AC 2012-4884: SENIOR PROJECT: USING DESIGN OF EXPERIMENT (DOE) TO IDENTIFY MATERIAL AND PROCESSING VARIABLES THAT IMPACT PART WARPAGE IN INJECTION MOLDING

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Senior Project: Using the Design of Experiments (DOE) to Identify Materials and Processing Variables that Impact Part Warpage of Injection Molded Plastics Parts

Abstract

The injection molding of plastic parts consists of a series of events that include mold closing, injection of molten plastics into closed mold, cooling of molten plastics, mold opening, and ejecting of molded parts. Of these events, the cooling process comprise 75% of the injection molding cycle time. Consequently, identifying the material and processing variables and/or their interactions that significantly influence the cooling process is of utmost importance in understanding and optimizing the cooling process and in preventing part warpage. Many studies have investigated different aspects of the cooling process in injection molding including the role of the thermal diffusivities of the materials being processed. These studies have examined the role of thermal diffusivity by incorporating it into equations for estimating cooling times. Thermal diffusivity measures how fast thermal energy travels through materials and thus affects the rate of thermal energy (heat transfer) removal during the cooling process. It appears that the thermal diffusivity of a plastic plays a crucial role in the cooling process given that the ratio of the thermal diffusivities of the materials generally involved in the cooling process, plastics, coolant (water), and steel is 1:1.6:50 (plastics:water:steel). This implies that thermal diffusivity of plastics may be the controlling or limiting variable in the cooling process. Therefore in this study, by using the design of experiments (DOE), it is expected to examine the roles processing and material variables play in the cooling process, and in plastics part warpage. These variables include plastics thermal diffusivity, coolant flow rates, cooling time, coolant temperature, and injection back pressure.

The goals of this study are twofold: firstly, to provide a hands-on platform for students in the MET program to integrate materials covered in a design of experiments course with the topics covered in a plastics course in addressing technical issues that may arise in the injection molding of plastics, and secondly, to provide a framework for a lab in the trouble-shooting of injection molding processing problems using the design of experiments as a vehicle.

Introduction

The injection molding of plastics parts consists of a sequence of interconnected events, and the time required to complete these events is known as the cycle time of the process. These events include closing the mold, injection molten plastics into the closed mold, cooling the molten plastics, and opening the mold and ejecting the sufficiently cooled plastics parts. Among this series of event, the cooling process seems to play a critical role in a successful injection molding process because it alone generally accounts for about 75 percent of the cycle time.[1] Furthermore, the cooling process has a large influence on plastics part quality.[2]

Rosato et.al[3] expressed the overall heat-transfer coefficient, *U*, of the cooling process by equation 1.

$$\frac{1}{U} = \frac{1}{KS} + \frac{1}{\pi D h_i} \qquad \text{(Eqn. 1)}$$

where U = overall heat-transfer coefficient, W/m^2-°C or Btu/ft^2-hr-°F
K = thermal conductivity of mold material (metal), W/m-°C or Btu/ft-hr-°F
S = conduction shape factor of the cooling channels
D = diameter of the cooling channel, m or ft
h_i = inner (inside of cooling channel) convective heat-transfer coefficient, W/m^2-°C or Btu/ft^2-hr-°F

As equation 1 suggests, the cooling process is primarily influenced by the mold material through its thermal conductivity (K), the cooling channel shape factor (S), and the inner convective heat-transfer coefficient (h_i). h_i is related to the coolant properties and coolant flow rate by equation 2.[4] Equation 2 is valid for Reynolds number, N_{RE}, greater or equal to 6,000.

$$\frac{h_i}{c_p G}\left(\frac{c_p \mu}{k}\right)^{\frac{2}{3}}\left(\frac{\mu_w}{\mu}\right)^{0.14} = \frac{0.023}{\left(DG/\mu\right)^{0.2}} \qquad \text{(Eqn. 2)}$$

where c_p = specific heat capacity of the coolant at constant pressure, J/g-°C or Btu/lb-°F
D = diameter, m or ft
G = mass velocity, kg/m^2-s or lb/ft^2 –s ($G = V\rho$)
h_i = inner (inside of cooling channel) convective heat-transfer coefficient, W/m^2-°C or Btu/ft^2-hr-°F
k = thermal conductivity of coolant, W/m-°C or Btu/ft-hr-°F
V = average velocity, m/s or ft/s
ρ = density of coolant, kg/m^3 or lb/ft^3
μ = viscosity of coolant, kg/m-s or lb/ft-s,
μ_w = viscosity of coolant at wall temperature

