# Optimization of Process Parameters in Plastic Injection Mold Simulation for Auto Lock-Parts Using Taguchi-Grey Method Based on Multi-Objective

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***Abstract*— Locks may be inserted during the production of certain auto lock-parts. Warpage of auto lock-parts during injection molding is the most critical problem facing product quality. This warpage is mostly affected by the processing parameters and design of the injection mold. In this paper, the influences of molding conditions on the warpage of auto-lock parts were studied using a mold filling analysis software. This study combines the Taguchi method and grey relational analysis to find the optimal set parameters for auto lock-parts and to analyze the effect of individual parameter on the warpage and the temperature distribution results. We then configure different cooling design change temperature distribution and reduce warpage, respectively, the original cooling, U-shaped cooling and conformal cooling with each other. From the results, it is shown that the factor that the most strongly affects the warpage is the mold temperature, with packing pressure being a secondary consideration. The optimum parameters that can minimize the warpage defects filling time (0.6 s), melt temperature (260°C), mold temperature (65°C), injection pressure (125 MPa) and packing pressure (140 MPa).**

***Keywords*— injection molding; taguchi method; grey relational analysis; warpage**

## I. INTRODUCTION

Computerized simulation techniques, such as computer aided design (CAD) and computer aided engineering (CAE) can be used to assist developers in analysis work that aims at predicting problems and their causes in the process of injection molding. This not only reduces the effort of testing with actual molds, costs, and time involved but also improves the product quality. In this research, CAE software was used for mold flow analysis. Using the finite element method, the condition of the plastic in the mold cavity during various stages of the injection molding was simulated. The observations formed the basis for formulating essential settings for injection molding and parameters for mold design, with the aim of reducing the time and costs of product and mold development [2]. Currently, injection molding is commonly used in the fabrication of auto parts and assemblies such as crossbeams, lamp fixtures, instrument panels, and connectors. Among these, spare parts of locking devices require high precision, are complex in form, and often have warpage, welding line, air traps, and other defects in the finished product. Consequently, the selection and setting of the fabrication process parameters are crucial. In this research, a set of spare parts of an actual auto locking device is examined. Warpage problems occurred during the fabrication process and resulted in parts that did not fit appropriately. Trial and error was used to determine the important parameters used in the actual production process. The quality of the product will decide if the parameter setting will be used or need to be changed; a process that is both time consuming and costly. In this research, CAE was used in conjunction with simulation analysis to overcome the situation. The uneven distribution of the structure body thickness causes uneven distribution of temperature, which results in deformation of the shape and size of the product. This in turn causes quality issues in the installation and assembly work that follows and requires changing the fabrication parameters to reduce the occurrence of warpage. Using CAE mold flow analysis software and Taguchi robust design process, a unique combination for quality optimization was determined and used to examine the warpage and the temperature distribution. From the Taguchi robust design and Grey relational analysis, an optimized combination for a multi-objective fabrication process was determined. A comparison of the warpage and temperature distribution was then made with the original fabrication process.

## II. SIMULATION ANALYSIS CONFIGURATION

### A. *Construction of Spare Auto Lock Parts*

In this research, the shapes of auto lock parts used and the original design comprising a four-cavity mold are shown in Fig. 1. Fig. 2 shows the dimensions of the spare parts. A surround-type water cooling system, 6 mm in diameter, was employed. An engineering plastic, nylon (Polyamide, PA66), was selected for the simulation and analysis of injection molding. Table I shows the basic characteristics of the material.

*B. Taguchi Robust Design Process and Grey Relational Analysis*

Using Taguchi robust design in practical applications, the single objective failed to reach the quality requirements on the manufacturing process, otherwise, the multiple objectives while providing quality to the process of requirement and improving the products of direction. Therefore, this study combines the Taguchi method and grey relational analysis to find the optimal set parameters for auto lock-parts and to analyze the effect of individual parameter on the warpage and the temperature distribution results.

