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Optimizing Molding Conditions to Improve the Quality of Injection-Molded Parts: A Design of Experiments Approach

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The performance of an injection-molded part is the result of a complex interaction of the inherent material properties and selected processing conditions. To increase stiffness and strength and reduce thermal expansion, short fibers are often incorporated in the resin. However, a key aspect of these fiber-reinforced materials is the complicated fiber orientation distribution produced during injection molding. The mixture of glass fibers and molten polymer is injected under high pressure into a mold cavity, which fills in a matter of seconds. The resulting velocity fields, which are generated during this mold-filling process, have a profound influence on the fiber orientation structure and hence on the composite mechanical properties. Typically, a layered structure is found throughout the thickness of the molding, and the orientation of each is highly dependent on the fiber characteristics, the melt flow pattern within the mold and the conditions used in the molding process [1]. The number and depth of each layer has been the topic of a number of studies. In general, most agree that five layers exist, forming a skin-shell-core structure [1-2]. However, some researchers have discovered the formation of up to nine layers from surface to surface [3].

The layer near the mold wall, referred to as the skin layer, is formed from the advancement of the flow front or fountain flow. The preferred orientation in this layer is random or slightly aligned in the flow direction. Adjacent to this layer, a shear-dominated layer is formed, given that the driving force for mold filling is the pressure derived from the injection phase and is known as the shell layer. This generates a region in which the fibers are mostly aligned in the flow direction. The central layer consists of mostly random or transverse oriented fibers and is known as the core layer. The formation of this layer is caused by the diverging flow at the melt front, plus the low levels of shear experienced by the mid-plane of the mold. As a consequence of the thermomechanical history imposed on the melt, the relative properties and thickness of each layer are dependent on the molding conditions used, and these determine the response under mechanical loading [4]. Therefore, it is necessary to know exactly the effects that processing conditions will have on part filling and ultimately on the properties of a part to produce a molding that meets specific requirements.

Design of Experiments

Given the large number of processing parameters that define the injection molding procedure, the most practical method of investigation is based on a design of experiments (DOE) technique. This type of experimental design enables engineers to study the effects of several variables affecting the response or output of a certain process [5]. DOE is a powerful design tool that is used to increase part quality, improve productivity and reduce product development time and cost.

A number of researchers have reported several successful applications of factorial design over the years. Sokele & Catic [6] used a 2^4 factorial design to examine the influence of processing conditions on the properties of an injection-molded part. They discovered the melt temperature to be the critical processing parameter, as it has the greatest influence on the mass of the molding and its surface waviness. Wang & Yoon [7] applied a 2^{4-1} fractional factorial, based on injection molding simulation software, to investigate the effects of conditions on the shrinkage and warpage of a part. As expected, the packing pressure was the most significant factor affecting shrinkage and warpage, as higher pressure can deliver a greater amount of material into the cavity more efficiently.

To perform a factorial design, the experimenter selects a number of levels for each factor and runs the experiments with each possible combination. Choosing the design parameters and their levels is not a trivial task, and even with a design tool such as factorial design, choosing the experimental parameters knowledgeably is crucial. For this investigation, it was decided to set each parameter at two levels. Although a wide region in space cannot be fully explored, the design can indicate major trends with relatively few runs and therefore determine a promising direction for further experimentation if so required [8]. It is advisable to experiment with the largest range possible to get a clearer indication of each design parameter on the output or response.

A full factorial design (represented by 2^k) is the preferred choice when all main and interaction effects are to be evaluated independently. However, even though it is possible to calculate all these effects, it does not imply that all are of appreciable size, also, the number of runs increases geometrically as k is increased. Under such circumstances, fractional factorial designs provide a reasonable alternative that still allows the experimenter to evaluate the main effects (they exploit the inherent redundancy of the full factorial design).

In this investigation, there were eight main adjustable influencing factors, and each parameter had two levels (+/–), as shown in *Table 1*. The design matrix selected contains 16 runs (a 2^{8-4} fractional design of resolution IV). The concept of design resolution concerns the confounding pattern of the design matrix. It is worth noting though that a design of resolution IV does not confound main effects and two-factor interactions, but does confound two-factor interactions with each other.

Factor	Description	Level 1	Level 2
1	Injection time, S_{inj} (s)	4	1
2	Melt temperature, T_{inj} (°C)	225	270
3	Mold temperature, T_m (°C)	35	65
4	Injection pressure profile, P_{inj} (%)	50	100
5	Packing pressure profile, P_{pack} (%)	50	100
6	Cooling time, t_{cool} (s)	25	55
7	Packing time, t_{pack} (s)	5	10

8	Cavity thickness, y_{cavity} (mm)	2	4

Table 1. *Factors and their levels studied in the experiment.*

These adjustable processing variables were examined for their influence on several quality parameters of the component: tensile strength, flexure strength, peak force during impact and weight. Also, the difference between the total energy absorbed by the sample E_T and the peak energy E_P during impact tests was also determined for each set of samples. This value $(E_T - E_P)$ is an indicator of the ductility of the sample, for example, the brittleness of a sample increases considerably as this value approaches zero [4].