It is important to note that the heat transfer properties of the plastics material being injection molded is missing from equations 1 and 2. This is because studies that have considered the role of the thermal diffusivity of plastic in the cooling process incorporate it in the equations for estimating cooling times.[5,6] Equations 3 and 4 express the cooling times for a plaque and a cylinder, respectively.

$$t_c = \frac{h^2}{\alpha \pi^2} \ln\left[\frac{4}{\pi}\left(\frac{T_m - T_w}{T_e - T_w}\right)\right] \qquad \text{(Eqn. 3 for plaque)}$$

$$t_c = 0.173\frac{R^2}{\alpha} \ln\left[1.6023\left(\frac{T_m - T_w}{T_e - T_w}\right)\right] \qquad \text{(Eqn. 4 for cylinder)}$$

where α = thermal diffusivity, m^2/s or ft^2/hr
h = plaque wall thickness, m or ft
R = radius of the cylindrical molding, m or ft
t_c = time required for the centerline temperature to reach the ejection temperature, s
T_m = melt temperature at the start of cooling, °C or °F
T_w = cavity wall temperature during cooling, °C or °F
T_e = ejection temperature of the plastic, °C or °F

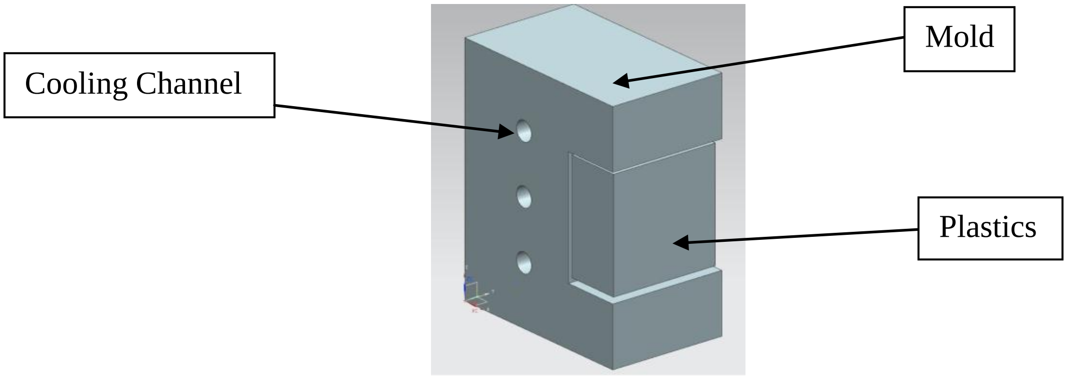

Figure 1. A schematic diagram of plastics in mold with cooling channels

As Figure 1 shows, the cooling process consisting of a series of heat transfer processes from the plastics to the mold and to the coolant. Several studies have examined different aspects of this process and how it could cause plastics parts warpage. For example, Zhil'tsova et.al[7], Song et, al[8] and Park and Ahn[9] studied the effects of processing parameters on the quality of injection molded parts. Other researchers such as Postawa, Kwiatkowski, Bociaga[10] and Kovacs and Bercsey[11] investigated the impact of mold properties on the quality of injection molded parts while others, Shuaib et. al[12], Tang et. al[13] and Kramschuster et. al[14], focused their efforts on elucidating the factors that cause warpage in injection molded parts. In this work, the authors examined the influence of processing variables and material's property, namely, coolant flow rates, coolant temperature, cooling time, back pressure, and thermal diffusivity, on warpage of injection molded plastics parts using the design of experiments.

Definitions

Thermal diffusivity, α, is defined as the rate thermal energy diffuses through a substance. It is expressed as

$$\alpha = \frac{k}{c_p \rho} \qquad \text{(Eqn. 3)}$$

where α = thermal diffusivity, mm^2/s or ft^2/hr
k = thermal conductivity of plastics, W/m-°C or Btu/ft-hr-°F
c_p = specific heat capacity of plastics at constant pressure, J/g-°C or Btu/lb-°F
ρ = density of plastics, kg/m^3 or lb/ft^3

The authors acknowledge that heat transfer properties of substances are a function of temperature[15], but in this study thermal diffusivity of plastics were assumed to be constant.

