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Warpage Analysis of Injection Molded Thin-Walled Chassis Part by RSM and FEM

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Abstract

Warpage is one of the common defects seen in thin-walled injection moldings. There are several ways to reduce warpage in injection molding process such as optimizing process conditions, changing mold design or part design. In this study, warpage of the injection molded thin-walled chassis part of an air conditioner was investigated by finite element method (FEM) and response surface method (RSM). The material was polypropylene with 20% glass fiber and 4% chemical foaming agent. The key parameters in FEM analysis and RSM were cooling time, mold temperature and flow rate of the coolant. It has been seen that mold temperature was the most significant parameter on warpage. RSM and FEM were satisfactorily successful in predicting the warpage values.

Keywords: *Plastic Injection Molding, Thin-Walled, Warpage, Finite Element Analysis, Response Surface Method.*

1. Introduction

Injection molding is a widely used plastic processing method and plays an important role in plastic industry due to its high production rate, economical efficiency and ability to produce complex articles with high precision [1-3]. The quality of the molded part depends not only on the plastic material properties but also on the process parameters. Optimum process parameters reduce the cycle time and increase the quality of the product. In practice, setting the process parameters is mainly based on the experience of the plastic engineer. However, polymer material exhibits a complex thermo-viscoelastic property. In this regard, sufficient knowledge about mold design, polymeric materials, especially rheology of the polymer as well as many other parameters are the requirements for producing a cost-effective product [4-7].

In recent years, numerical simulation techniques have become popular tools for mold designers and process engineers in injection molding. Many authors studied numerical simulation of injection molding process, and some related computer aided engineering software such as Moldflow, Moldex, HSCAE and Z-mold [6]. These finite elements based methods play an important role in determining the appropriate mold design. Besides all, FEM helps to determine the optimum process parameters and to reduce the defects of the product before manufacturing [7].

Warpage is one the of most known problem in plastic injection molding process. There are several complicated reasons of warpage, primarily caused by variations in shrinkage during the injection molding process. Material properties, part design, mold design, and processing conditions are factors

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influencing variations in the part shrinkage [8]. Researchers still focus on shrinkage and warpage. Yena et al. [9] used the Taguchi method and simulated it by using the Moldflow software. They optimized the gating system, and reduced the warpage. Huang and Tai [10] used the Taguchi experimental design method to optimize the injection molding process and simulated the molding process of plastic part using the C-MOLD software. Altan [11] used Taguchi and neural network for predicting shrinkage of polypropylene and polystyerene. Liao and Liu [12] studied on the effect of packing process of plastic part by using the Moldflow software. Although there is a considerable amount of studies that focused on the optimization of injection molding process parameters with DOE and Moldflow analysis [13,14], warpage of thin-walled parts is still under investigation. In this paper, a case study was realized for investigating the warpage of the thin-walled chassis part of an air conditioner during injection molding process. Finite element method and response surface method were used and the results were compared with actual measured results.

2. Experimental Procedure

2.1 Material

The polymer material used in the experimental study was glass fiber reinforced (20% wt.) polypropylene including 4% of chemical foaming agent. The material specifications are given in Table 1.

The polypropylene containing foaming agent was not present in the material library of Moldflow. Therefore, the polymer specifications had to be identified to the material library of the software. In this regard, thermal and rheological test were applied as reported in [15]. Finally, a new material data was created in the database of the software.

Table 1. Summary of Polymer Specifications

Property	Method	Condition	Unit	Spec.
Melt Index	D-1238	230°C 2,16 kg	g/10 min	8
Ash Content		550°C 2hr	%	20±1
Foaming Agent Content		23°C	%	4±0.3
Density	D-792		g/ cm^3	1.04±0.01
Tensile Strength	D-638	50 mm/min	kgf/ cm^2	750±50
Elongation	D-638	50 mm/min	%	5 over
Flexural Modulus	D-790	30 mm/min	kgf/ cm^2	35000±5000
Impact Strength	D-256	Izod (23°C) notched	kgf/cm	6±2
HDT	D-648	4.6 kgf / ㎠	°C	140±10
Flammability	UL-94	T = 1,6 mm	Class	HB
Hardness	D-785	R-scale		100 over

2.2 Response Surface Method

Response surface method was utilized for prediction of the response, by second-order polynomial model, as given in Eq.1, where *b0, bj* and *bij* are the regression coefficients with *i, j* = 1, 2, …, k and *Xi* are the *k* input variables. The key parameters were selected as cooling time, mold temperature and flow rate of coolant as given in Table 2. Box Behnken Design (BBD) matrix was used (Table 3). According to BBD matrix, (-1) corresponds to Level 1 of the parameters, (+1) corresponds to Level 2 of the parameters, and (0) corresponds to the arithmetic average (midpoint) of two levels of each parameter.