Analyzing experimental results was based on analysis of variance (ANOVA). This is essentially an investigation into the variation of responses around an average value. If a factor varies and the response does not vary much about this average, this factor can be said to have little or no effect on the response. Nevertheless, if the response fluctuates significantly from the average value when a factor is adjusted, then this factor has a considerable influence on the output.

Experimental Program

Material and Equipment. The study was performed on a Sandretto 65-185 injection molding machine, with a maximum clamping force of 65 tons and a calculated shot volume of 124 cm^3. A Piovan controller was used for mold heating and cooling. A dumbbell-shaped specimen, according to standards ISO 3167 [9] and ISO 294-1 [10], is produced in the mold (see *Figure 1*). The dimensions of the part, according to the standards, give the length as 150 mm, the width of the gage section 10 mm ± 0.2, the width of the tab sections 20 mm ± 0.2 and the radius between them at 20 mm. The gage length is specified as 80 mm ± 2.

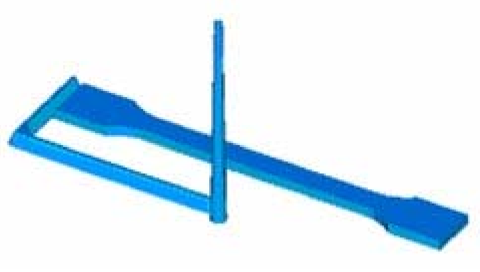

Figure 1. *Test specimen.*

The material used is a commercial-grade polypropylene, RTP 105 [11]. This material contains 30% glass fiber with a specific gravity of 0.90. A total of 16 sets of experiments were performed for the combination of high and low values of the primary variables. *Table 2* shows the design table used and the factor levels. After establishing the parameters, 20 moldings of each condition were made. The levels of the individual parameters were adjusted until a total of 320 moldings were made for the 16 experimental runs.

Run	S_{inj} (mm/sec.)	T_{inj} (°C)	T_M (°C)	P_{inj} (%)	P_{pack} (%)	t_{cool} (s)	t_{pack} (s)	y_{cavity} (mm)
1	10	225	35	100	100	55	5	4
2	50	225	35	50	50	55	10	4
3	10	270	35	50	100	25	10	4
4	50	270	35	100	50	25	5	4
5	10	225	65	100	50	25	10	4
6	50	225	65	50	100	25	5	4
7	10	270	65	50	50	55	5	4
8	50	270	65	100	100	55	10	4
9	50	270	65	50	50	25	10	2
10	10	270	65	100	100	25	5	2
11	50	225	65	100	50	55	5	2
12	10	225	65	50	100	55	10	2
13	50	270	35	50	100	55	5	2
14	10	270	35	100	50	55	10	2
15	50	225	35	100	100	25	10	2
16	10	225	35	50	50	25	5	2

Table 2. *A 16-run, 2^{8-4}_{IV} design matrix.*

Testing. Tensile strength tests were carried out on a Hounsfield H50K-S testing machine at a rate of 5 mm/sec. and a room-controlled temperature of 23°C. The samples were clamped around the end tabs, using roller-type clamps, which increased the clamp force as a sample was subjected to an increasing tensile force. At least five samples per condition were tested, all carefully positioned in the clamps to ensure the sample was in pure tension and no torque forces existed. From the force-deflection curves, shown in *Figure 2* (runs 10 and 12 and runs 6 and 3), the maximum force applied was chosen to evaluate the tensile behavior. Flexure tests were also carried out on the Hounsfield testing machine at a slower loading rate of 1 mm/sec. Again, from the force deflection curves, the maximum force applied was used in all calculations of strength.