*C. Taguchi Robust Design Process*

*1)* L16 orthogonal table is employed, and through the characteristic root cause diagram (Fig. 3) and Table II, we have the arrangement of the control factors. Next, the mold flow simulation and analysis is conducted, and from the S/N value we can have the optimized parameters for the injection molding of auto lock parts, the objectives being the warpage and average temperature difference.

*2) Grey Relational Analysis*

In conjunction with the results of the Taguchi robust design, the optimized combination for multi-objective fabrication process was obtained, and comparison was made with the original process in terms of warpage and temperature distribution.

TABLE I. PA66 MATERIAL CHARACTERISTICS

| ***Mechanical Properties*** | ***PA66*** |
|---|---|
| Polymer Density | 1.14 (g/cc) |
| Polymer Poisson's ratio | 0.3 |
| Polymer Modulus E | 2e+010 (dyne/cm$^2$) |
| Polymer CLTE | 7.5e-005 (1/K) |
| Fiber Weight Percentage | 33 (%) |
| Melt Temperature | 275-305 (°C) |

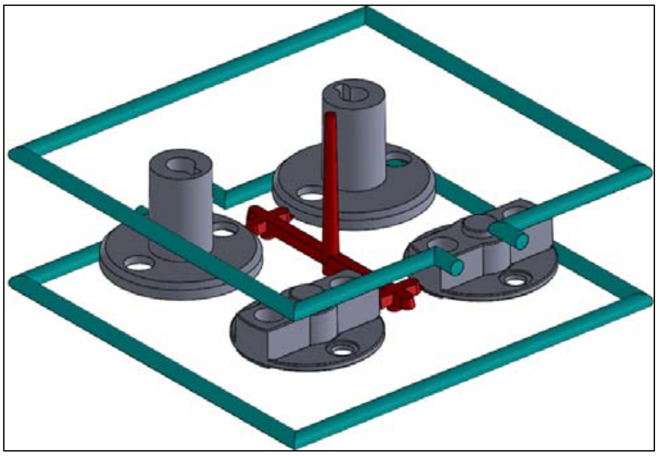

Fig. 1. The plot of loss tangent v. temperature of three EP materials [10].

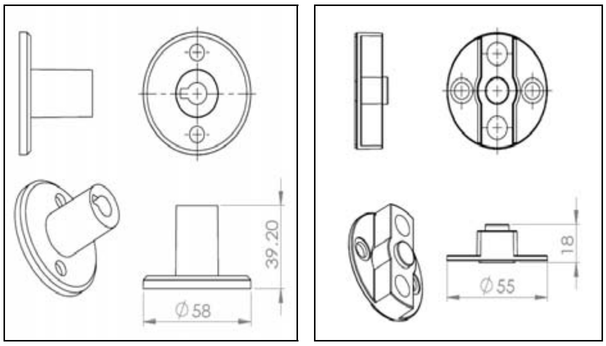


Fig. 2. Dimensions of parts

TABLE II. CONTROL FACTORS AND LEVELS

| ***Control Factors*** | ***Level*** | | | |
|---|---|---|---|---|
| | ***1*** | ***2*** | ***3*** | ***4*** |
| A.Injection Duration(s) | 0.6 | 0.8 | 1 | 1.2 |
| B.Plastics Temp. (℃) | 245 | 255 | 265 | 275 |
| C.Mold Temp.(℃) | 65 | 75 | 85 | 95 |
| D.Injection Press.(MPa). | 120 | 125 | 130 | 135 |
| E.Holding Press.(MPa) | 130 | 135 | 140 | 145 |

