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Optimization of Processing Parameters for Minimizing Warpage of Large Thin-walled Parts in Whole Stages of Injection Molding*

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Abstract This study investigated total warpage of a type of motorcycle seat support made of polypropylene (PP) during the entire process of injection molding and free-cooling after demolding. Finite element modeling (FEM) analysis for injection molding and its associated thermal deformation was carried out in the study. The effects of processing parameters on warpage occurring in different stages were analyzed by Taguchi optimization method. It was found that packing pressure is the major factor that affects warpage in the injection stage, whereas cooling time is the major factor in free-cooling stage. From an overall evaluation, melt temperature affects the total warpage most, followed by cooling time, packing pressure, packing time and mold temperature. The result proved that optimum parameters for minimizing final warpage of the injected parts can be obtained only when the deformation in the entire manufacturing process is addressed in both molding and demolding stages.

Keywords: Injection molding; Warpage; Demolding; Numerical simulation; Taguchi optimization method.

INTRODUCTION

Injection molding is the most widely used manufacturing technique for producing plastic parts economically with various shapes and complex geometry. Warpage is a kind of defect of the injected parts that usually presents a bend-like shape deviation from the designed geometry along a certain direction. This frequently encountered defect not only has adverse impacts on the appearance, but also on assembly and performance of the products. Till date, extensive studies have been conducted on warpage in injection molding[1–4], and currently, it is commonly thought that the uneven shrinkages caused by inconsistent cooling and different molecular orientations within the material are the major reasons for the phenomenon[5–9].

Being a complicated process involving extensive changes of thermodynamic conditions and material properties, injection molding together with the warping behavior is affected by many factors and their interactions, including geometry and material component of the parts, mold designing, processing parameters, and so on. In recent years, with the development of Computer Aided Engineering (CAE) technologies and the improving fundamental knowledge on injection molding process, numerical simulation has been widely utilized in the analysis of warpage. Meanwhile, for optimizing processing parameters for minimizing warpage, rational techniques such as Taguchi optimization method[1, 10–15], neural network algorithm[16–19] and genetic algorithms[18, 19], are frequently used. Conclusions drawn in these studies regarding the influence of processing

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parameters on warpage depended on the shapes and materials of the parts. For instance, in the study of injection molding of an ABS thin plate, Tang *et al.*[9] found that the most effective factor on warpage is melt temperature, filling time only slightly influenced on the warpage; Ozeclik *et al.*[10] found that the most influential parameter on the warpage of a thin-shell cell phone cover produced with PC/ABS material was packing pressure; Gao *et al.*[11] utilized a surrogate-based process optimization for reducing warpage of an injected cellular phone cover, and found injection time to be a very important factor in the chosen range because it caused a sharp change in warpage, whereas mold temperature had little effect on the warpage. They also found packing time to be a remarkable effective factor; nevertheless, when packing time was beyond a certain value, it had no effect on the warpage. Chen *et al.*[12] stated that melt temperature and packing pressure were the most significant factors in the injection molding process of thin-shell plastic parts made of PA9T.

Till date, almost all studies on the warpage of injected plastic parts focused on the stage of injection molding. However, as reported by the authors[20], continuous warpage of a large thin-walled workpiece was found occurring dramatically during the free-cooling stage after ejection. As the major changes in the physical and chemical conditions of the plastic were accomplished by then, and based on the measured temperature on the real parts, it can be deduced that the formation mechanism of this warping is different from that in the injection process, to be specific, mostly caused by the existence of temperature difference in various sections of the part immediately after ejection from the mold.

Therefore, in the optimization of processing parameters for reducing warpage of the injected workpiece, especially the large thin-walled ones, it is not sufficient to consider the stage of injection molding alone. In the current study, a type of motorcycle seat support was used to analyze the combined effect of processing parameters on warpage in injection and free-cooling stages for minimizing the total warpage of the part.

