has a certain impact on the warpage of plastic parts. With the extension of injection time, the warpage of plastic parts decreases gradually. When the injection time was 1s, the warpage reaches the minimum, and then increases with the further extension of the injection time. It is concluded that the proper extension of injection time is beneficial to reduce the warpage of plastic parts.

As can be seen from figure 3, the effect of mold temperature on the warping deformation of plastic parts is not stable. When the mold temperature was controlled at 70°C, the warpage of plastic parts reaches the minimum (0.7596mm), and the mold temperature was greater than 70°C, the warpage...
gradually increases. On the whole, the mobile phone case should adopt low mold temperature injection molding.

As can be seen from figure 4, with the increase of melt temperature, the warpage of plastic parts gradually decreases. This is because with the melt temperature increases, the crystallization rate increases, which is conducive to the relaxation process of polymer, molecular orientation effect is small, reduce the deformation of plastic parts. When the melt temperature reaches 298℃, the warpage reaches the minimum value (0.7342mm). It is concluded that appropriate increase of melt temperature is beneficial to reduce the warping deformation of the mobile phone shell.

As can be seen from figure 5, when the retaining pressure increases, the warpage of plastic parts gradually decreases. This is because the pressure retaining process can play the role of compaction mold cavity melt, and melt shrinkage caused by the gap in time to reduce the warping deformation [6].

4.3. CAE simulation verification
Due to the best process parameter combination A3B2C4D1E4 was not included in the orthogonal experiment scheme, CAE simulation platform was used to experiment the optimal combination scheme of process parameters again, and the warpage was 0.6454mm. The analysis results were shown in figure 6. Compared with the orthogonal experiment scheme, the warpage was smaller than the minimum value (0.6938mm) in the experiment scheme, reducing by 6.98%. The injection molding process parameters after optimization meet the requirement that the smaller the quantity of warpage, the better the quality index, and the effect was significant.

5. Conclusion
Effect of different injection process parameters on the warpage of the mobile phone shell were analyzed in detail through numerical simulation analysis, and the following results were obtained finally:

(1) When the injection time is 1 s, the mold temperature is 70℃, the melt temperature is 298℃, the pressure packing time is 4 s, and the pressure packing pressure is 64 MPa, the shell of this mobile phone has the smallest warping deformation, A3B2C4D1E4 is the best combination of technological parameters to control the warpage.

(2) According to the range R of different factors, the order in which the effect of injection process parameters on the warpage of the product can be obtained from large to small is: Pressure packing pressure>Injection time>Melt temperature>Mold temperature>Pressure packing time.

(3) With the extension of injection time, the warpage of plastic parts decreases first and then increases. With the increase of mold temperature, the change of warpage was not stable. The warpage decreases with the increase of melt temperature. With the increase of pressure packing pressure, the warpage decreases gradually.

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