Fuzzy assessment of process parameter interactions on warpage defect modelling in plastic injection molding

Abstract

Studying the interactions among major plastic injection molding process parameters is necessary to understand how they collectively influence major defects such as warpage hence enabling optimization of the process for improved product quality. Existing process parameter interaction studies have used statistical approximations, which have limitations such as reduced predictive power and limited accuracy. To overcome these limitations, this study presents an alternative method of analysis of the interactions among process parameters based on fuzzy logic intelligent algorithm. Through computer aided engineering (CAE), factorial design of experiment and fuzzy logic modelling, the study evaluated the effects of major injection molding process parameter interactions on warpage. The results obtained indicated a general increase in warpage with increase in parameters such as melt temperature, mold temperature, injection pressure and cool time whereas an increase in parameters such as ambient temperature and packing pressure decreased warpage. Parameter interactions were obtained both statistically and based on fuzzy logic model and their significance tested through ANOVA. Ambient temperature (30.6%) and melt temperatures (18.7%) had the greatest effect on warpage all with P-values of 0.000 whereas cooling time (0.1%) had the least effect with P-value of 0.250. The largest two way interaction affecting warpage involved melt temperature and cooling time with a contribution of 12.2% whereas the largest three way interaction involves ambient temperature, packing pressure and injection pressure with a contribution of 2.7%. Also, despite cooling time having the least mains effect, most interaction terms with greater effect on warpage involved cooling time and melt temperature. The results from this study provides an insight on targeted injection molding process parameter control for defect minimization.

Keywords: Injection molding, warpage, interaction effect, fuzzy logic, ambient temperature

Glossary

ρ	Density (kg/m^3)
t	Time (s)
u	Speed vector (m/s); Displacement tensor (m)
v	Specific volume (m^3/kg)
g	Gravitational acceleration (m/s^2)
P	Pressure (Pa); Hydrostatic pressure (Pa)
cp	Specific heat capacity (JK^{-1}Kg^{-1})
T	Temperature (K)
$\bar{T}$	Cycle averaged temperature (K)
β	Coefficient of volume expansion (K^{-1})
k	Thermal conductivity (Wm^{-1}K^{-1})
$\dot{\gamma}$	Shear rate (1/s); Effective shear rate (1/s)
η_0	Zero shear viscosity (Ns/m^2)
τ^*	Reference shear stress (Pa)
n	Power law index

C	Universal Tait constant; Stiffness tensor
$V(0,T)$	Temperature dependence of volume at zero pressure
$B(T)$	Pressure sensitivity of the material (Pa)
x, y, z	Cartesian coordinates
σ	Stress tensor (Pa); Standard deviation
ε	Strain tensor
α	CLET tensor
μ	Mean
η	Dynamic viscosity (Pa.s)

1 Introduction

In plastic injection molding, design for assembly guidelines requires strict conformity of the product to the tight tolerances and dimensional requirements provided by part designers [1]. A deviation in the part dimensions as a result of various defects will affect functionality of the part. Warpage is among the major defects in plastic injection molding which influences product dimensional stability and accuracy. It is largely caused by variations in operating process parameters [2]. Most molding environments still operate in ambient conditions with the surrounding air temperature having the largest influence on the molding environment. Process parameters are thus subject to changes as a result of the instability caused by environmental factors such as air temperature and humidity [3]. This partly explains the causes for variability of plastic injection molding process and its dependence on the molding environment. Determination of the effects of variation in ambient temperature to the molded product defects is essential for the process control especially in response to changes in the conditions of the molding environment.

Various studies have investigated the effects of changes in major process parameters such as ambient temperature among other parameters on warpage of a molded product. A study by Chen et al. [4] on optimization of process parameters for warpage control obtained ambient temperature as the most significant parameter affecting warpage. A study by Wen et al. [5], carried out optimization of process parameters for minimization of warpage and established that the most significant factors affecting warpage was melt temperature, followed by cooling time, packing pressure, packing time and mold temperature. The results of this study were in line with those obtained by [6] and [7]. Kitayama et al. [8] obtained a substantial reduction in cycle time and warpage through optimization of process parameters.

