2023 2nd International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS) | 979-8-3503-5883-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICMEAS58693.2023.10379241

The 2nd International Conference on Multidisciplinary Engineering and Applied Sciences (ICMEAS-2023)

Effect of process parameter interactions on short shot defect modeling in plastic injection molding

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***Abstract*—This paper presents an analysis of the effect of interactions of major injection molding process parameters on short shot defects. The factorial design of the experiment and numerical modeling techniques were used. Parameter mains effect and interaction effect sizes were computed, and their significance was tested through ANOVA. It was demonstrated that injection pressure setting and melt temperature were the most influential parameters affecting short shot defects with contributions of 92% and 7% respectively as well as their interactions. The most significant interactions affecting short shot defects involved melt temperature. Knowledge of significant parameter interactions affecting short shot defects could enhance a targeted approach to defect control. The approach and the results presented herein can be adopted in plastic injection molding entities to minimize such defects.**

***Keywords*—Factorial design, Finite element, Injection molding, Interaction effect, Short shot**

I. INTRODUCTION

The Simulation of injection molding process through Computer Aided Engineering (CAE) has become an influential tool to support engineers and researchers in process optimization and defect control [1]. The integration of the design of experiments and CAE has necessitated process modeling and optimization [2], [3]. A short shot defect is one of the major defects in plastic injection molding and results from incomplete mold cavity filling as a result of factors associated with polymer material, part geometry design, mold design, and process parameters [4]. Factors such as material, part geometry, and mold design can be optimized and fixed at the initial design stages. However, process parameters are liable to changes because of the influence of operating conditions during the molding period and would thus induce short shot defects.

Previous studies have typically concentrated on the investigation of process parameter mains effects on short shots [5] and it is not clear which process parameter interactions majorly affects this defect. Further research is needed to determine the major process parameter interactions and their effects on short shot. This could serve as a defect minimization strategy through targeted process parameter group control. As such, this paper presents an analysis of the effect of interactions of major injection molding process parameters on short shot defect using factorial design of the experiment and numerical modelling techniques.

II. METHOD

A. Study Design

This study was carried out through design of experiment and CAE as illustrated on Fig. 1. Numerical modelling was carried out using commercial CAE software Moldex3D® to model polymer melt flow. Factorial analysis was carried out statistically through computation of mains effects, interaction effects and significance test.

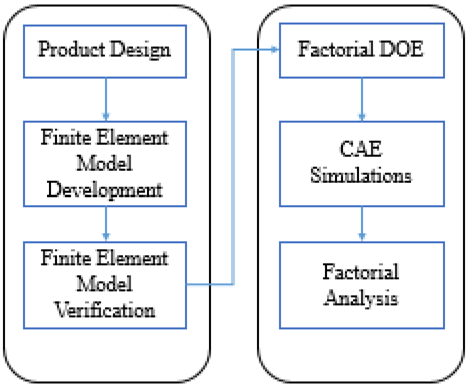

Fig. 1 Study design

B. Finite Element Model Development

A test specimen of a packaging bottle cap was developed from which a two cavity injection mold was modelled as a finite element and a mesh size of 0.2mm selected upon a series of iterative mesh refinement test. The finite element model of the injection mold was verified through assessing it's characterization of pressure-volume-temperature relationship at end of fill. Numerical material density changes were obtained through simulation at given conditions of temperature and pressure and the results compared to analytically computed density. A match in the densities was achieved and hence the model used for successive simulations. To capture the effects of post-molding related short shot defects, a complete warp analysis was carried out.

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Fig. 2 shows a finite element model of the mold used for the study.