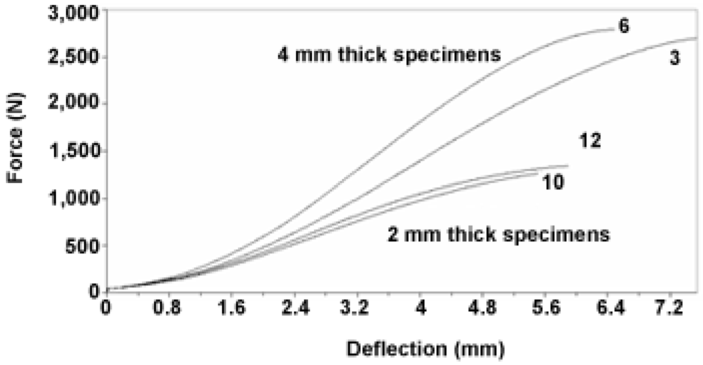

Figure 2. *Force deflection curve for tensile test.*

Impact tests were performed in an instrumented falling weight impact test machine at 1 m/sec. and at a room-controlled temperature of 23°C. The impactor tip was hemispherical with a 10 mm diameter and a mass of 7.5 kg. The samples were clamped around a 40 mm diameter perimeter. Again, at least five samples per condition were tested, each positioned on the anvil to ensure the impact strikes each sample always on the same site. The peak force was recorded for each test along with the difference between the total energy absorbed and the peak energy ($E_T - E_P$). All samples were selected at random for the determination of their mechanical properties; also all samples were conditioned (at a room temperature of 23°C) before testing for one week after molding.

Results and Discussion

Analysis of Variance. Because of the limited size of the present article, only a selection of results will be presented. *Table 3* gives the results calculated for the effects and their interactions. A negative sign indicates that the slope of the line joining high and low levels is negative, for instance, the response at low level is greater than the response at high level.

Calculated Contrasts	Tensile Strength	Flexure Strength	Peak Force	$(E_r - E_p)$	Weight
Mean	65.9 MPa	3.51 MPa	5.59 kN	3.308 J	6.194 g
$l_1 \rightarrow 1$	0.053	0.113	0.031	-0.024	0.0893
$l_2 \rightarrow 2$	–0.013	–0.051	–0.206	–0.126	0.0808
$l_3 \rightarrow 3$	–0.165	–0.015	–0.324	–0.081	–0.0615
$l_4 \rightarrow 4$	0.173	0.008	–0.101	0.091	0.0045
$l_5 \rightarrow 5$	1.66	0.233	–0.069	0.041	0.1863
$l_6 \rightarrow 6$	–0.645	–0.045	0.089	0.154	0.0273
$l_7 \rightarrow 7$	0.69	0.168	–0.066	0.011	0.104
$l_8 \rightarrow 8$	1.79	–1.95	3.466	–1.676	4.2975
$l_{12} \rightarrow 12 + 37 + 48 + 56$	1.36	0.023	0.011	–0.061	-0.0465
$l_{13} \rightarrow 13 + 27 + 46 + 58$	0.373	–0.133	0.054	–0.011	–0.0033
$l_{14} \rightarrow 14 + 28 + 36 + 57$	0.16	0.035	0.009	0.211	–0.0213
$l_{15} \rightarrow 15 + 26 + 38 + 47$	-0.253	0.04	0.044	0.216	–0.027
$l_{16} \rightarrow 16 + 25 + 34 + 78$	0.428	–0.118	0.016	–0.059	–0.054
$l_{17} \rightarrow 17 + 23 + 45 + 68$	–0.158	0.04	–0.034	–0.159	0.0193
$l_{18} \rightarrow 18 + 24 + 35 + 67$	–0.385	–0.113	–0.046	0.044	–0.0243

***Table 3.** Estimated effects from a 2_{IV}^{8-4} factorial design.*

The ANOVA of tensile and flexure strengths is given in *Tables 4* and *5*. It is evident that the cavity thickness has the most significant influence on both the tensile and flexure strength, along with packing pressure and packing time. Doubling the cavity thickness notably increases the tensile strength, as the cross sectional area of the part has increased, thus requiring greater strength to cause failure. Packing pressure and packing time have similar effects in that they allow more material to fill the cavity, thus reducing the effects of shrinkage and accordingly increasing the overall strength.

Ho and Jeng [1] determined that increasing the injection speed by reducing the injection time resulted in a thicker shear region. However, as the flexure test applies tension and compression to opposite sides of the test piece, the occurrence of higher alignment of fibers in this thicker region leads to an increase in the flexure strength. In tensile testing, however, adjusting the injection speed had negligible influence due to the increase in core layer thickness, which has a random, almost transverse orientation, with a faster fill rate.