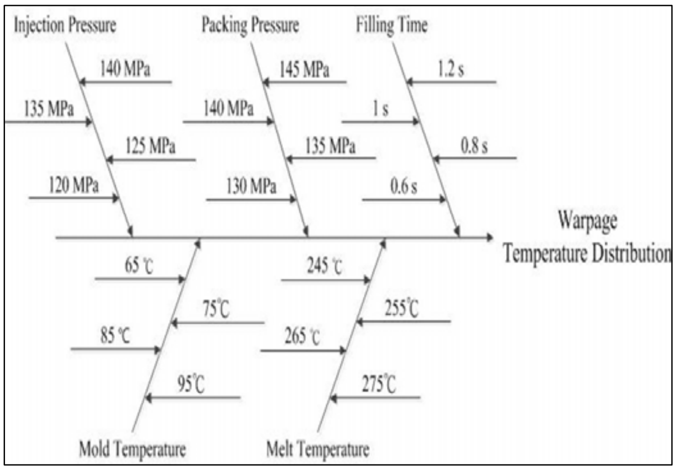


Fig. 3. Characteristics root cause diagram–fish bone diagram

## III. SIMULATION ANALYSIS RESULTS

Simulation analysis were conducted with the 16 combinations of process parameters configured according to the orthogonal table of the Taguchi robust design process, and the analyzed warpage and S/N values are shown in Table III. The obtained warpage S/N value response table is shown in Table IV. From the different levels of each process parameter, the degree of influence on the warpage is determined and ranked as follows: holding pressure, plastics temperature, injection duration, mold temperature, and injection pressure. From the warpage S/N values of the process parameters, the degree of contribution was analyzed against the variance as in

Table V. The optimized fabrication parameter combination is A1B2C2D1E4, with a warpage of 0.61 mm.

The temperature distribution and obtained S/N values from the analysis results are shown in Table III. The temperature distribution S/N value response of fabrication parameters under different levels are shown in Table VI. From the different levels of fabrication parameters, the degree of influence on temperature distribution is known and ranked as follows: mold temperature, injection pressure, plastics temperature, injection duration, and holding pressure. From the temperature distribution S/N values of the process parameters, the degree of contribution was analyzed against the variance as in Table VII. The optimized fabrication parameter combination is A1B1C1D2E1. Hence, this is the optimized parameter combination for the temperature distribution of injection molding fabrication, with an average temperature difference of 7.59°C.

TABLE III. SIMULATION ANALYSIS RESULTS

| ***Trial*** | ***Average Temperature Difference ()*** | ***S/N*** | ***Warpage(mm)*** | ***S/N*** |
|---|---|---|---|---|
| 1 | 9.19 | 3.27 | 0.69 | -19.27 |
| 2 | 11.28 | 3.80 | 0.65 | -21.05 |
| 3 | 14.36 | 3.82 | 0.64 | -23.14 |
| 4 | 16.74 | 3.72 | 0.65 | -24.48 |
| 5 | 11.73 | 4.00 | 0.63 | -21.39 |
| 6 | 14.12 | 3.83 | 0.64 | -22.99 |
| 7 | 21.35 | 3.48 | 0.67 | -26.59 |
| 8 | 12.33 | 2.79 | 0.73 | -21.82 |
| 9 | 15.41 | 2.92 | 0.71 | -23.75 |
| 10 | 16.66 | 3.01 | 0.71 | -24.43 |
| 11 | 10.27 | 3.95 | 0.63 | -20.23 |
| 12 | 11.42 | 3.25 | 0.69 | -21.15 |
| 13 | 14.04 | 2.70 | 0.73 | -22.95 |
| 14 | 14.00 | 4.08 | 0.62 | -22.92 |
| 15 | 13.29 | 3.09 | 0.70 | -22.47 |
| 16 | 11.52 | 3.02 | 0.71 | -21.23 |

TABLE IV. WARPAGE S/N VALUE RESPONSE TABLE

| | ***A*** | ***B*** | ***C*** | ***D*** | ***E*** |
|---|---|---|---|---|---|
| Level 1 | 3.65 | 3.22 | 3.52 | 3.51 | 3.04 |
| Level 2 | 3.53 | 3.68 | 3.54 | 3.31 | 3.30 |
| Level 3 | 3.28 | 3.59 | 3.40 | 3.46 | 3.40 |
| Level 4 | 3.22 | 3.20 | 3.23 | 3.39 | 3.94 |
| effect | 0.43 | 0.49 | 0.31 | 0.21 | 0.90 |
| Rank | 3 | 2 | 4 | 5 | 1 |