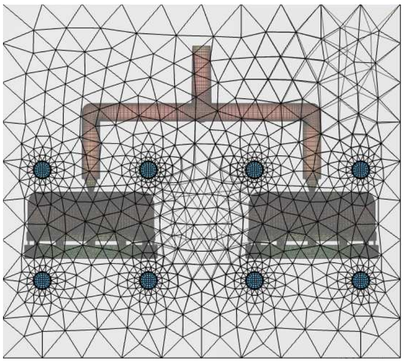

Fig. 2. Finite Element Model of the injection mold

Numerical analysis was based on the flow of the polymer as governed by equations (1-3) derived from the principles of conservation of mass, energy and momentum conservation respectively and viscosity of the polymer melt modelled based on modified cross exponential viscosity model (4) [6].

$$\frac{D\rho}{Dt} = -\rho\nabla \cdot u \tag{1}$$

$$\rho\frac{\partial v}{\partial t} = \rho g - \nabla p + \nabla \cdot \eta D - \rho v \cdot \nabla v \tag{2}$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + v \cdot \nabla T\right) = \beta T\left(\frac{\partial P}{\partial t} + v \cdot \nabla P\right) + \eta\dot{\gamma}^2 + k\nabla^2 T \tag{3}$$

$$\eta(\dot{\gamma}, T, P) = \frac{\eta_0(T,P)}{1 + \left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{4}$$

$$\eta_0(T,P) = B\exp\left(\frac{T_b}{T} + DP\right) \tag{5}$$

Where ρ is the density, t is the time, u is the speed vector, v is the specific volume, g is the gravitational acceleration, P is the hydrostatic pressure, Cp is the specific heat, T is the temperature, β is the heat expansion coefficient, k is the thermal conductivity, $\dot{\gamma}$ is the shear rate, $\eta_0$is the zero shear viscosity, $\dot{\gamma}$ is the effective shear rate, τ^* is the reference shear stress, n is the power law index, P is the pressure T is the temperature and the other material constants given by B, D and T_b.

Boundary conditions applied included specification of melt temperature at the inlet, zero pressure at the melt front, uniform temperature at the point of injection and zero pressure gradients across mold edges and walls [7].

C. *Design of Experiment*

To determine the effects of process parameter interactions on short shot defect possibility, a half fractional factorial design of resolution VI was used. Six process parameters were used each at two levels recommended for Total 2001 PBK 44 HDPE material as illustrated on Table 1 yielding a 32 run array. To isolate the effects of fill time setting which has a direct contribution to short shot defect, the simulations were carried out at a constant fill time of 0.31s.

TABLE I. PROCESS PARAMETERS AND LEVELS

Process Parameters	**Levels**	
	Min	**Max**
Melt Temperature (°C)	200	235
Mold Temperature (°C)	30	50
Maximum Injection Pressure (MPa)	200	300
Maximum Packing Pressure (MPa)	200	300
Cooling Time (s)	8	15
Packing Time (s)	3	5

After carrying out a warp analysis, values of maximum cavity pressure were obtained from the fill results of each run and short shot possibility factor computed based on (6) [8].

$$S_f = \frac{Max.\,Cavity\ Pressure}{Injection\ Pressure\ Setting} \tag{6}$$

Mains effect and interaction effect sizes were computed based on difference of means and their significance ascertained through ANOVA analysis.

III. RESULTS AND DISCUSSIONS

The short shot possibility ratios expresses the possibility of occurrence of short shot defects. A larger ratio indicate a higher chances of having short shot while a smaller ratio indicate lower chances. Runs with the lowest maximum cavity filling pressure yielded the smallest short shot possibility ratios. As shown on Table 2, run 10 yielded the lowest short shot possibility.