Although significant strides have been made with respect to evaluation of the effects of variation in process parameters to warpage defect, the exploration of the effects of process parameter interactions to the defect is unclear. Most studies have concentrated on the investigation of the parameter mains effects affecting warpage and it is not clear how interactions among the major process parameters contribute to this defect. Studies report that evaluation of mains effects without consideration of significant interaction effects may result majorly to wrong statistical inferences [9]. Studies such as Chiang & Chang [10] reported on the statistical significance of interaction terms without further exploration of the terms and their effects on the defect. Massah et. al. [11]

obtained qualitative statistical estimates of the effects of process parameter interactions on warpage defect. Similarly, Liu et. al. [12] and Guerra et. al. [13] obtained statistical estimates of the significance of process parameter interaction terms on warpage defect. However, statistical estimation of the effect of parameter interactions is subject to various limitations in terms of the limited accuracy and reduced predictive power. Statistical approximations often assume linear relationships and may not capture the complex and nonlinear interactions between process parameters.

Therefore, further research is needed to understand how the effect of variations in a particular process parameter depend on the levels of other process parameters in warpage defect modelling. This would serve as an important insight to the injection molding process and would inform precise process control through targeted parameter variation. Moreover, the application of intelligent algorithms such as fuzzy inference systems in the evaluation of the effects of process parameter interactions to warpage would address the limitations associated with statistical approximation models. Fuzzy logic could thus provide a robust tool in the evaluation of interaction terms and their effects to warpage defect. Therefore, this study presents an analysis of the effects of process parameter interactions on warpage through design of experiments, numerical modelling and fuzzy logic approach.

2 Methods

This study was carried out through Design of Experiments (DOE), Computer Aided Engineering (CAE) and Fuzzy Logic Modelling as illustrated on Figure 1. Moldex3D® was utilized for CAE modelling while MATLAB Fuzzy Logic Designer Toolbox was used for the fuzzy inference model development. A 100 mm by 70 mm by 30 mm electronic component casing was developed as a test specimen based on Total HDPE 2007 material and a single cavity injection mold developed as a finite element model. Maximum mesh element sizes of 0.5 mm were utilized upon mesh convergence test.

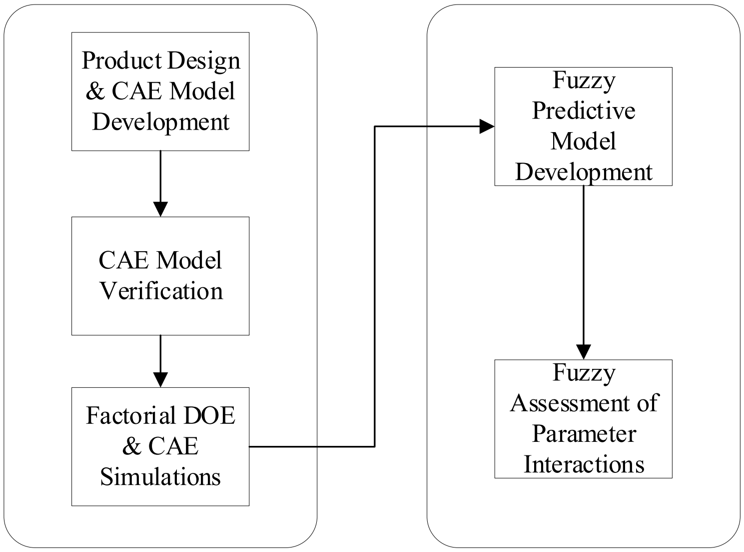


Fig. 1 Study design

CAE modelling of the filling stage of the process was based on Hele-Shaw simplifications of equations governing the conservation of mass, momentum and energy [14]. The viscosity of the polymer melt was modelled based on the cross exponential viscosity model given by Equation 1 [15].

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

Where $\dot{\gamma}$ represents the effective shear rate, τ^* the reference shear stress, n the power law index, P the pressure, T the temperature and the other material constants given by B, D and T_b.
The position of the polymer melt front during the molding process was determined based on a volume fraction function governed by the transport Equation 2.

$$\frac{\partial f}{\partial t}+\nabla\cdot(uf)=0 \tag{2}$$

The packing stage of the process was governed by the Modified Tait Equation 3 [16].

$$V(P,T)=V(0,T)\left[1-C\cdot ln\left(1+\frac{P}{B(T)}\right)\right]+V_t(P,T) \tag{3}$$

