Warpage Analysis of a Plastic Spur Gear Injection Molding

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ABSTRACT
The effect of various factors on the amount of warpage in an injection molded product was investigated and a plastic spur gear was used as an example. The research involved the design of a mold and die, computer-aided engineering, simulation analysis, and the determination of the plastic material and parameters. Simulation results were verified by experiment using the fabricated mold and die. Small warpage was determined using software, and the Taguchi and Response Surface Methods were used to determine the optimal parameter combinations. The optimum parameters were found to be: injection pressure, 105 MPa; packing pressure, 70 MPa; packing time, 19 s; mold temperature, 60 °C; and plastic temperature, 190 °C. The experiments were repeated, and the results were compared with the simulations to verify the reliability of the simulation results.

1. Introduction
Plastic molding is the most common method for manufacturing many products such as electronics and other 3C parts, mobile phone shells, automobile and motorcycle parts, and even aviation components. Plastic injection molding is a rapid and inexpensive method for the manufacture of products with complex geometric shape and makes control of the dimensional accuracy of finished products easy. Radhwan et al. [1] used the Taguchi method to optimize the shrinkage of plastic parts. The factors considered were: mold temperature, plastic temperature, holding pressure, holding time, and cooling time. Hyounjun et al. [2] investigated the injection molding of a display panel and simulated the parameters with Taguchi $L_{27}$ and Moldflow analysis. The results revealed that packing pressure and cooling time were significant...
factor and the filling time was less important. Ta and Ping [5] used Response Surface Methodology (RSM) to analyze the shrinkage and warpage of a mobile phone shell. Experimental results were obtained using a good predictive mathematical model, and the actual shrinkage and warpage of each group.

| Table 1. Control factor level. |
|-------------------------------|
| Factors                      | Level 1 | Level 2 | Level 3 | Level 4 |
| A. Injection pressure (MPa)  | 90      | 105     | 120     | 135     |
| B. Packing pressure (MPa)    | 50      | 60      | 70      | 80      |
| C. Packing time (s)          | 5       | 7       | 13      | 17      |
| D. Mold temperature (°C)    | 65      | 80      | 95      | 110     |
| E. Plastic temperature (°C) | 195     | 205     | 215     | 225     |

| Table 2. Experimental data. |
|-----------------------------|
| A. Injection pressure (MPa) | 90 50 90 105 120 135 |
| B. Packing pressure (MPa)  | 50 60 50 60 70 80 |
| C. Packing time (s)        | 5 7 13 7 13 20 |
| D. Mold temperature (°C)  | 65 80 95 65 80 105 |
| E. Plastic temperature (°C)| 195 205 215 195 205 225 |

| Table 3. The warpage and S/N ratio of each group. |
|--------------------------------------------------|
| A     | B     | C     | D     | E     | Warpage (mm) | S/N ratio |
|-------|-------|-------|-------|-------|-------------|----------|
| 1     | 1     | 1     | 1     | 1     | 0.286       | 10.8727  |
| 2     | 1     | 2     | 2     | 2     | 0.290       | 10.7520  |
| 3     | 1     | 3     | 3     | 3     | 0.287       | 10.8424  |
| 4     | 1     | 4     | 4     | 4     | 0.290       | 10.7520  |
| 5     | 2     | 1     | 2     | 3     | 0.300       | 10.4576  |
| 6     | 2     | 2     | 1     | 4     | 0.300       | 10.4576  |
| 7     | 2     | 3     | 4     | 1     | 0.259       | 11.7340  |
| 8     | 2     | 4     | 3     | 2     | 0.266       | 11.5024  |
| 9     | 3     | 1     | 3     | 4     | 0.288       | 10.8122  |
| 10    | 3     | 2     | 4     | 3     | 0.264       | 11.5679  |
| 11    | 3     | 3     | 1     | 2     | 0.303       | 10.3711  |
| 12    | 3     | 4     | 2     | 1     | 0.293       | 10.6626  |
| 13    | 4     | 1     | 4     | 2     | 0.273       | 11.2767  |
| 14    | 4     | 2     | 3     | 1     | 0.291       | 10.7221  |
| 15    | 4     | 3     | 2     | 4     | 0.288       | 10.8122  |
| 16    | 4     | 4     | 1     | 3     | 0.296       | 10.5742  |

| Table 4. S/N ratio of the optimal factor combination being A2B3C4D1E1. |
|---------------------------------------------------------------|
| Level 1. | 10.80 | 10.85 | 10.57 | 11.00 | 11.19 |
| Level 2. | 11.04 | 10.87 | 10.67 | 10.98 | 10.97 |
| Level 3. | 10.85 | 10.94 | 10.97 | 10.86 | 10.81 |
| Level 4. | 10.85 | 10.87 | 11.32 | 10.71 | 10.58 |
| Effect   | 0.23  | 0.09  | 0.76  | 0.29  | 0.61  |
| Rank     | 4     | 5     | 1     | 3     | 2     |
| Best factor | A2  | B3   | C4   | D1   | E1   |

Figure 1. The response figure of quality characteristics.
warpage were 37.8 and 53.9% more favorable than the original. Piao et al. [6] used computer-aided engineering (CAE) with Taguchi L_{18} for plastic parts injection molding for simulation. They compared the simulated values of mold temperature, plastic temperature, packing pressure, and injection rate to determine optimal combinations. Tsan et al. [7] analyzed the shrinkage of the outer layer of fiber optic cables, which typically affects both the capacity and communications distance, the shrinkage rate was considered to affect the key factors. Baoshou et al. [8] used the Taguchi method and CAE to simulate the amount of warpage during injection molding. Their experimental data were based on the relationship between the reaction surface method and warpage. Chen et al. [9] investigated

Figure 2. Contour maps of the factors: (a) Warpage, mold temperature, and packing time; (b) warpage, plastic temperature, and packing time; and (c) warpage, plastic temperature, and mold temperature.