Warpage is defined as "a distortion where the surfaces of the molded part do not follow the intended shape of the design. Part warpage results from molded-in residual stresses, which, in turn, is caused by differential shrinkage of material in the molded part."[16]

Experimental

Materials

Two polypropylene-based (PP) materials, supplied by the RTP Company, were used in this work. These materials were selected because of their thermal properties and identical processing parameters as shown in Table 1. Except for drying the materials, they were used as received.

Table 1. Polypropylene-based Materials' Properties and Processing Parameters

Property	**RTP Compounds 199 X 104849 A (PP)**	**RTP Compounds 199 X 91020 A Z (PP)**
Feature	Thermally Conductive	Thermally Conductive
Density	1.50 g/cm^3	2.00 g/cm^3
Thermal Conductivity	12 Btu-in/hr-ft^2-°F	4.2 Btu-in/hr-ft^2-°F
Specific Heat Capacity	0.445 Btu/lb-°F	0.445 Btu/lb-°F
Calculated Thermal Diffusivity, α	0.023 ft^2/hr	0.006 ft^2/hr
Drying Temperature	175 °F	175 °F
Drying Time	2.0 hr	2.0 hr
Processing (melt) Temperature	375 – 450 °F	375 – 450 °F
Mold Temperature	90 – 150 °F	90 – 150 °F
Injection Pressure	10000 – 15000 psi	10000 – 15000 psi
Back Pressure	50 – 100 psi	50 – 100 psi
Fill Speed	2 – 3 in/s	2 – 3 in/s
Screw Speed	60 – 90 rpm	60 – 90 rpm

Equipment

A Sandretto 60-ton injection molding machine was used to mold ASTM tensile test specimens. A Conair Mold Temperature Controller (MTC), model TCI-DI, was used to control coolant temperature and supply the mold with coolant. The inlet and outlet temperatures of the coolant (water) were measured with two CEN-TECH P3777 digital thermocouples, which were inserted into the hoses carrying the coolant. These temperatures were used to determine the mold temperature and to determine state steady conditions, which is achieved when the temperature reading were constant. Two Omega flow meters, model FL-2300ABR, and ball valves were used to control the coolant flow rate to the mold. A Thermolyne digital pyrometer was used to measure the plastics' melt temperature. Conair dehumidifying dryer (model CD-30) was used in drying the materials.

Procedure

There were two sets of experiments conducted in this study. The first set of experiments, shown in Table 2, was a 2^4 factorial design with 2 replicates resulting in 32 experimental runs. For each run about ten specimens were produced after state steady conditions were attained. The specimens were allowed to equilibrate to room temperature (~72 – 74 °F) for 48 hours; then part warpage was measured using a bench steel block from Smith Tool and Engineering Company and a digital spring gage on five randomly selected test specimens produced at each run. The run order was randomly generated by Minitab® 16. Minitab is a statistical application software. The variables considered in this set of experiments were coolant flow rate, mold temperature, cooling time, and PP thermal diffusivity.

Table 3. 2^4 Factorial design with 2 replicates

StdOrder	**RunOrder**	**CenterPt**	**Blocks**	**Mold Temp**	**Coolant Flow**	**Alpha**	**Cooling Time**
32	1	1	1	160	1.4	High	40
30	2	1	1	160	0.5	High	40
28	3	1	1	160	1.4	Low	40
11	4	1	1	80	1.4	Low	40
2	5	1	1	160	0.5	Low	10
27	6	1	1	80	1.4	Low	40
4	7	1	1	160	1.4	Low	10
25	8	1	1	80	0.5	Low	40
24	9	1	1	160	1.4	High	10
20	10	1	1	160	1.4	Low	10
14	11	1	1	160	0.5	High	40
15	12	1	1	80	1.4	High	40
26	13	1	1	160	0.5	Low	40
6	14	1	1	160	0.5	High	10
12	15	1	1	160	1.4	Low	40
21	16	1	1	80	0.5	High	10
16	17	1	1	160	1.4	High	40
18	18	1	1	160	0.5	Low	10
31	19	1	1	80	1.4	High	40
10	20	1	1	160	0.5	Low	40
8	21	1	1	160	1.4	High	10
1	22	1	1	80	0.5	Low	10
5	23	1	1	80	0.5	High	10
23	24	1	1	80	1.4	High	10