TABLE V. WARPAGE VARIANCE ANALYSIS TABLE

| ***Symbol*** | ***Process Parameter*** | ***DOF*** | ***SS*** | ***MS*** | ***Contribution(%)*** |
|---|---|---|---|---|---|
| A | Injection Duration | 3 | 0.49 | 0.16 | 14.92 |
| B | Plastics Temperature | 3 | 0.75 | 0.25 | 22.68 |
| C | Mold Temperature | 3 | 0.24 | 0.08 | 7.31 |
| D | Injection Pressure | Pooled | | | |
| E | Holding Pressure | 3 | 1.71 | 0.57 | 51.96 |
| | Error | 3 | 0.10 | 0.03 | 3.13 |
| | Total | 15 | 3.29 | | 100 |

TABLE VI. TEMPERATURE DISTRIBUTION S/N VALUE RESPONSE TABLE

| | ***A*** | ***B*** | ***C*** | ***D*** | ***E*** |
|---|---|---|---|---|---|
| Level 1 | -21.98 | -21.84 | -20.93 | -22.48 | -22.00 |
| Level 2 | -23.2 | -22.85 | -21.51 | -21.51 | -23.15 |
| Level 3 | -22.39 | -23.11 | -22.91 | -22.55 | -22.56 |
| Level 4 | -22.39 | -23.17 | -24.61 | -23.42 | -22.25 |
| effect | 1.21 | 1.27 | 3.68 | 1.91 | 1.16 |
| Rank | 4 | 3 | 1 | 2 | 5 |

TABLE VII. TEMPERATURE DISTRIBUTION VARIANCE ANALYSIS TABLE

| ***Symbol*** | ***Process Parameter*** | ***DOF*** | ***SS*** | ***MS*** | ***Contribution (%)*** |
|---|---|---|---|---|---|
| A | Injection Duration | 3 | 3.10 | 1.03 | 6.23 |
| B | Plastics Temperature | 3 | 4.15 | 1.38 | 8.34 |
| C | Mold Temperature | 3 | 32.21 | 10.74 | 64.70 |
| D | Injection Pressure | 3 | 7.35 | 2.45 | 14.75 |
| E | Holding Pressure | Pooled | | | |
| | Error | 3 | 2.98 | 0.99 | 5.98 |
| | Total | 15 | 49.79 | | 100 |

Grey correlation is conducted on the S/N values of the parameters in the 16 combinations of the Taguchi orthogonal table for the two single-objective groups, producing normalized data. The degree of correlation and ranking are shown in Table VIII. The degree of Grey correlation is used to generate a response table for the various factors at different levels as shown in Table IX. From this, we can observe the changes of each factor at different levels. With the optimized Grey correlation combination, the warpage is 0.61 mm, while the simulated warpage with the original fabrication process parameters is 0.90 mm. Clearly, the optimized combination of fabrication process parameters obtained from Grey correlation analysis significantly reduces the warpage. With this optimized condition, the average temperature difference is 10.16°C. From the bar graph in Fig. 4, comparing the temperature distribution, we know that the average temperature at the end of filling is between 220°C and 260°C, which is 73.47% of the time, while, under optimized conditions, it is between 220°C and 260°C, which is 85.28% of the time. The variation in the ratio of the temperature distribution to the main temperature range is smaller, and this helps to reduce deformation that is caused by large differences in the temperature distribution.