Figure 3. Response surface maps of the factors: (a) Warpage, mold temperature, and packing time; (b) warpage, plastic temperature, and packing time; and (c) warpage, plastic temperature, and mold temperature.
the plastic injection molding or forming of thin-sheet parts. In the present study, CAE mold flow analysis software was used for model simulation as well as the Taguchi and response surface methods. The optimal combination of parameters was obtained and the quality of the molded product was improved. A parametric study is carried out for asymmetric high contact ratio spur gears based on load sharing method to determine the improvement in load carrying capacity [10]. An experimental technique based on strain gage has been proposed to measure the gear mesh stiffness of healthy spur gear as well as of cracked spur gear pair system [11].

2. Study Methods
In this study, we first investigated the factors affecting warpage during injection molding using the Analytic Hierarchy Process and then applied the Taguchi method and Reaction Surface Method to optimize the processing of the plastic gears. Moldex3D mold flow software is a set

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**Figure 4.** Warpage comparison between the optimal combinations of the Taguchi experimental method and the Response Surface Method.
of CAE programs used with CAE simulation and practical data to determine optimal results. Solidworks was used to draw the geometry of a spur gear and Moldex3D R13.0 Designer was then used for the import of the initial grid, and mold flow analysis was done by setting the parameters: injection pressure, packing pressure, holding time, and mold temperature. We used the Taguchi L_{16} method and RSM to determine the optimal parameter combination and compared the result with parameters from actual injection molded products. RSM aims to determine the quantitative relationship between the test index and each factor and the derivation of the optimal factor-level

![X and Z directions thermal displacement](image1.png)

![Y direction thermal displacement](image2.png)

![Total thermal displacement](image3.png)

**Figure 4.** (Continued).

### Table 5. Taguchi method and Response Surface Method setting.

| Parameter                              | Taguchi method | Response surface methodology |
|----------------------------------------|----------------|------------------------------|
| Maximum injection pressure (MPa)       | 105            | 105                          |
| Maximum holding pressure (MPa)         | 70             | 70                           |
| Holding time (s)                       | 17             | 19                           |
| Mold temperature °C                    | 65             | 60                           |
| Plastic temperature °C                 | 195            | 190                          |
| Filling time (s)                       | 0.37           |                              |
| Injection volume (cm³)                 | 9.21373        |                              |
| Cooling time (s)                       | 17.2           |                              |
| Ejection temperature °C                | 136.85         |                              |
| Air temperature °C                     | 25             |                              |
| VP Switch %                            | 98             |                              |
the factors were selected according to the material-forming condition, as shown in Table 1. Five control factors were selected using $L_{16}(4^5)$ for simulation (Table 2). After the analysis was performed using Moldex3D, the S/N ratio was calculated using the warping results (Table 3). The warpage figures shown in Table 3 were used to derive the reaction table (Table 4) and reaction figure (Figure 1), the optimal factor combination being A2B3C4D1E1. This was associated with an injection pressure of 105 MPa, a holding pressure of 70 MPa, a holding time of 17 s, a mold temperature of 65 °C, and a plastic temperature of 195 °C. The holding time, factor C, had a significant influence on the warping deformation, while the holding pressure, factor B, had less (Table 4). The most parameter contribution is 55%, factor C; and the second contribution is 31.2%, factor D. The contribution is pooled for factor B. The confirmation experiment of optimal parameters is 0.246 mm for warpage.

### 3. Results and Discussion

The objective of this experiment was to reduce the warpage of plastic spur gears. The quality characteristic is small and is expressed as follows:

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

(1)

where $n$ represents the number of experiments and $y_i$ represents the experimental data for each experiment.

The following control factors were selected: injection pressure (MPa), holding pressure (MPa), holding time (s), mold temperature (°C), and plastic temperature (°C). Polyoxyymethylene was used as the molding material and the factors were selected according to the material-forming condition, as shown in Table 1. Five control factors were selected using $L_{16}(4^5)$ for simulation (Table 2). After the analysis was performed using Moldex3D, the S/N ratio was calculated using the warping results (Table 3).

The warpage figures shown in Table 3 were used to derive the reaction table (Table 4) and reaction figure (Figure 1), the optimal factor combination being A2B3C4D1E1. This was associated with an injection pressure of 105 MPa, a holding pressure of 70 MPa, a holding time of 17 s, a mold temperature of 65 °C, and a plastic temperature of 195 °C. The holding time, factor C, had a significant influence on the warping deformation, while the holding pressure, factor B, had less (Table 4). The most parameter contribution is 55%, factor C; and the second contribution is 31.2%, factor D. The contribution is pooled for factor B. The confirmation experiment of optimal parameters is 0.246 mm for warpage.
Figure 5 shows the mold polishing process for finished injection products. Figure 6 shows a finished experimental product. The simulated warpage results are shown in Figure 7; the simulated warpage was 0.1886 mm, with an error of approximately 2.7% compared with the experimental warpage of 0.1835 mm. This shows the simulated parameters to be reliable.

4. Conclusion

This study explored different injection molding factors and their effect on the amount of warpage in a molded product, using a plastic spur gear as an example. The study involved the design and construction of a mold, CAE simulation analysis, and the determination of the...
plastic material and parameters. The optimum parameters were found to be: injection pressure, 105 MPa; packing pressure, 70 MPa; packing time, 19 s; mold temperature, 60 °C; and plastic temperature, 190 °C. The simulated warpage was 0.1886 mm, with an error of approximately 2.7% compared to the experimental warpage of 0.1835 mm.

**Disclosure Statement**

No potential conflict of interest was reported by the authors.

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