SIMULATION OF INJECTION MOLDING PROCESS OF MOTORCYCLE SEAT SUPPORT

Analysis Model

Figure 1 shows the motorcycle seat support and its injection mold used in the study. It is a typical large thin-walled injection molded part with the maximum length of about 688 mm, transverse width of about 260 mm, and average thickness of 3 mm. The part is made of Generic PP, which belongs to crystalline thermoplastic polymer. Table 1 lists the properties of the as-received PP material. Model of the injection molding machine is HTF450-3W. A straight center gate was used in the single-cavity injection mold.

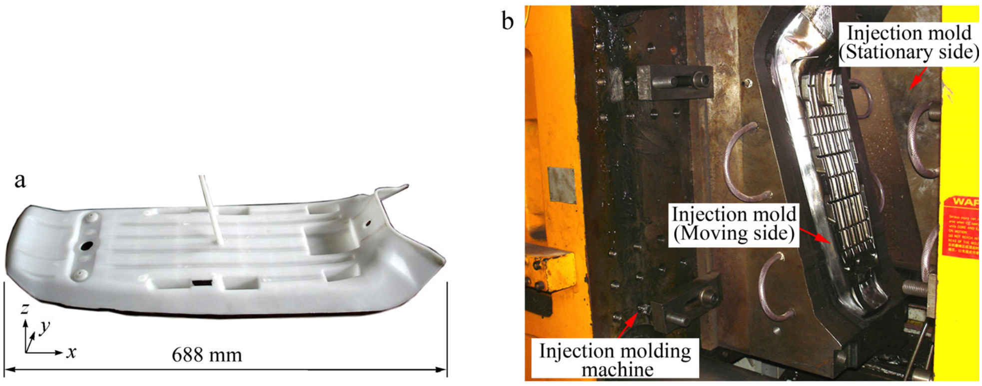

Fig. 1 Motorcycle seat support and the injection mold

In the practice, large warpage of the product was found, that is, the measured height in direction Z at the left end of the part (see Fig. 1 a) exceeds nearly 7 mm of the designed value. For the manufacturer, such a defect must be controlled without too much increase in cost.

Table 1. Material properties of PP

Solid density (kg/m^3)	895
Elasticity modulus (MPa)	840
Poisson's ratio	0.4
Specific heat (J/kg·K)	200
Heat conduction ratio (W/m·K)	0.164
Thermal expansion coefficient	1.7×10^{-4}

Simulation of Injection Molding Process

The analyses were conducted in Moldflow Plastics Insight (MPI) software. Simulation of injection molding for solving pressure, flow, temperature fields, and warpage in MPI is based on hybrid finite element/finite difference method; related theories have already been extensively discussed elsewhere and are not repeated here[18]. Mesh type used was “Midplane Mesh”. Because the shape of the part is complex and there are numerous strengthening ribs at the bottom, HyperMesh, which is a professional software for meshing, was used first to extract the middle surfaces. To inhibit the features that were too small, some shared edges and key points were merged, whereas relatively larger geometrical features such as holes and strengthening ribs at the bottom were retained. After handling the middle surfaces, meshing of the geometry was conducted with global element length controlled between 0.5 mm to 8 mm. Subsequently, the model was imported into MPI using an appropriate file format such as NAS. Figure 2 shows the CAE model constructed according to the actual mold including the cooling water channels. Manufacturing parameters used in the process are listed in Table 2. Considering the large number of strengthening ribs and corners in the part, corner effect[5] was taken into account in the calculation.

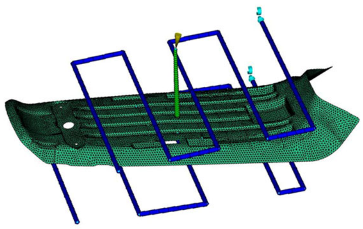

Fig. 2 Analysis model for injection molding process

Table 2. Manufacturing parameters

Mold temperature (°C)	40
Melt temperature (°C)	220–260
Ejection temperature (°C)	90–100
Injection pressure (MPa)	75
Injection time (s)	7
Packing pressure (MPa)	75
Packing time (s)	3
Cooling time (s)	15–20
Temperature of cooling water (°C)	25

In the beginning of the injection process, the polymer melt spreads outward from the center gate. According to the simulation, at 2.4 s, the melt filled the mold cavity completely. Time difference between filling the two sides, that is, the left and right sides of the part, is very small (about 0.013 s), indicating that position of the gate is reasonable for balance of the melt flow.