29	25	1	1	80	0.5	High	40
13	26	1	1	80	0.5	High	40
22	27	1	1	160	0.5	High	10
19	28	1	1	80	1.4	Low	10
9	29	1	1	80	0.5	Low	40
17	30	1	1	80	0.5	Low	10
3	31	1	1	80	1.4	White	10
7	32	1	1	80	1.4	Black	10

In Table 3, mold temperature is in °F; cooling time is in seconds; coolant flow rate is in gallons per minute, gpm, and thermal diffusivity, alpha (α), high = 0.023 ft^2/hr and low = 0.006 ft^2/hr. The second set of experiments, shown in Table 3, was a 2^2 factorial design with two replicates resulting in eight experimental runs. The experimental procedure was similar to the first set of experiment, but the variables studied in these experiments were PP thermal diffusivity and injection molding back pressure.

Table 3. 2^2 Factorial design with 2 replicates

StdOrder	**RunOrder**	**CenterPt**	**Blocks**	**Alpha**	**Back Pressure**
2	1	1	1	High	75
8	2	1	1	High	150
5	3	1	1	Low	75
3	4	1	1	Low	150
1	5	1	1	Low	75
7	6	1	1	Low	150
4	7	1	1	High	150
6	8	1	1	High	75
2	1	1	1	High	75

In Table 3, injection back pressure is in lb/in^2 (psi).

Table 4 contains processing variables that were kept constant during the experiment.

Table 4. Injection molding processing parameters

Processing Parameter	**Values used during the experiment**
Injection Speed	1.4 in/s
Screw Speed	75 rpm
Materials' Drying Temperature	175 °F
Drying Time	2 hours
Nozzle temperature	450 °F

Front barrel temperature	450 °F
Middle barrel temperature	430 °F
Rear barrel temperature	400 °F
Estimated melt temperature	423 – 445 °F
Mold temperature for 2nd experiments	120 °F
Injection pressure	1500 psi
Packing pressure	400 psi
Holding pressure	200 psi
Coolant flow rate for 2nd experiment	1.4 gpm

Results

Figure 2 shows that for the first set of experiments, the variable that was found statistical significant to influence part warpage was the PP thermal diffusivity. The same results are represented numerically in Table 4. Figure 3 shows the relative effects of the variables on part warpage.