TABLE VIII. ORDER OF TAGUCHI-GREY CORRELATION OF THE SIMULATTION ANALYSIS GROUPS

| | *Warpage* | *Temp. Distribution Diff* | *Grey Correlation* | *RANK* |
|---|---|---|---|---|
| 1 | 1.00 | 0.70 | 0.85 | 5 |
| 2 | 0.86 | 0.87 | 0.86 | 4 |
| 3 | 0.73 | 0.88 | 0.81 | 7 |
| 4 | 0.67 | 0.84 | 0.76 | 9 |
| 5 | 0.83 | 0.96 | 0.90 | 2 |
| 6 | 0.74 | 0.89 | 0.82 | 6 |
| 7 | 0.59 | 0.77 | 0.68 | 13 |
| 8 | 0.80 | 0.61 | 0.71 | 12 |
| 9 | 0.70 | 0.63 | 0.67 | 14 |
| 10 | 0.68 | 0.65 | 0.66 | 16 |
| 11 | 0.91 | 0.93 | 0.93 | 1 |
| 12 | 0.85 | 0.71 | 0.78 | 8 |
| 13 | 0.74 | 0.59 | 0.67 | 15 |
| 14 | 0.75 | 1.00 | 0.87 | 3 |
| 15 | 0.77 | 0.67 | 0.72 | 11 |
| 16 | 0.84 | 0.66 | 0.75 | 10 |

TABLE IX. GREY CORRELATION AVERAGE VALUE RESPONSE TABLE

| | *A* | *B* | *C* | *D* | *E* |
|---|---|---|---|---|---|
| Level 1 | 0.82 | 0.77 | 0.86 | 0.80 | 0.73 |
| Level 2 | 0.77 | 0.80 | 0.81 | 0.79 | 0.74 |
| Level 3 | 0.76 | 0.77 | 0.76 | 0.78 | 0.77 |
| Level 4 | 0.75 | 0.75 | 0.69 | 0.74 | 0.86 |
| effect | 0.07 | 0.05 | 0.17 | 0.06 | 0.12 |
| Rank | 3 | 5 | 1 | 4 | 2 |

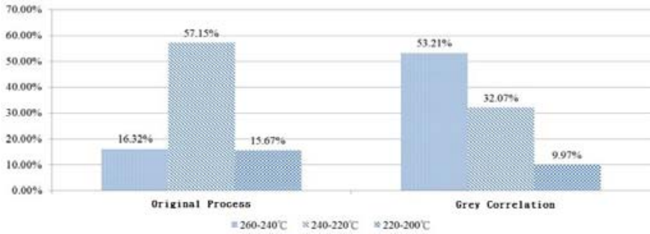

Fig. 4. Process temperature distribution ranges comparison chart

## IV. CONCLUSIONS

Based on the results of the simulation analysis investigation, conclusions can be drawn as follows

1. From the simulation results based on the Taguchi robust design process and optimization analysis, we obtained the optimized combination for warpage in auto lock parts. The optimized injection molding condition is A1B2C2D1E4, which is as follows: A1 injection duration (0.6 s), B2 plastics temperature (255°C), C2 mold temperature (75°C), D1 injection pressure (120 MPa), and E4 holding pressure (145 MPa). The total warpage is 0.61 mm, which is 0.29 mm less than that of the original fabrication process.

2. From the simulation results based on the Taguchi robust design process and optimization analysis, we obtained the optimized combination for the temperature distribution in auto lock parts. The optimized injection molding condition is A1B1C1D2E1, which is as follows: A1 injection duration (0.6 s), B1 plastics temperature (250°C), C1 mold temperature (65°C), D2 injection pressure (125 MPa), and E1 holding pressure (130 MPa). The average temperature difference is 7.59°C, which is 6.84°C less than that of the original fabrication process.

3. From Grey correlation analysis, we obtained multi-objective optimized parameters, where the quality objectives are minimum warpage and minimum difference in temperature distribution. From the simulation analysis, the multi-objective optimized parameters obtained are A1B2C1D2E4, which is as follows: A1 injection duration (0.6 s), B2 plastics temperature (260°C), C1 mold temperature (65°C), D2 injection pressure (125 MPa), and E4 holding pressure (140 MPa). The corresponding warpage is 0.61 mm and the average temperature difference is 10.1°C, which are lower by 0.29 mm and 4.27°C, respectively, compared with those of the original fabrication process.

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