Because of the complex, thin-walled structure, and large size, temperature distribution of the part was inevitably uneven when the melt fully filled the mold cavity, and eventually lead to an uneven shrinkage and warpage of the part. Figure 3 shows the warpage at conclusion of the injection, which presents a bend-like shape with both sides gradually moving upward from the center (near the gate). The fine outlines represent the designed shape of the part. Maximum warpage appears in the left end and is close to 3.4 mm.

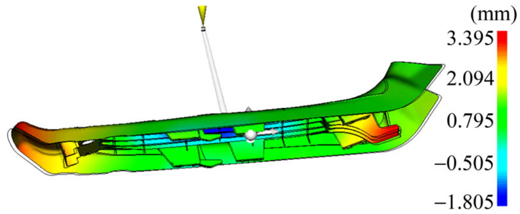

Fig. 3 Warpage in injection molding

SIMULATION OF THERMAL DEFORMATION IN FREE-COOLING STAGE AFTER DEMOLDING

Initial Temperature Distribution

Proper selection of ejection temperature is important in the production cycle, as it has direct impact on the productivity and quality. Commonly, the ejection temperature of the parts made of PP ranges from 80 °C to 100 °C[16]. Figure 4(a) is the simulated temperature distribution of the seat support at conclusion of the injection. As center gate was used on the injection mold, it can be found that at the moment the temperature at the center is about 90 °C, at the surrounding area, it is about 55–70 °C. Such a temperature distribution was verified by measurement using an AR882 noncontact Infrared Thermometer at the work site.

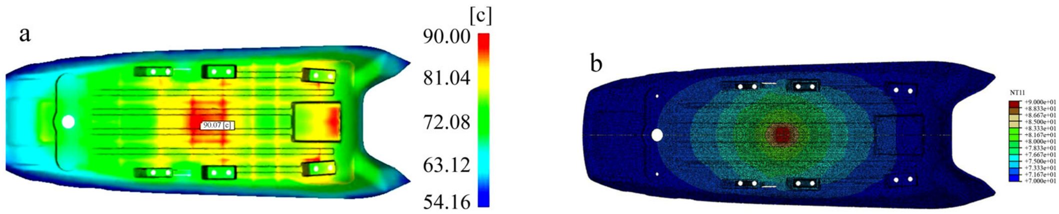

Fig. 4 Uneven temperature field after demolding, (a) by MPI (time = 35 s); (b) by ABAQUS

After the part was taken out from the mold, it cooled freely in the air to room temperature under an unconstrained condition. As mentioned earlier, obvious warping of the plastic parts was observed in this stage, and mostly it was induced by the uneven thermal shrinkage associated with the nonuniform initial temperature distribution of the part. Before conducting the thermal deformation calculation, temperature field of the part immediately after demolding needs to be constructed. Thus, simulation in CAE codes ABAQUS comprises two steps. First, heat transfer analysis was employed to obtain an initial temperature gradient that is consistent with the actual situation. Subsequently, warpage of the part after cooling to room temperature was calculated with the temperature distribution using a coupled analysis of thermal displacement.

According to the law of energy conservation, control equation of heat transfer can be written as:

$$-\frac{\partial q_i}{\partial x_i}+Q-\rho c\frac{\partial T}{\partial t}=0 \tag{1}$$

where q_i is the component of heat flux vector; Q is the heat supplied externally into the body per unit volume; ρ is the density, c is the specific heat, and T is temperature of the material; t is time.

Heat conduction is governed by the Fourier's law, therefore, heat flux can be written by,

$$q_i=-\lambda_{ij}\frac{\partial T}{\partial x_j} \tag{2}$$

where λ_{ij} is the component of thermal conductivity tensor in the designated direction. For isotropy material, λ_{ij} remains constant in all directions.