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i \chi_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} \chi_i \chi_j + \sum_{i=1}^{k} \beta_{ij} \chi_{i2} \qquad (1)$$

Table 2. Levels of the key parameters

No	Parameter	Level 1	Level 2
X1	Cooling time (sec)	18	24
X2	Mold temperature (◦C)	15	45
X3	Flow rate of the coolant (l/min)	37,8	39

Table 3. Box Behnken Design Matrix

No	X1	X2	X3
1	1	1	1
2	1	0	1
3	1	-1	1
4	1	-1	0
5	0	1	1
6	0	0	1
7	0	0	0
8	0	-1	1
9	0	-1	0
10	-1	1	1
11	-1	0	1
12	-1	0	0
13	-1	-1	1
14	-1	-1	0
15	-1	-1	-1

2.3 Moldflow analysis

The part model was imported into the Autodesk Moldflow for the simulation of injection molding process. "Dual Domain" mesh was used in this analysis that converted the model with triangular elements. The meshed part included triangles is given in Figure 1. The average mesh aspect ratio decreased by mesh revision [7]. Although the recommended aspect ratio is 6 for this type of complex geometry, a higher quality mesh is created by selecting this value as 4. After the meshing step, the model transferred into a complete multi-cavity design, which included sprue, runner, gate and cooling system, as shown in Figure 2. The injection location and cooling lines were certain cause of this is existing mold. As previously described earlier, the process factors, such as coolant temperature, packing time, packing pressure, mold temperature and melt temperature, were the most significant parameters, which affect warpage and shrinkage of injection-molded part, according to the literature and material testing. The simulation was performed by selecting the "Cool + Fill + Pack + Warp" analysis of these materials to obtain warpage and maximum volumetric shrinkage at the plastic part. Woojin 650 tonnes was determined as the injection molding machine in process simulation. 1.2343 injection mold steel was selected as the mold material. The diameter of the cooling channels is 12 mm.

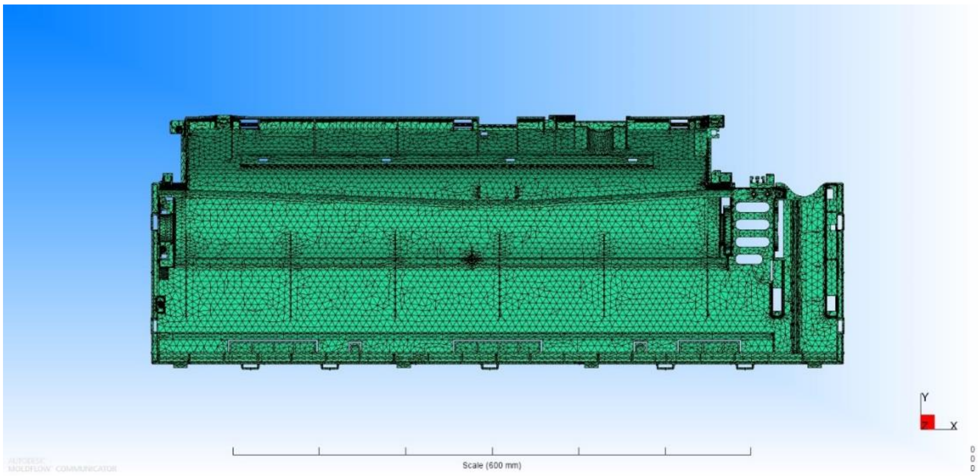

Figure 1. Meshed chassis part

The part model was imported into the Autodesk Moldflow for the simulation of injection molding process. “Dual Domain” mesh was used in this analysis that converted the model with triangular elements. The meshed part included triangles and then average mesh aspect ratio decreased by mesh revision [7]. After the meshing step, the model transferred into a complete multi-cavity design, which included sprue, runner, gate and cooling system, as shown in Fig. 2. The injection location and cooling lines were certain cause of this is existing mold. As previously described earlier, the process factors, such as coolant temperature, packing time, packing pressure, mold temperature and melt temperature, were the most significant parameters, which affect warpage and shrinkage of injection-molded part, according to the literature and material testing. The simulation was performed by selecting the “Cool + Fill + Pack + Warp” analysis of these materials to obtain warpage and maximum volumetric shrinkage at the plastic part. Woojin 650 ton was determined as the injection molding machine in process simulation. 1.2343 injection mold steel was selected as the mold material.