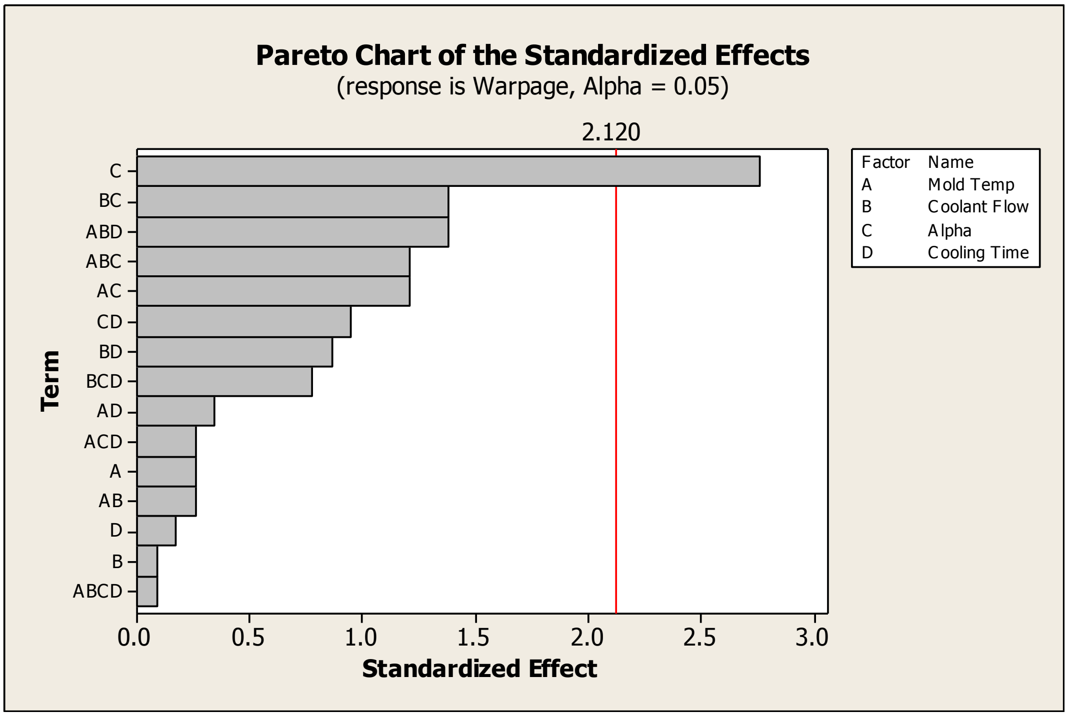

Figure 2. Alpha (α) is statistically significant in affecting part warpage.

Table 4: Factorial Fit: Warpage versus Mold Temp, Coolant Flow, ...

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Estimated Effects and Coefficients for Warpage (coded units)

Term                                    Effect       Coef   SE Coef      T
Constant                                         0.007938  0.000725  10.95
Mold Temp                             0.000375   0.000188  0.000725   0.26
Coolant Flow                         -0.000125  -0.000063  0.000725  -0.09
Alpha                                -0.004000  -0.002000  0.000725  -2.76
Cooling Time                         -0.000250  -0.000125  0.000725  -0.17
Mold Temp*Coolant Flow                0.000375   0.000187  0.000725   0.26
Mold Temp*Alpha                       0.001750   0.000875  0.000725   1.21
Mold Temp*Cooling Time                0.000500   0.000250  0.000725   0.34
Coolant Flow*Alpha                   -0.002000  -0.001000  0.000725  -1.38
Coolant Flow*Cooling Time            -0.001250  -0.000625  0.000725  -0.86
Alpha*Cooling Time                    0.001375   0.000688  0.000725   0.95
Mold Temp*Coolant Flow*Alpha         -0.001750  -0.000875  0.000725  -1.21
Mold Temp*Coolant Flow*Cooling Time  -0.002000  -0.001000  0.000725  -1.38
Mold Temp*Alpha*Cooling Time          0.000375   0.000188  0.000725   0.26
Coolant Flow*Alpha*Cooling Time      -0.001125  -0.000563  0.000725  -0.78
Mold Temp*Coolant Flow*Alpha*        -0.000125  -0.000062  0.000725  -0.09
  Cooling Time

Term                                     P
Constant                             0.000
Mold Temp                            0.799
Coolant Flow                         0.932
Alpha                                0.014  Significant (< 0.05)
Cooling Time                         0.865
Mold Temp*Coolant Flow               0.799
Mold Temp*Alpha                      0.245
Mold Temp*Cooling Time               0.735
Coolant Flow*Alpha                   0.187
Coolant Flow*Cooling Time            0.401
Alpha*Cooling Time                   0.357
Mold Temp*Coolant Flow*Alpha         0.245
Mold Temp*Coolant Flow*Cooling Time  0.187
Mold Temp*Alpha*Cooling Time         0.799
Coolant Flow*Alpha*Cooling Time      0.449
Mold Temp*Coolant Flow*Alpha*        0.932
  Cooling Time