TABLE II. NUMERICAL RESULTS

Run	Melt Temp	Mold Temp	Inj. Press.	Pack Time	Pack Press.	Cool Time	Cavity Press.	Short shot
1	200	30	300	3	200	15	86.4	0.288
2	235	50	200	3	300	15	79.41	0.397
3	200	50	300	5	200	15	86.67	0.289
4	200	30	300	5	200	8	86.3	0.288
5	200	50	200	3	300	8	88.4	0.442
6	235	50	200	5	300	8	79.07	0.395
7	200	50	200	5	300	15	88.62	0.443
8	200	30	300	5	300	15	88.61	0.295
9	235	50	200	3	200	8	77.1	0.386
10	235	30	300	3	200	8	77.03	0.257
11	200	30	200	5	300	8	88.25	0.441
12	200	30	200	3	200	8	86.3	0.432
13	200	30	300	3	300	8	88.25	0.294
14	235	30	200	3	200	15	77.4	0.387
15	200	50	300	3	300	15	88.62	0.295
16	200	50	300	5	300	8	88.4	0.295
17	200	50	300	3	200	8	86.37	0.288
18	200	30	200	5	200	15	86.66	0.433
19	200	50	200	3	200	15	86.67	0.433
20	200	50	200	5	200	8	86.37	0.432
21	235	30	200	3	300	8	79	0.395
22	235	50	200	5	200	15	77.44	0.387
23	235	50	300	3	300	8	79.07	0.264
24	235	30	300	5	200	15	77.39	0.258
25	235	50	300	5	200	8	77.1	0.257
26	235	30	300	5	300	8	79	0.263
27	235	30	200	5	200	8	77.03	0.385
28	200	30	200	3	300	15	88.61	0.443
29	235	50	300	3	200	15	77.44	0.258
30	235	50	300	5	300	15	79.41	0.265
31	235	30	200	5	300	15	79.37	0.397
32	235	30	300	3	300	15	79.37	0.265

A. *Mains Effects*

As illustrated on the mains effect plot on Fig. 3, the results obtained indicated a general decrease in short shot possibility with an increase in melt temperature and injection pressure, an increase in packing pressure and cooling time resulted to an increase in short shot possibility whereas factors such as mold temperature and packing time had no major impact on short shot possibility. A combined numerical and experimental study by Moayyedian et al. [8] obtained similar trends in terms of a decrease in short shot possibility with an increase in melt temperature and slight increase in short shot possibility with increasing cooling time and holding times.

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Higher melt temperatures lowers the molten material viscosity making it flow easily into the mold cavity hence reducing the likelihood of incomplete filling and short shots [9]. For complex geometries such the product used in this study, increasing the injection pressures helps to overcome flow resistance brought about by features such as undercuts thereby improving material flowability which lowers chances of incomplete fill and short shot [10]. Major computed mains effect sizes were -0.138 for injection pressure and -0.039 for melt temperature indicating a reduction in short shot possibility factor with an increase in the two factors and 0.008 for pack pressure and 0.001 for cooling time indicating an increase in short shot possibility factor with an increase in the two factors.

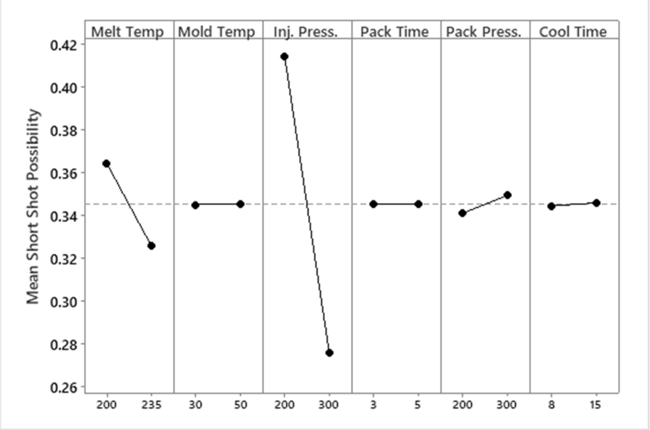

Fig. 3. Mains effect plot for short shot possibility

To visualize the extent of mains effect and interaction effects on short shot possibility, Pareto plot on Fig. 4 was constructed at a 95% confidence level and showing 15 of the largest effects. The chart illustrates that injection pressure setting has the largest effect on short shot possibility followed by melt temperature while the largest interaction effect involved the two. The largest three way interaction involve the melt temperature, injection pressure and packing time. Individual effect of a parameter like packing time is lower than the effects of most interactions involving the parameter.