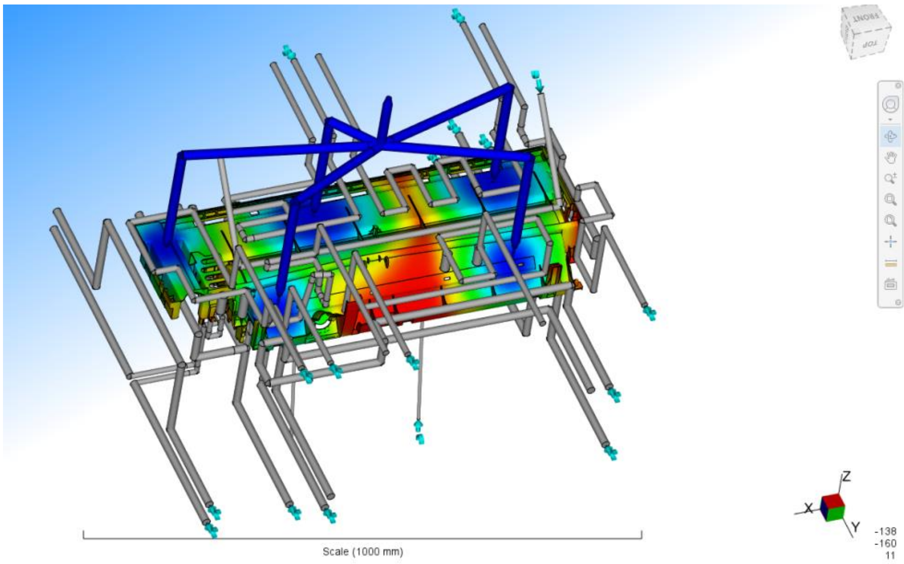

Figure 2. Cavity design with sprue, runner and cooling channel

2.4 Measurement of the warpage

The photograph of the chassis part is given in Figure 3. Warpage along the length of part as given in red dashed lines was investigated. The warpage was measured with a digital calipers with an accuracy of 0.001 mm by fixturing the part.

Figure 3. Thin-walled chassis part (800x280x 2,3 mm)

3. Results and Discussions

The warpage results given in Table 4 were obtained by Moldlfow analysis. The constant parameters are as follows; injection pressure (130 bar), holding pressure (45 bar), melt temperature (205 ◦C), holding time (17 s). The regression table of RSM and model summary are given in Table 5. RSM was applied in 90% confidence. R-sq (adj) with 97,61% shows that the analysis was performed in the confidence limits. P -values lower than 0.1 defines the significance of the parameters on the process. Mold temperature was the most critical parameter in this case study with 0.000 of P-value. The second order Response (Y) equation (Eq.2) was determined by the coefficients given in regression table.

Table 4. Warpage results

No	X1	X2	X3	Warpage (mm)
1	24 (+1)	45 (+1)	39 (+1)	1,976
2	24 (+1)	30 (0)	39 (+1)	1,727
3	24 (+1)	15 (-1)	39 (+1)	1,544
4	24 (+1)	15 (-1)	38,4 (0)	1,544
5	21 (0)	45 (+1)	39 (+1)	1,961
6	21 (0)	30 (0)	39 (+1)	1,708
7	21 (0)	30 (0)	38,4 (0)	1,707
8	21 (0)	15 (-1)	39 (+1)	1,545
9	21 (0)	15 (-1)	38,4 (0)	1,545
10	18 (-1)	45 (+1)	39 (+1)	1,815
11	18 (-1)	30 (0)	39 (+1)	1,683
12	18 (-1)	30 (0)	38,4 (0)	1,675
13	18 (-1)	15 (-1)	39 (+1)	1,548
14	18 (-1)	15 (-1)	38,4 (0)	1,549
15	18 (-1)	15 (-1)	37,8 (-1)	1,556

Table 5. Regression Table of RSM

Condition	Coef	SE Coef	T-Value	P-Value
Coefficient	1,7070	0,0134	127,17	0,000
Cooling time	0,03150	0,00822	3,83	0,112
Mold temperature	0,19125	0,00822	23,27	0,000
Flow rate of coolant	0,001	0,00822	0,12	0,908
Cooling time * Cooling time	-0,018	0,0121	-1,49	0,197
Mold temperature * Mold temperature	0,0320	0,0121	2,64	0,046
Flow rate of coolant * Flow rate of coolant	0,0140	0,0121	1,16	0,299
Cooling time * Mold temperature	0,0415	0,0116	3,57	0,016
Cooling time * Flow rate of coolant	-0,0020	0,0116	-0,17	0,870
Flow rate of coolant * Mold temperature	0,0000	0,0116	0,00	1,000