S = 0.00410030   PRESS = 0.001076
R-Sq = 51.43%    R-Sq(pred) = 0.00%   R-Sq(adj) = 5.90%
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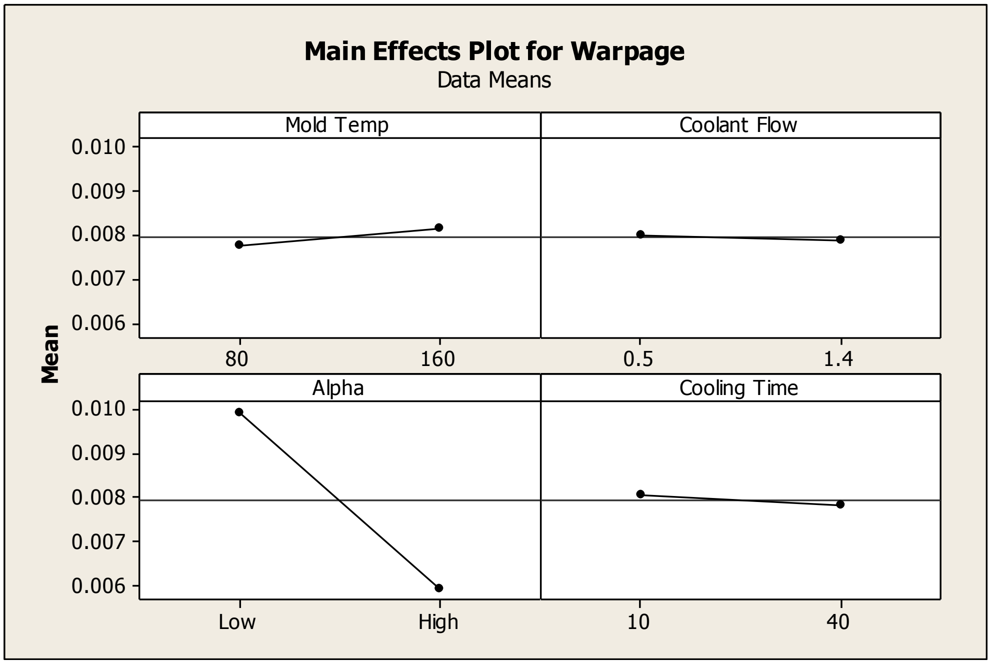

Figure 3. The relative effects of the variables on part warpage

In the second set of experiments, the variables considered were PP thermal diffusivity and back pressure since cooling time, coolant flow rate and mold temperature were found to be statistically insignificant in influencing part warpage.

For this set of experiments, Figure 4 shows that PP thermal diffusivity and back pressure were statistically significant in affecting part warpage while the interaction effects of both variables on part warpage were not significant. The same results are presented numerically in Table 5.

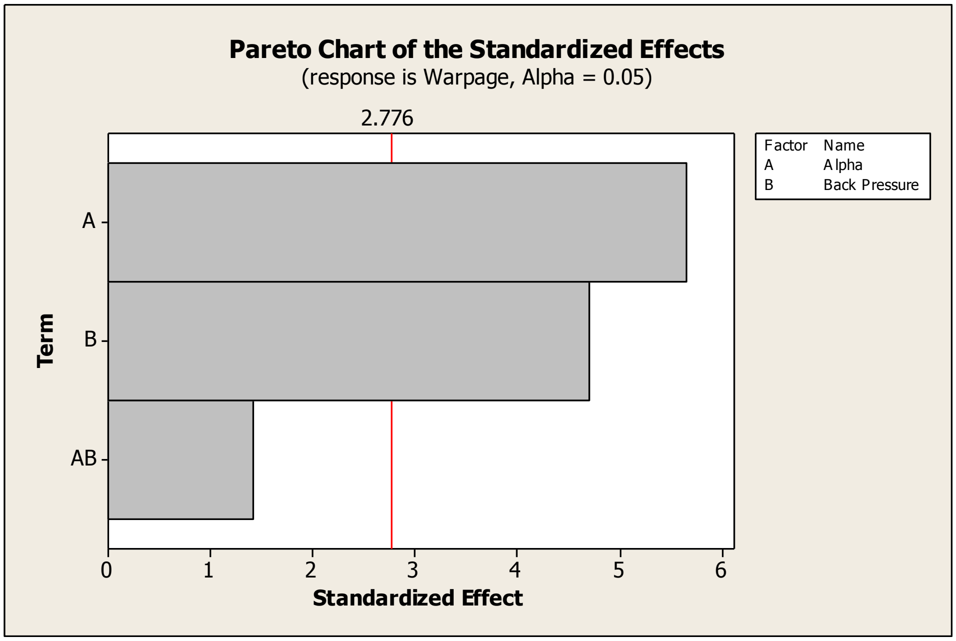

Figure 4. Alpha and back pressure are statistical significant in affecting part warpage.