Temperature near the gate of the part was set to 90 °C, whereas at the margin temperature was set to a lower value ranging from 70 °C to 90 °C. On account of the lateral symmetry of the parts, half of the geometry was used in the simulation after imposing the constraints and boundary condition properly. Tetrahedral elements were used in the calculation. Figure 4(b) is the temperature distribution calculated by ABAQUS, where the geometry was mirror duplicated to be shown as a whole.

Thermal Deformation of the Part in Free Cooling Stage

Compared with the overall dimensions of the part, the amount of warpage caused by shrinkage during free cooling is small; therefore, it is assumed to be an indirect coupled problem of temperature and stress with small deformation within the linear elastic range, that is, temperature influence stresses and on the contrary, the influence of stress on temperature is ignored. The heat dissipation and thermal expansion (shrinkage) coefficient were considered to be uniform. Considering the thermal deformation, total strain ε of the material consists of two parts:

$$\varepsilon = \varepsilon^{\mathrm{e}} + \varepsilon^{\mathrm{th}} \tag{3}$$

where ε^{e} is elastic strain that obeys the Hooke's Law, and it is assumed to preserve after the part cooled; $\varepsilon^{\mathrm{th}}$ is thermal strain, which is related to temperature and thermal expansion coefficient of the material; it can be determined by the temperature variable of the structure to reference temperature when there is no thermal stress;

$$\frac{\partial \varepsilon_{ij}^{\mathrm{th}}}{\partial t} = \alpha_{ij}(T)\frac{\partial T}{\partial t} \tag{4}$$

where left of the equation is the change rate of thermal strain tensor; $\alpha_{\mathrm{ij}}(T)$ is temperature-dependent coefficient of transient thermal expansion.

Figure 5 shows the theoretical result of warpage after cooling to room temperature. In the plot, displacement in U3 or direction Z was magnified by five times to get a distinct display. After the cooling, higher initial temperature at center leads to larger shrinkage of the material, whereas the relatively lower initial temperature at the edge leads to smaller shrinkage, resulting in a bend-like combined deformation of the part with both sides moving upwards, which is consistent with the actual situation totally.

Fig. 5 Warpage in free-cooling with initial temperature at center/edge of 90 °C/70 °C

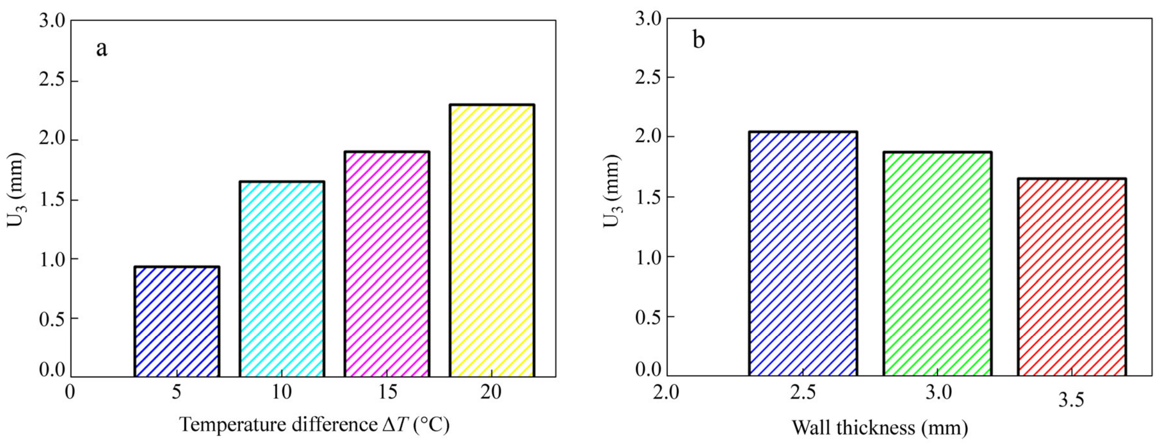

Fig. 6 Warpage versus temperature difference (a) and wall thickness (b) (Initial temperature at center is 90 °C.)