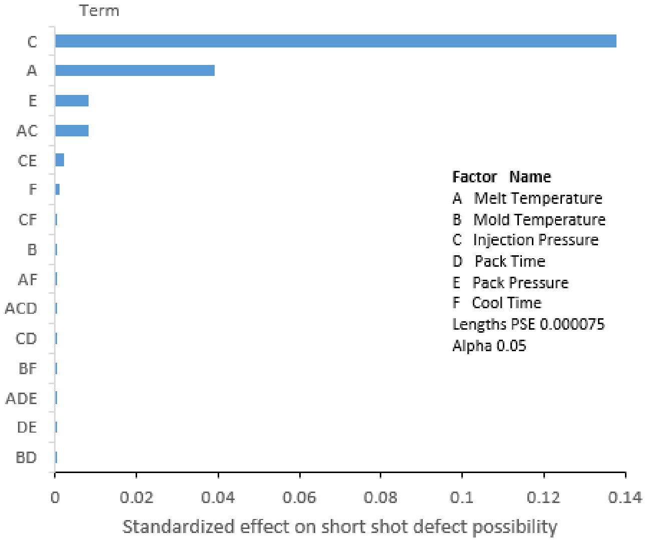

Fig. 4. Pareto chart of standardized effects on short shot possibility

B. Interaction Effects

Some of the major computed interaction effects are given in the Table 3. Negative values signify a reduction in short shot possibility factor while positive value imply an increase in short shot possibility factor. A combined effect of increasing the melt temperature and injection pressure simultaneously reduces short shot possibility ratio by 0.008. When considered individually, increasing the melt temperature decreases short shot possibility factor by 0.039 while increasing injection pressure decreases the factor by 0.138. However, when the two factors are increased simultaneously, the extent of reduction in short shot possibility factor is decreased by 0.008. This shows that the combined effects of the two factors diminishes their respective individual effects. Melt temperature influences material viscosity while injection pressure influences material flow. At higher melt temperature and injection pressure, material delivery into the mold cavity is enhanced and thus less short shot possibility. Therefore, a well-balanced and jointly optimized melt temperature and injection pressure would help overcome short shot defects.

TABLE III. INTERACTION EFFECT SIZES

Interaction	Effect Size
Melt Temp.*Inj. Press.	-0.008
Inj. Press.*Pack Press.	-0.002
Inj. Press.*Cool Time	-0.0003
Melt Temp*Cool Time	0.0001
Melt Temp*Inj. Press.*Pack Time	-0.0001

The interaction between melt temperature and injection pressure is illustrated on a contour plot on Fig. 5. Short shot possibility is higher at lower melt temperature and injection pressure and lower at higher values. Contour plot trends are not horizontal indicating a significant interaction effect between the two parameters. At constant melt temperature, an increase in injection pressure reduces short shot possibility but the rate of reduction depends on the level of melt temperature. At 200°C, increasing injection pressure from 200MPa to 250MPa reduces short shot possibility factor to 0.37 whereas at 235°C, a similar increase in injection pressure reduces short shot possibility factor to 0.33. With such information about parameters with the largest interaction effect on short shot, a targeted approach to the defect control could be used.

