Simulation and optimization for a plastic component

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Abstract: This paper presents the simulation of injection moulding process of the subject component and noting the deflection results using finite element software. Subsequently some changes were made to the tool and part design of the subject component and the modifications which gave the minimum deflection were incorporated and used for further optimization of warpage using design of experiments.

1. INTRODUCTION

Plastic injection moulding is widely used throughout the world to produce plastic parts \cite{2}. Plastic Injection Moulding consists primarily of 3 parts, mould, machine and the plastic raw material. It is a cyclic process which involves mould closing, injection, packing, cooling, mould opening and ejection of the plastic part and again mould closing for the entire cycle to repeat. One of the main challenges of injection moulded component is the moulding defect of warpage \cite{3}.

The quality of moulded parts depends on the material, part and mould designs and the process parameters used to get the desired design. The main cause of warpage is non uniform shrinkage throughout the part \cite{5}. The other factors which influence the warpage in a component are material properties, part design, part geometry, mould design and mechanical stiffness\cite{1}.

By using Autodesk Moldflow Insight for injection molding simulation and OA for optimization, they found that the significant parameter was pack pressure. S.H. Tang, Y.J. Tan, S.M.Sapuan, S. Sulaiman, N. Ismail and R. Samin (2006) \cite{4} have investigated a thin plate with for warpage testing. The factors that they have investigated are melt temperature, fill time, pack time and pack pressure and have found out that the most effective factor was the melt temperature.

In this study, a switchgear component is analysed using the existing tool and part design of the subject component. The material chosen for making the plastic component is PA66 with 50\% glass fibre. Then further analyses are done by an iterative process of making some modifications to the tool and part design by trial and error. Then the design with the least warpage is selected for further optimization using design of experiments (DOE). The component chosen for study is shown in figure 1.
2. 3D WARP SIMULATION

The shrinkage of solidified layers of the injection moulded parts is prevented as the part is constrained in the mould during the process. This leads to formation of in cavity residual stresses during solidification stage which causes shrinkage and when this shrinkage is non-uniform throughout the part, it leads to warpage. [7]

For a 3D thermo-viscous-elastic residual stress model, the solidified part is assumed to have linear elastic behaviour, whereas the melt is assumed to behave in a purely viscous manner. For the fibre filled materials, the material model used is orthotropic model.[6]

The moduli, Poisson’s ratios and thermal expansion coefficients of the composite material predicted from fibre simulation are put into structural tetrahedral elements. The following is the 3D orthotropic stress-strain relationship: [6, 7]

\[
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\tau_{xy} \\
\tau_{yz} \\
\tau_{zx}
\end{bmatrix} =
\begin{bmatrix}
\frac{1-v_{yz}v_{zy}}{E_xE_z} & \frac{v_{yz}+v_{zx}v_{xz}}{E_xE_y} & \frac{v_{xx}+v_{yy}v_{xy}}{E_yE_z} & 0 & 0 & 0 \\
\frac{v_{yz}+v_{zx}v_{xz}}{E_xE_y} & \frac{1-v_{xx}v_{yz}}{E_yE_z} & \frac{v_{xx}+v_{yy}v_{xy}}{E_yE_z} & 0 & 0 & 0 \\
\frac{v_{xx}+v_{yy}v_{xy}}{E_yE_z} & \frac{v_{xx}+v_{yy}v_{xy}}{E_yE_z} & \frac{1-v_{xy}v_{yx}}{E_xE_y} & 0 & 0 & 0 \\
0 & 0 & 0 & G_{xy} & 0 & 0 \\
0 & 0 & 0 & 0 & G_{yz} & 0 \\
0 & 0 & 0 & 0 & 0 & G_{zx}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\gamma_{xy} \\
\gamma_{yz} \\
\gamma_{zx}
\end{bmatrix}
\]  

(1)

Where;

\[
\Delta = \frac{1-v_{yz}v_{zy}-v_{zx}v_{xz}-v_{xx}v_{yy}-2v_{xy}v_{yx}v_{zy}v_{zy}}{E_xE_yE_z}
\]  

(2)

is the determinant of stiffness matrix

\[
\{\sigma_g\} = -[D_g]\{\varepsilon_{g0}\} + \{\sigma_{g0}\}
\]  