Figure 6(a) is the relationship of warpage and initial temperature difference between the center and surrounding area; Fig. 6(b) is the relationship of warpage and wall thickness, which is assumed to be 2.5 mm, 3 mm, 3.5 mm, respectively, with a temperature difference of 10 K. The results demonstrate that higher the temperature difference is, the larger is the warpage. If there is no temperature difference, in other words, if the temperature distribution within the part is entirely uniform at the moment of ejection, only isotropic homogeneous shrinkage occurs and there would be no warpage. Moreover, warpage decreases with wall thickness; certainly, material consumption and weight would increase when thickness increased.

OPTIMIZATION OF PROCESSING PARAMETERS FOR MINIMIZING TOTAL WARPAGE OF THE PART

When geometry and material of the part together with the injection mold were specified, adjustment of molding process parameters is almost the only approach to reduce the warpage. Therefore, in this study, processing parameters of injection molding were optimized taking into consideration total warpage of the part during injection molding and free-cooling stages using numerical simulation and orthogonal Taguchi method, which is a powerful and so far the most commonly used technique for Design of Experiment[10–15].

As mentioned in several literatures[1, 11], five parameters, namely, mold temperature (A), melt temperature (B), packing pressure (C), packing time (D) and cooling time (E) were considered as model variables that influence the total warpage in the study. According to generally recommended range of the parameters, an orthogonal table of $L_{16}(4^5)$ with five four-level factors was established, as shown in Table 3. Based on the table, 16 groups of calculation using MPI were conducted to attain the warpage and ejection temperature field of the part. Subsequently, ABAQUS was utilized for further analysis of the warpage during free-cooling stage. Because it was observed that warpage in both stages presents deformation in the same direction, final warpage of the parts is then assumed to be a cumulative deformation in these stages. The results are summarized in Table 4. On the whole, the simulated amount of total warpage is lower than the tested value with a deviation less than 1 mm, indicating that the theoretical results are acceptable.

Table 3. Technological parameters and levels

Levels	Mold temperature (°C)	Melt temperature (°C)	Packing pressure (MPa)	Packing time (s)	Cooling time (s)
	A	B	C	D	E
1	30	220	70	3	15
2	40	230	75	5	20
3	50	240	80	7	25
4	60	250	85	9	30

Extreme Difference Analysis was employed to determine how much the factors affect the warpage; the result is listed in Table 5. Figure 7 shows the effect curves of the factors that affect the warpage in injection and free-cooling stage. It can be found that the dominating factor that affects warpage in injection molding process is packing pressure, followed by melt temperature, packing time and cooling time. Mold temperature has only a little effect on the warpage. Higher packing pressure implies that more melt can flow into the mold cavity and offset the gaps caused by cooling shrinkage; the enhanced shrinkage compensation and density of the parts finally lead to less shrinkage and reduced warpage. However, molecular orientation of the polymer may change under high pressure, which would lead to an undesired effect on the deformation. The best combination of the parameters is $A_4B_2C_3D_4E_3$, namely, mold temperature of 60 °C, melt temperature of 230 °C, packing pressure of 80 MPa, packing time of 9 s, and cooling time of 25 s.

Table 4. Results of orthogonal design experiment

No.	A	B	C	D	E	Simulated warpage (mm)		
						Injection	Cooling	Total
1	1	1	1	1	1	3.35	2.46	5.81
2	1	2	2	2	2	2.71	2.30	5.01
3	1	3	3	3	3	2.68	1.88	4.56
4	1	4	4	4	4	2.62	1.82	4.44
5	2	1	2	3	4	2.82	2.10	4.92
6	2	2	1	4	3	2.86	1.98	4.84
7	2	3	4	1	2	2.88	2.18	5.06
8	2	4	3	2	1	2.72	2.30	5.02
9	3	1	3	4	2	2.84	2.20	5.04
10	3	2	4	3	1	2.71	2.12	4.83
11	3	3	1	2	4	3.20	1.94	5.14
12	3	4	2	1	3	2.80	1.96	4.76
13	4	1	4	2	3	2.74	2.15	4.89
14	4	2	3	1	4	2.67	1.68	4.35
15	4	3	2	4	1	2.82	2.00	4.82
16	4	4	1	3	2	3.01	1.78	4.79