Where;

$$V_0(T)=\begin{cases} b_{1L}+b_{2L}\bar{T}, T>T_t, melt\ state \\ b_{1s}+b_{2s}\bar{T}, T\le T_t, solid\ state \end{cases}$$

$$B(T)=\begin{cases} b_{3L}\exp(-b_{4L}\bar{T}), T>T_t, melt\ state \\ b_{3s}\exp(-b_{4s}\bar{T}), T\le T_t, solid\ state \end{cases}$$

$$V_t(P,T) = \begin{cases} 0, T > T_t, melt\ state \\ b_7 \exp(b_8\bar{T} - b_9 P), T \leq T_t, solid\ state \end{cases}$$

$$\bar{T} = T - b_5$$

$$T_t = b_5 + b_6 P$$

$$b_{1L} = b_{1s}\ for\ amorphous\ polymers$$

$$b_{1L} > b_{1s}\ for\ crystalline\ polymers$$

$$C = 0.0894$$

Warpage phase was modelled by generalizations of Hooke's law given by Equations 4 and 5.

$$\sigma = C(\varepsilon - \varepsilon^0 - \alpha\Delta T) \tag{4}$$

$$\varepsilon = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

Where σ is the stress tensor, C is the stiffness tensor, ε is the strain tensor, u is the displacement tensor and α is the CLET tensor.

A numerical solver based on 3D Finite Element approximation was utilized. The boundary conditions applied included zero pressure gradients in directions normal to the mold edges and walls; melt pressure, temperature and flow rate specified at inlet; zero pressure at the flow front; specified mold surface temperature; no-slip condition at the fluid-solid boundary; mass flow rate specified based on part volume and fill time; and the ejection temperature specified [17]. The model was based on assumptions such as the flow considered laminar, inertial force ignored, heat conduction in melt flow direction ignored and the fluid assumed to vary smoothly over time and space [14].

Verification of the finite element model of the injection mold was carried out through pressure-volume-temperature relationship characterization. Six probes were placed at various points on the CAE model. A warp simulation was carried out and the values of temperature, pressure and numerical density obtained from each probe. Using the values of pressure and temperature obtained from each probe, equivalent analytical densities were computed based on the modified Tait Equation and the results compared to the numerically obtained densities. A match in the densities was satisfactory as illustrated on Figure 2 and hence the model used for successive simulations.

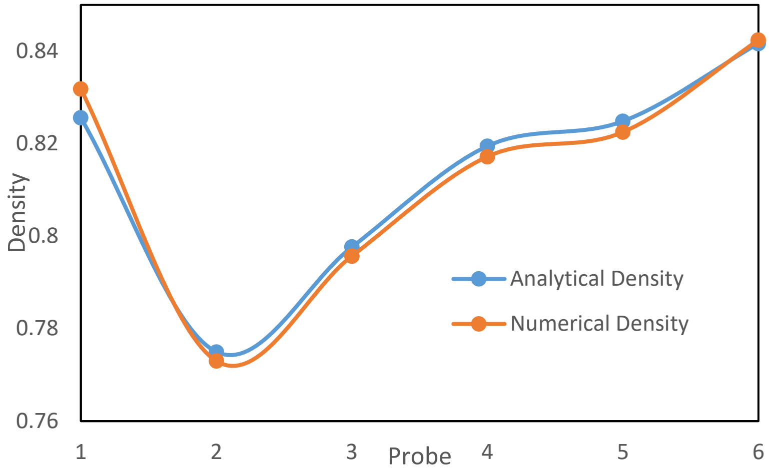


Fig. 2 Comparative density verification plots

A factorial design of experiment was utilized based on six process parameters each at two levels of application as illustrated on Table 1. The choice of the levels were as recommended by HDPE 2007 material processing guide.

Table 1 Selected process parameters and levels

Process Parameters	**Levels**	
	Min	Max
Ambient Temperature (°C)	20	35
Melt Temperature (°C)	200	240
Mold Temperature (°C)	30	50
Maximum Packing Pressure (MPa)	80	100
Injection Pressure (MPa)	80	100
Cooling Time (s)	4	8

To establish the effects of process parameter interactions, a Mamdani fuzzy inference model was developed based on the results from CAE simulations. A Mamdani fuzzy inference system was developed to represent the relationship between the six input parameters and warpage response. Each of the six inputs had two membership functions mapping the lower and upper levels while twenty membership functions were defined for the output warpage response. Gaussian membership function types were defined for both the input and output and 32 rules defined to map the inputs into outputs. Figure 3 illustrates the membership function configuration for one input variable. As illustrated by the plot, ambient temperature values in the range of 20 to 27.5 degrees have higher degrees of membership in the "low" membership function whereas ambient temperature values in the range of 27.5 to 35 degrees have higher degrees of membership in the "high" membership function. Figure 4 illustrates the membership function configuration for warpage response indicating the values of warpage ranges associated with each of the twenty membership functions. W1 is the first membership function and comprise warpage values between 1.00 and 1.0265 mm with the highest degree of membership being at 1.00 mm.