Source	Sum of Squares	df	Mean Square	F	% Contribution
Main effects	27.747	8	3.468	2.494	
Injection time (s)	1.10E-02	1	1.10E-02	0.008	0.04
Melt temp. (°C)	6.50E-02	1	6.50E-02	0.047	0.234
Mold temp. (°C)	0.109	1	0.109	0.078	0.393
Injection pressure (MPa)	0.12	1	0.12	0.086	0.432
Packing pressure (MPa)	11.02	1	11.02	7.927	39.716
Cooling time (s)	1.664	1	1.664	6.45	5.99
Packing time (s)	1.904	1	1.904	3.594	6.86
Cavity thickness (mm)	12.852	1	12.852	9.242	46.320
Error	9.734	7	1.391		
Total	69527.713	16			

Table 4. *Analysis of variance table for tensile strength.*

Source	Sum of Squares	df	Mean Square	F	% Contribution
Main effects	15.532	8	1.942	67.482	
Injection time (s)	5.06E-02	1	5.06E-02	1.76	0.361
Melt temp. (°C)	6.50E-02	1	6.50E-02	0.047	0.418
Mold temp. (°C)	9.00E-04	1	9.00E-04	0.031	5.79E-03
Injection pressure (MPa)	2.25E-04	1	2.25E-04	0.008	1.45E-03
Packing pressure (MPa)	0.216	1	0.216	7.515	1.39
Cooling time (s)	8.10E-03	1	8.10E-03	0.282	0.052
Packing time (s)	0.112	1	0.112	3.901	0.72
Cavity thickness (mm)	15.132	1	15.132	525.942	97.420
Error	0.201	7	2.88E-02		
Total	213.136	16			

Table 5. *Analysis of variance table for flexure strength.*

Melt temperature also has an effect on the flexural properties and slightly less influence on the tensile strength. Increasing the melt temperature can greatly increase the thermal energy of the melt and thus reduce the melt viscosity. This in turn improves melt flow and helps fill the cavity more readily. Nevertheless, increasing the melt temperature too much will result in significant degradation of the material, and hence a loss in properties, as can be seen in *Table 3*, where both the flexure and tensile properties are diminished to differing degrees
(–0.051 for flexure and –0.013 for tensile).

The cooling time is next in sequence. In this case, however, increasing the cooling time has an adverse effect on the strength, more appreciably so for tension than for flexure. A longer rate of cooling leads to an increase in the temperature gradient between the material at the mold wall and the melt at the core. This reduces the structural and mechanical properties (increased nucleation density). From another point of view, the residence time of the melt in the barrel will increase with longer cooling times. The longer the melt is in the barrel, the longer the heat history of the melt and the greater the possibility of melt degradation. Consequently, the cooling time should be kept low; not only will this reduce cycle time, but it will also prevent melt degradation.

Based on ANOVA, the degree to which each processing parameter affects part performance can be determined and the importance of each factor can be ranked. However, it should be noted that the responses are only dependent on the range chosen for each variable, such as the levels selected. Consequently, if a factor has little effect on a response, it can only be interpreted as unimportant to the response in this chosen range. This might not be the case outside this range [7]. Surprisingly, absent from a number of these results is the injection time as a significant factor, possibly as a consequence of the selected range of variation.

From the selected experiments chosen in this factorial design, a number of factors are considerably more influential on the final part performance than others. It has been determined that cavity thickness is the most dominant factor, along with packing pressure, packing time and melt temperature. To ascertain that the assumed model is accurate, a check on the assumptions on which the model is based must be performed. This is possible by studying the behavior by which the effects are plotted on normal probability paper, a method discovered by Daniel in 1959 [8].

Normal Probability Plots. Normal probability plots and half normal probability plots are obtained by adjusting the vertical axis of a sigmoid cumulative frequency curve such that the curve now plots as a straight line. Any deviations of data from this straight line indicate that the effects being represented cannot be easily explained by chance occurrence. A half normal plot is similar to a full normal plot but uses the absolute values of the calculated contrasts and half the normal score. A probability plot for the tensile strength response is shown below in *Figure 3*.

Figure 3. *Half normal plot of contrasts; tensile strength.*

Excluding interactions between factors, the main effects controlling the tensile strength properties are factors 8, 5, 7 and 6, (cavity thickness, packing pressure profile, packing time and cooling time). Again, factors 8, 5, and 7 are significant in optimizing the flexural properties. Similar results are obtained for the impact test and weight calculations, cavity thickness being the single largest influencing factor. However, it was determined that adjusting the thickness had a negative effect on the energy difference, for example, samples were found to be more brittle due to the increase in core layer and thus the higher degree of crystallinity. Melt and mold temperatures also produced noticeable effects. Reducing these temperatures gives the best impact results as they provide moderate levels of orientation in the skin layers, as it has been suggested that high levels of orientation are detrimental to impact performance [4].

Conclusion

It has been shown that with systematic planning and with an appropriate investigation method such as factorial design, it is possible to determine precisely and economically the overall effect of several processing parameters on the quality and performance of an injection-molded component. The experiment performed here is known as a screening operation, whereby a number of variables are expected to be important, but which subset of parameters is unknown. In this particular trial, cavity thickness, packing time, packing pressure and melt temperature are shown to be the main factors that influence the mechanical performance of this injection-molded component.

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