S	R-sq	R-sq (adj)	R-sq (pred)
0,0232487	99,15 %	97,61 %	86,32 %

$$\boldsymbol{Warpage} = 57,3 + 0,109 * X1 - 0,0151 * X2 - 2,96 * X3 - 0,002 * X1 * X1 + 0,000142 * X2 * X2 + 0,0389 * X3 * X3 + 0,000922 * X1 * X2 + 0,00111 * X1 * X3 \quad (2)$$

The response surface contour diagrams of the response and process parameters are given in Figure 4. These graphs show that with 24 sec cooling time, 15 °C constant mold temperature and 38.4 l/min flow rate of coolant could reduce warpage value to lower values than 1.6 mm. According to the resulting graphs, increasing cooling time and decreasing mold temperature could reduce warpage. However, flow rate of the coolant did not Show apparent effect on warpage.

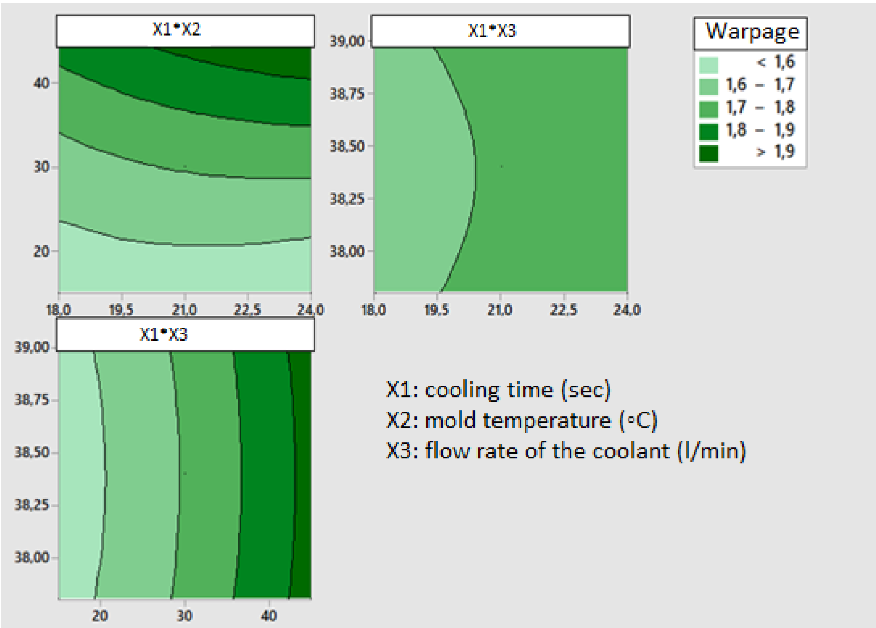

Figure 4. Contour diagrams of warpage vs process parameters

Confirmation tests were done for 4 different process conditions as given in Table 6. The injection molding test was applied on Woojin injection molding machine with 650 ton. The measured results were compared with second order equation (Eq.2) and FEM. The error in comparison with FEM and RSM are is avg. 0.198% and 0.171%, respectively. The measured warpage values were quite different from RSM and FEM due to the uncontrollable cooling of the part at ambient temperature after ejection of from the mold.

Table 6. Warpage values obtained by FEM, RSM and experimental

No	Paramaters	Method			Error	
	X1(s)-X2 (C)-X3 (l/min)	FEM	RSM	Experimental	Error[1] (%)	Error[2] (%)
1	24-15-39	1,54 mm	1,59 mm	1,76 mm	0,125	0,096
2	21-15-39	1,54 mm	1,63 mm	2,40 mm	0,358	0,320
3	24-30-39	1,72 mm	1,78 mm	2,20 mm	0,218	0,190
4	24-15-38,8	1,54 mm	1,57 mm	1,70 mm	0,094	0,076

(1) According to FEM (2) According to RSM

4. Conclusion

Warpage of the thin walled injection molded chassis part was investigated by response surface method and finite element method. The mold temperature, cooling time and flow rate of the coolant were selected as key parameters. It has been seen that mold temperature was more effective than other parameters on thin-walled part. 24 sec cooling time, 15 ° C constant mold temperature and 38.4 l / min flow rate of coolant could reduce warpage value to lower values than 1.6 mm. The second order equation was obtained to predict the warpage. The experimentally measured warpage values were compared with FEM, RSM . It has been seen that the warpage values could be predicted with errors of 0.198% (FEM) and 0.171% (RSM).

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