(3)

\[
[D_g] = [T^T]\{D\}[T]
\]  

(4)

\[
[\varepsilon_{g0}] = [T^{-1}]\{\varepsilon_{l0}\}
\]  

(5)

Where;

g: Global coordinate
l: Local coordinate
T: Transformation matrix from global strains to local strains
[D]: Stress-strain relationship matrix
\{\sigma_{g0}\}: \text{Initial stress}\\
\{\varepsilon_{g0}\}: \text{Initial strain from zero pressure state}

Warpage and moulded-in residual stresses can be calculated once the mould is released from its constraints. Starting from initial conditions at time zero the incremental stresses and strains are calculated from the equilibrium equations from t to t+\Delta t at steps k=1,2,3,…[6, 7]

\[
\int_V C_{ijrs} \Delta \varepsilon_{rs}^{(k)} \delta \Delta \varepsilon_{ij}^{(k)} dV + \int_V \Delta t S_{ij}^{(k)} \delta \Delta \eta_{ij}^{(k)} dV = \\
- \int_V \Delta t S_{ij}^{(k-1)} \delta \Delta \varepsilon_{ij}^{(k-1)} dV + \int_V C_{ijrs} \Delta \varepsilon_{rs}^{(ini)} \delta \Delta \varepsilon_{ij}^{(k-1)} dV
\]

(6)

Where;

- \(C_{ijrs}\): Stress-strain tensor
- \(\Delta \varepsilon_{ij}^{(k)}\): Linear incremental strain tensor for iteration k
- \(\Delta \eta_{ij}^{(k)}\): Non-linear incremental strain tensor for iteration k
- \(\delta \Delta \varepsilon_{ij}^{(k)}\): Linear incremental strain tensors corresponding to virtual incremental displacement.
- \(\delta \Delta \eta_{ij}^{(k)}\): Non-linear incremental strain tensor corresponding to virtual incremental displacement.
- \(\Delta \varepsilon_{rs}^{(ini)}\): Incremental initial strain tensor for iteration k
- \(S_{ij}^{(k-1)}\): Second Piola-Kirchhoff stress strain tensor after iteration (k-1) at time t+\Delta t

3. METHODOLOGY

3.1. Analysis of the injection molded component

In the current study, the first analysis of the component was done using the existing design of the subject component and putting the processing conditions used during the tool trial. The warpage was measured and modifications to the component and tool design were analyzed by doing various iterations. The modified design of component and tool where minimum deflection was observed was used for further optimization using DOE. The warpage/deflection is to be reduced by first identifying the most significant cause of warpage and then using the flow chart shown in figure 2 for reducing the warpage.[8]

![Figure 2. Flowchart to reduce warpage](image-url)
3.2. Optimization of the processing parameters using Design of Experiments

First we perform screening experiments to identify the significant factors out of a large pool of potential factors that have an effect on the deflection. Taguchi’s OA are used to estimate the main effects using a few experimental runs.

After screening experiment, ANOVA is used to identify the significant factors out of all the potential factors. The significant factors thus obtained are used to optimize warpage using a suitable Orthogonal array.

4. WARPAGE ANALYSIS USING FEA SOFTWARE

4.1. Initial analysis using existing design

The analysis was carried out by using the FEA software and using the mould trial processing parameters values which gave the results as shown in figure 3.

![Figure 3. Deflection due to: all effects (topleft), differential shrinkage (top right), orientation effects (bottom left) and differential cooling (bottom right).](image)

The existing mould design had a direct sprue gate and no baffle cooling. The maximum deflection noted here due to all effects was 0.5584mm. The existing part was analysed for warpage. The most significant causes of deflection were differential shrinkage (0.4119mm) and orientation effects (0.4305). From the flowchart presented in figure 2 we use the following points: change gate location and reduce thickness variations to reduce the deflection. Processing conditions changes are to be considered while optimizing the problem using design of experiments.

4.2. Analysis with modification to tool and part design

The following modifications were implemented step by step and the deflection results were noted.