Table 5. Factorial Fit: Warpage versus Alpha, Back Pressure

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Estimated Effects and Coefficients for Warpage (coded units)

Term                       Effect       Coef   SE Coef       T       P
Constant                            0.008750  0.000530   16.50   0.000
Alpha                   -0.006000  -0.003000  0.000530   -5.66   0.005  significant (<0.05)
Back Pressure            0.005000   0.002500  0.000530    4.71   0.009  significant (<0.05)
Alpha*Back Pressure     -0.001500  -0.000750  0.000530   -1.41   0.230


S = 0.0015       PRESS = 0.000036
R-Sq = 93.36%    R-Sq(pred) = 73.43%    R-Sq(adj) = 88.38%
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Figure 5 shows the relative effects on PP thermal diffusivity and injection molding back pressure on part warpage. It shows that high values of PP thermal diffusivity (alpha) had the least effect on part warpage while low back pressures had the least effect on part warpage.

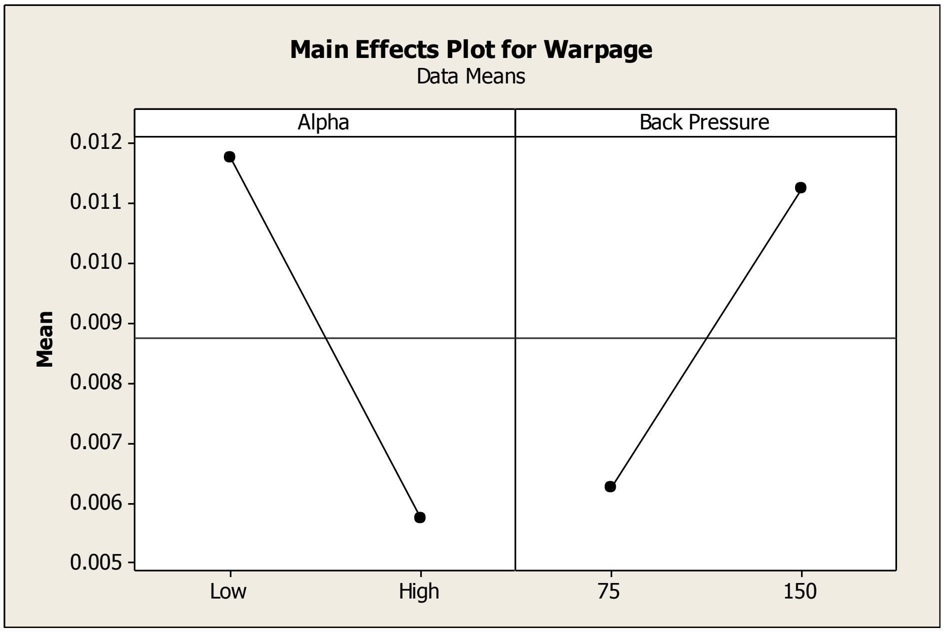

Figure 5. The relative effects of PP thermal diffusivity and back pressure on part warpage

Assessment

This work started as a capstone project for a student and was continued as an independent study by another student. Both students graduated in 2009 and 2010, respectively and are gainfully employed in the manufacturing industry, where they reported using the skills gained from working on this project.

Going forward, the work has become the basis of a lab that will be incorporated into a junior level plastics course that emphasizes projects in plastics materials and processing. On completing the projects, students will write reports of their projects and present their findings to their classmates as partial fulfillment of the course requirements.

Conclusion

This study is the combined efforts of two students, who have integrated materials from a design of experiments course and a plastics course to investigate the effects of plastics materials thermal diffusivity, injection molding cooling time, back pressure, coolant flow rate and coolant temperature on part warpage. The finding suggests that only PP thermal diffusivity and injection molding back pressure had statistically significant influence on part warpage.

This finding is important for custom injection molders, who process a variety of plastics materials for their clients. Unlike, dedicated injection processors that process one or few plastics materials, custom injection molders are at the mercy of their clients as far as the spectrum of plastics materials they can process. For these injection processors, the frequent changing of plastics materials presents its unique problems because different plastics have varying properties that affect machine settings. Generally, achieving the optimal machine settings requires considerable operator’s experience and time, and time is money. This study suggests that an understanding of the role plastics thermal diffusivity plays in part quality may help reduce set-up time and/or facilitate troubleshooting problems associated with part warpage.

Furthermore, this study provides a framework for incorporating the design of experiments into a plastics processing course in an undergraduate program.

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