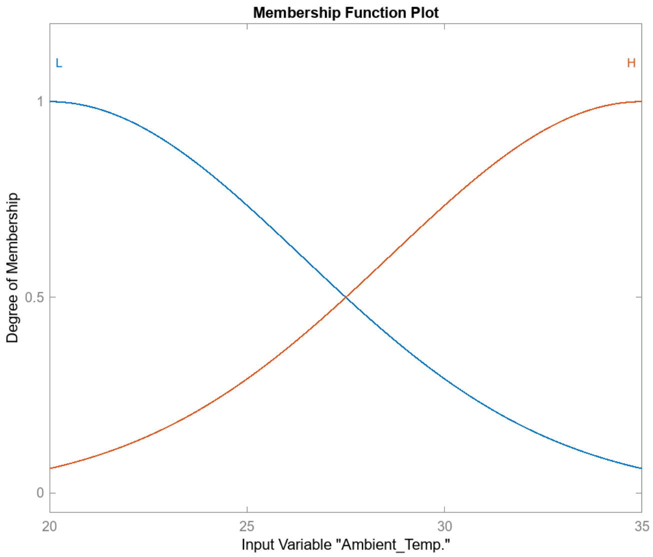


Fig. 3 Ambient temperature membership function

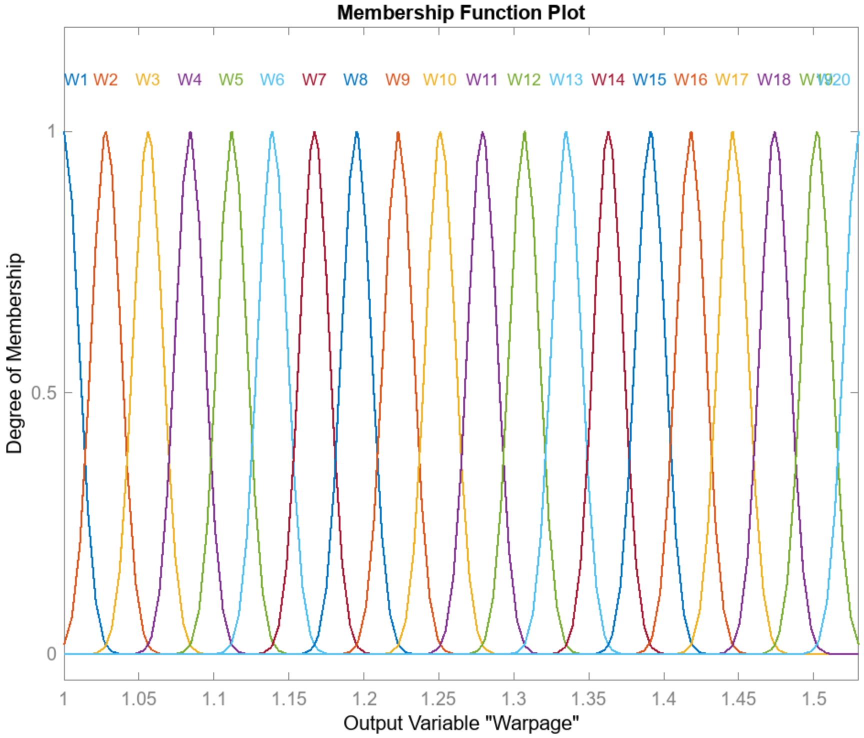


Fig. 4 Warpage response membership functions

3 Results and discussions

Results obtained from the numerical simulations are illustrated on Table 2. The lowest warpage of 1.049 mm was obtained from run 17 giving a warp ratio of 1.05% expressed as a percentage of the maximum part length whereas the highest value of 1.529 mm was obtained from run 9 giving a warp ratio of 1.5% expressed as a percentage of the maximum part length.