Table 5. Extreme difference analysis

Test index	*K*	A	B	C	D	E
Warpage in injection molding	K_1	2.840	2.938	3.105	2.925	2.900
	K_2	2.820	2.738	2.787	2.842	2.860
	K_3	2.888	2.895	2.728	2.805	2.770
	K_4	2.810	2.788	2.738	2.785	2.828
	R	0.078	0.200	0.377	0.140	0.130
	Rank	5	2	1	3	4
Warpage in free cooling	K_1	2.115	2.228	2.040	2.070	2.220
	K_2	2.140	2.020	2.090	2.172	2.115
	K_3	2.055	2.000	2.015	1.970	1.993
	K_4	1.903	1.965	2.067	2.000	1.885
	R	0.237	0.263	0.075	0.202	0.335
	Rank	3	2	5	4	1

K_i: average warpage value in i-th level of each factor;
i: levels of each factor (i =1, 2, 3, 4);
R: range fluctuations index of each factors' maximum warpage;
Rank: influence rank of all factors

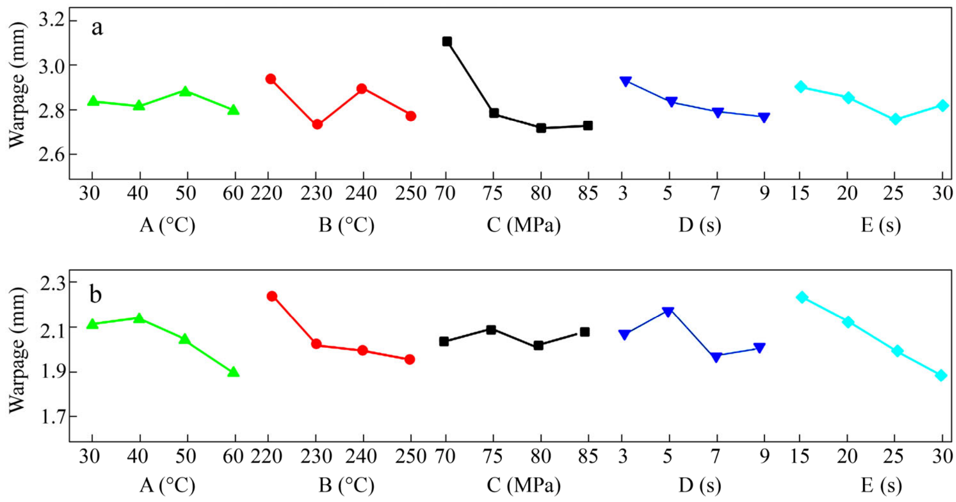

Fig. 7 Influence of processing parameters on warpage in different stages: (a) injection and (b) free cooling

As for the warpage in cooling stage, the result indicates that the order of the importance of factors is cooling time, melt temperature, mold temperature, packing time and packing pressure; the best combination of parameters is $A_4B_4C_3D_3E_4$. In Fig. 7(b), it can be found that warpage in the cooling stage decreases obviously with the increase in cooling time. The main reason is that longer cooling time would lead to smaller temperature difference of the workpiece after injection, and homogeneous temperature distribution is helpful to decrease the warpage during free-cooling. Considering the productivity and quality of the product, there should be a balance in the selection of the parameters.

Comprehensive scoring method with total warpage obtained by sum of warpage in injection and cooling stages as a comprehensive index was employed to optimize the molding processing parameters. The result of Extreme Difference Analysis is listed in Table 6. Table 7 is the result of Analysis of Variance (ANOVA). The effect curves of the factors are presented in Fig. 8. It can be concluded that the most effective factor of injection parameters on total warpage is melt temperature, followed by the cooling time, packing pressure, mold temperature, and packing time. The optimum combination of process parameters that can minimize the warpage are $A_4B_4C_3D_3E_4$, namely, mold temperature of 60 °C, melt temperature of 250 °C, packing pressure of 80 MPa, packing time of 7 s, and cooling time of 30 s, respectively.