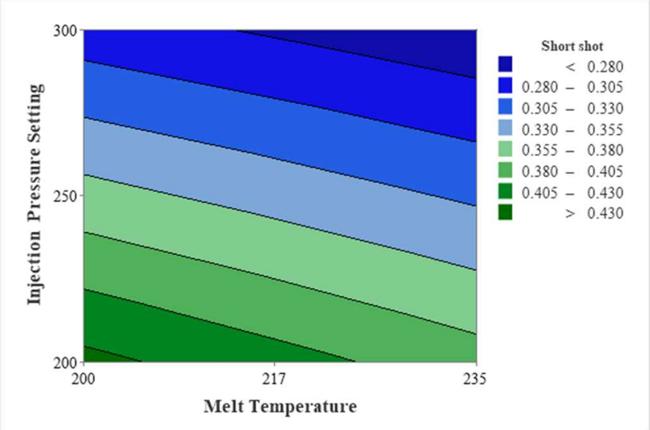

Fig. 5. Contour plot of melt temperature against injection pressure setting

C. Analysis of Variance

Section of results of ANOVA carried out at 95% confidence level are shown on Table 4. Of the six process parameters, only the packing time (P=0.265) did not significantly affect short shot possibility. However, an interaction between injection pressure and pack time as well as that between melt temperature, pack pressure and pack time significantly contributed to short shot. Most significant interactions involved the melt temperature having a contribution of 7% despite injection pressure with a contribution of 92% being the most significant parameter affecting short shot defect. This could be due to the fact that melt temperature affects material viscosity and flow and therefore an interaction between melt temperature and these properties would greatly influence short shot defect possibility.

TABLE IV. ANOVA OF MAINS EFFECTS AND INTERACTIONS

Source	DF	Seq SS	% Cont.	Adj MS	F-Value	P-Value
A	1	1.2E-02	7.17%	1.2E-02	1080190	0.0000
B	1	7.0E-07	0.00%	7.0E-07	63.71	0.0000
C	1	1.5E-01	92.19%	1.5E-01	13893464	0.0000
D	1	1.5E-08	0.00%	1.5E-08	1.39	0.2650
E	1	5.5E-04	0.33%	5.5E-04	49722.24	0.0000
F	1	1.4E-05	0.01%	1.4E-05	1286.08	0.0000
AC	1	4.8E-04	0.29%	4.8E-04	43911.48	0.0000
AF	1	1.7E-07	0.00%	1.7E-07	15.48	0.0030
CD	1	7.0E-08	0.00%	7.0E-08	6.4	0.0300
CE	1	2.0E-05	0.01%	2.0E-05	1829.77	0.0000
CF	1	8.9E-07	0.00%	8.9E-07	80.88	0.0000
BF	1	3.6E-08	0.00%	3.6E-08	3.99	0.0500
ACD	1	7.7E-08	0.00%	7.7E-08	6.98	0.0250
ADE	1	5.6E-08	0.00%	5.6E-08	5.06	0.0480
Error	10	1.1E-07	0.00%	1.1E-08		
Total	31	1.7E-01	100.00%			

Table 5 illustrates the model summary for the two ANOVA carried out. Addition of interaction terms to the model increased both the R-squared, adjusted R-squared and predicted R-squared indicating that the interaction terms improved the model. Also, the difference between R-squared and predicted R-squared was lower indicating a lower possibility of model data overfitting.

TABLE V. MODEL SUMMARY

Model	R-squared	R-squared (Adjusted)	R-squared (Predicted)
ANOVA with mains effects only	99.70%	99.62%	99.50%
ANOVA with mains and interaction terms	99.87%	99.81%	99.74%

IV. CONCLUSIONS

The purpose of the study was to establish major interactions among process parameters and their effect on short shot possibility. In addition to major parameters affecting short shot defects, interactions among these parameters were obtained and their significance tested. The following conclusions were made from this study;

1. Understanding parameter interactions in defect modelling could enhance a precise control strategy in defect minimization through targeted process improvement.
2. Injection pressure setting and melt temperature have larger effect on short shot possibility with percent contributions of 92% and 7% respectively.
3. Most significant parameter interactions in short shot defect modelling involve the melt temperature
4. Lower short shot possibility are obtained at higher melt temperature and injection pressure levels.

This study forms a basis for injection molding quality control through defect minimization and the results presented herein can be adopted in targeted optimization of process parameters whose interaction largely influences short shot defect. This study was limited to investigation of interaction effects among process parameters while holding other variables such as polymer material properties, part features and mold design features constant. Further studies could explore the effects of interactions among all the major variables contributing to short shot defects.

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