*Gate modification.* The direct sprue gate was replaced with 1 edge gate, 2 edge gates and finally with
a diaphragm gate and iterations were simulated. It was noted that after the analyses, the least deflection (0.4587mm) was observed when diaphragm gate was used. Thus, this gate has been used for further analyses.

**Part design modification.** Various iterations of part modifications were analysed and finally least deflection (0.4237mm) was obtained after removal of ribs and scooping (material removal). Thus, this part design modification was incorporated for further analyses.

**Tool design modification.** Baffle cooling channel was added to the tool and analysed. The deflection drastically reduced to 0.3690mm.

Thus, the final tool and part design used for further analyses using DOE has baffle cooling added to the tool, sprue gate replaced with diaphragm gate and ribs removal and scooping the part.

**4.3. Final modified design for further analysis**
The final design selected for further analysis using design of experiments replaces direct sprue gate with diaphragm gate, removal of ribs below the rack and scooping out the chamfered portion along with addition of baffles. The final modified design used for further analysis is as shown in figure 4.

![Final modified design](image)

**Figure 4.** Final modified design

**5. PROCESS OF EXPERIMENTAL DESIGN**

To determine the significant processing factors for warpage reduction, Taguchi method has been selected. Therefore, the factors to be selected should be such that the warpage is dependent on them. First a screening experiment is run to eliminate the factors which are not so significant leaving us with only the ones that are significant.

There are several processing parameters. Each has a different effect on the quality of moulded component. This project particularly aims at reducing the warpage problem in the moulded part. As per the findings of many researchers the 7 process parameters selected for carrying out the screening experiment are:

- Coolant temperature in baffle ($T_{baffle}$)
- Melt temperature ($T_{melt}$)
- Coolant temperature in channels ($T_{channel}$)
- Fill time ($t_{fill}$)
- Pack time ($t_{pack}$)
- Pack pressure ($P_{pressure}$)
- Cooling time ($t_{cool}$)
The screening experiment is performed using L8 orthogonal array. The factors and their level selected are given in table 1. The analysis is conducted by using the processing parameters at levels specified in the table 1, whereas the remaining processing parameters are kept the same i.e. those taken during the trial of the tool and the results of the output (deflection) for each run i.e. treatment condition (TC) are tabulated in table 2.

| Table 1: Factors along with their levels selected for screening experiment |
| --- |
| Levels | Factors |
| | A | B | C | D | E | F | G |
| 1 | 25 | 265 | 25 | 2 | 2 | 4 | 20 |
| 2 | 80 | 285 | 80 | 5 | 7 | 15 | 35 |

Table 2: Simulation result as per L8 OA

| TC | Factors/levels | Maximum deflection, Y |
| --- | --- | --- |
| A | B | C | D | E | F | G | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.3896 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 0.3623 |
| 3 | 1 | 2 | 2 | 1 | 1 | 2 | 0.2843 |
| 4 | 1 | 2 | 2 | 2 | 2 | 1 | 0.2777 |
| 5 | 2 | 1 | 2 | 1 | 2 | 1 | 0.4048 |
| 6 | 2 | 1 | 2 | 2 | 1 | 2 | 0.3807 |
| 7 | 2 | 2 | 1 | 1 | 2 | 2 | 0.5246 |
| 8 | 2 | 2 | 1 | 2 | 1 | 1 | 0.508 |

Using the table 2, we derive the ANOVA table as shown in table 3.

Table 3: ANOVA summary table for screening experiment

| Source | DOF | SS | V | % Contribution |
| --- | --- | --- | --- | --- |
| T_c | 1 | 3.17 × 10^{-2} | 3.17 × 10^{-2} | 55.8 |
| T_b | 1 | 4.08 × 10^{-4} | 4.08 × 10^{-4} | 0.73 |
| T Channel | 1 | 2.38 × 10^{-2} | 2.38 × 10^{-2} | 41.9 |
| u_fill | 1 | 7.72 × 10^{-4} | 7.72 × 10^{-4} | 1.35 |
| u_pack | 1 | 5.78 × 10^{-6} | 5.78 × 10^{-6} | 0.01 |
| P_pressure | 1 | 9.94 × 10^{-5} | 9.94 × 10^{-5} | 0.175 |
| u_cool | 1 | 2.17 × 10^{-6} | 2.17 × 10^{-6} | 0.03 |

From table 3 it is clear that the coolant temperature in the baffle is the most significant factor with 55.8% contribution followed by coolant temperature in channel (41.9%) and fill time (1.35%). These 3 process parameters will be further optimized using full factorial L27 orthogonal array which will give the optimized values of these 3 factors which give the least deflection.