Table 6. Extreme difference analysis for total warpage

K	A	B	C	D	E
K_1	4.955	5.165	5.145	4.995	5.120
K_2	4.960	4.758	4.877	5.015	4.975
K_3	4.943	4.895	4.742	4.775	4.762
K_4	4.712	4.753	4.805	4.785	4.713
R	0.248	0.412	0.403	0.240	0.407
Rank	4	1	3	5	2

Table 7. Analysis of variance

Factors	Sum of squares	DOF	Mean square	F value	Significance P
A	0.173	3	0.530	3.290	0.173
B	0.448	3	1.372	3.290	0.448
C	0.377	3	1.154	3.290	0.377
D	0.204	3	0.625	3.290	0.204
E	0.431	3	1.320	3.290	0.431

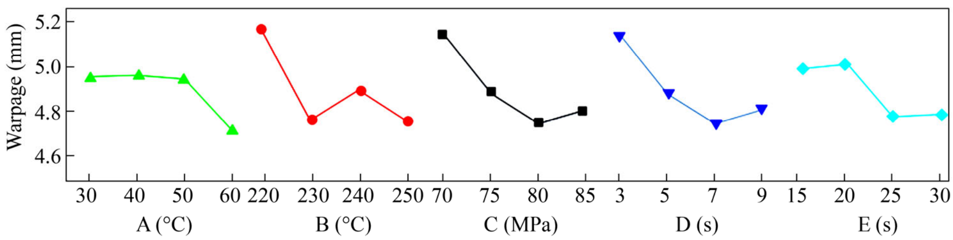

Fig. 8 Influence of processing parameters on total warpage

As an integral deformation of the part, it had been observed that local reinforcing ribs added on the part structure have limited influence on the reduction of the defect [20]; therefore, optimization of process parameters is of great significance in warpage control. In the confirmation test at worksite, final warpage of 20 injected parts produced with the processing parameters before and after optimization were measured. It was found that the total average had been reduced by about 33.8%, namely, the average amount of warpage decreased from the original 6.8 mm to 4.5 mm. The result supported the theoretical optimization strongly. If it is possible to improve the mold structure to a greater extent, including the cooling system, runner form, location, and so on, even less warpage of the part could be obtained with the achievement of more rational melt flow and uniform temperature field.

CONCLUSIONS

Warpage of the injected plastic parts results from many aspects; it can occur in the stages of injection molding and free-cooling after demolding. To meet the quality requirement of modern manufacturing, it is important to understand the effect of processing parameters on final deformation of the part. The current study investigated the warpage of a type of injected motorcycle seat support during both the injection and free-cooling stages using the methods of numerical simulation and Design of Experiment. The main conclusions are as follows:

(1) Because of the large thin-walled complex geometry of the part and the center gate design of the injection mold, uneven temperature distribution exists in the part at the moment of demolding, leading to a nonuniform shrinkage and consequent warping during the free-cooling stage. Therefore, it is difficult to attain an accurate prediction of the final warpage and then achieve a successful mold design and parameters selection if only the injection molding process is considered, especially for the large thin-walled parts.

(2) Results of simulation and orthogonal Design of Experiment indicated that packing pressure is the main factor affecting warpage in the stage of injection molding, followed by melt temperature, packing time, cooling time and mold temperature, whereas cooling time in the injection circle is the major factor affecting warpage in the free-cooling stage.

(3) Considering the total warpage in both the stages of injection molding and free-cooling, and in terms of a comprehensive evaluation, it was found that the major factor that affects the deformation is melt temperature, followed by cooling time, packing pressure, mold temperature and packing time. For the injection of motorcycle seat support made of PP, the optimum combination of molding processing parameters for minimizing the defect are $A_4B_4C_3D_3E_4$, namely, mold temperature of 60 °C, melt temperature of 250 °C, packing pressure of 80 MPa, packing time of 7 s, and cooling time of 30 s.

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