5.1. Full factorial experiment (L27 orthogonal array)
The significant factors obtained after the screening experiment are taken to get the optimum values of them using L27 OA. The significant factors along with their levels are shown in the table 4.

| Table 4: Factors and levels selected for L27 array |
| --- |
| Factors | Levels |
| --- | --- |
| A | Coolant temp in baffle | 25°C | 50°C | 75°C |
| B | Coolant temp in channels | 65°C | 75°C | 85°C |
| C | Fill time | 2secs | 3.5 secs | 5 secs |
Table 5: Simulation results for L27 OA.

| TC | Factors / Levels | Max. Deflection in 'mm' (Y) |
|----|------------------|-----------------------------|
| 1  | 1                | 0.4537                      |
| 2  | 1                | 0.3071                      |
| 3  | 1                | 0.2994                      |
| 4  | 1                | 0.3023                      |
| 5  | 1                | 0.2913                      |
| 6  | 1                | 0.2799                      |
| 7  | 1                | 0.2757                      |
| 8  | 1                | 0.2838                      |
| 9  | 1                | 0.2712                      |
| 10 | 2                | 0.3711                      |
| 11 | 2                | 0.3758                      |
| 12 | 2                | 0.3416                      |
| 13 | 2                | 0.3416                      |
| 14 | 2                | 0.3412                      |
| 15 | 2                | 0.3290                      |
| 16 | 2                | 0.3164                      |
| 17 | 2                | 0.3198                      |
| 18 | 2                | 0.3091                      |
| 19 | 3                | 0.4341                      |
| 20 | 3                | 0.4170                      |
| 21 | 3                | 0.4122                      |
| 22 | 3                | 0.4169                      |
| 23 | 3                | 0.4125                      |
| 24 | 3                | 0.3746                      |
| 25 | 3                | 0.3861                      |
| 26 | 3                | 0.3842                      |
| 27 | 3                | 0.3631                      |

From the above table 5 it is clear that at TC 9, when coolant temperature in baffle is at level 1, coolant temperature in channel is at level 3 and fill is at level 3, we get the least warpage of 0.2712mm.

6. RESULT

Least warpage was obtained by using diaphragm gate instead of direct sprue, scooping material from the component, removing the ribs below the gear profile of the subject component and by addition of baffle cooling near the gear profile. Figure 5 shows the minimum deflection obtained after using design of experiments along with an analysis software.

![Minimum deflection after optimization](Image)
From the table 5 it can be seen that the most effective processing parameter which influences the warpage is the coolant temperature in baffle followed by coolant temperature in channel and fill time. The least significant factor is the packing time. The optimum parameters that reduce warpage are coolant temperature in baffle (25°C), coolant temperature in channel (85°C) and fill time (5 sec). The deflection was drastically reduced to 0.2712 mm.

7. CONCLUSION

The subject injection moulded component used in switchgear was simulated using CAE software. Deflection of the component was estimated using the CAE software and the process parameters for the design were optimized using Taguchi’s orthogonal arrays and ANOVA. Deflection in the component was drastically reduced by successful integration of CAD, CAE and statistical techniques such as DOE and ANOVA. 27 trials were run using Taguchi method. The optimum parameters that reduce warpage are coolant temperature in baffle (25°C), coolant temperature in channel (85°C) and fill time (5 sec). The deflection was drastically reduced to 0.2712 mm from 0.5584 mm. Thus, there was 51.43% reduction in warpage.

The analysis helps in simulating the process of injection moulding which helps us know the problems which may arise in the moulded component. Due to this necessary changes in the design or processing parameters can be made beforehand i.e. during the design development stage itself, thus saving a lot of time and also the cost of practical iterations.

There is a tremendous scope for using the CAE analysis and DOE for optimizing various quality aspects of injection molded parts, namely, weld lines, sink marks, cycle time, air traps, hesitation etc.

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