Table 2 Numerical simulation results

Run	Ambient Temp	Melt Temp	Mold Temp	Pack Press.	Injection Press.	Cool Time	Warpage (mm)
1	35	200	50	80	100	8	1.33
2	20	240	50	80	80	4	1.521
3	20	200	30	100	100	4	1.175
4	20	240	30	100	80	4	1.249
5	35	200	50	100	100	4	1.071
6	35	200	30	100	100	8	1.15
7	35	240	50	80	100	4	1.346
8	20	240	30	100	100	8	1.278
9	20	240	50	100	100	4	1.529
10	35	200	50	80	80	4	1.152
11	20	200	50	100	80	4	1.19
12	35	240	50	100	80	4	1.306
13	35	200	50	100	80	8	1.114
14	20	240	50	80	100	8	1.359
15	20	200	30	80	80	4	1.242
16	20	200	50	80	100	4	1.271
17	35	200	30	100	80	4	1.049
18	20	240	30	80	80	8	1.333
19	20	240	50	100	80	8	1.309
20	20	200	50	80	80	8	1.292
21	35	240	30	80	100	8	1.211
22	20	200	30	80	100	8	1.331
23	35	240	30	100	80	8	1.158
24	35	240	30	80	80	4	1.213
25	35	200	30	80	100	4	1.119
26	35	240	50	80	80	8	1.241
27	20	240	30	80	100	4	1.333
28	35	240	30	100	100	4	1.129
29	35	200	30	80	80	8	1.217
30	20	200	30	100	80	8	1.267
31	20	200	50	100	100	8	1.239
32	35	240	50	100	100	8	1.194

The contour plots indicating the maximum and minimum warpage runs are illustrated on Figure 5. The nodes subjected to the maximum warpage are represented in red whereas those subjected to minimum warpage are represented in blue. Higher values of warpage were obtained on the nodes at the bottom edges and corners while lower values of warpage obtained at the central part of the part. This resulted from the polymer melt material flow pattern where the material flow started from the part center towards the part corners and edges. The higher warpage values at the bottom edges and corners compared to the central part are primarily due to the differential cooling rates caused by the polymer melt flow pattern. The material starts cooling at the center, leading to more uniform shrinkage, while the edges and corners, which cools later, experience greater shrinkage and thus more warpage.

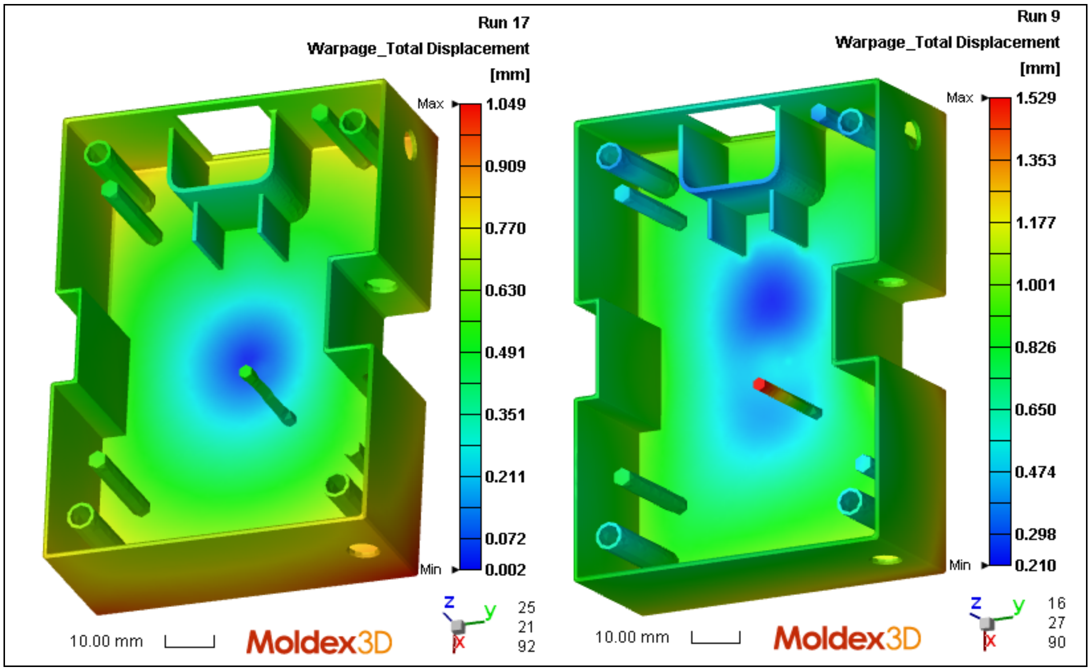


Fig. 5 Plots of the lowest and highest values of warpage

The mains and interaction effects were initially determined statistically through statistical analysis of the factorial design. Figure 6 shows the resulting Pareto plot showing the relative sizes of the mains effects and major interaction effects. Ambient temperature had the largest effect on warpage followed by melt temperature. Similarly, a study by Chen et al. [4] obtained ambient temperature as the parameter with the largest effect on warpage followed by melt temperature. Cooling time had the least individual effect on warpage. A two-parameter interaction with the largest effect involves the melt temperature and cooling time whereas a three-parameter interaction with the largest effect involves the ambient temperature, packing pressure and injection pressure.

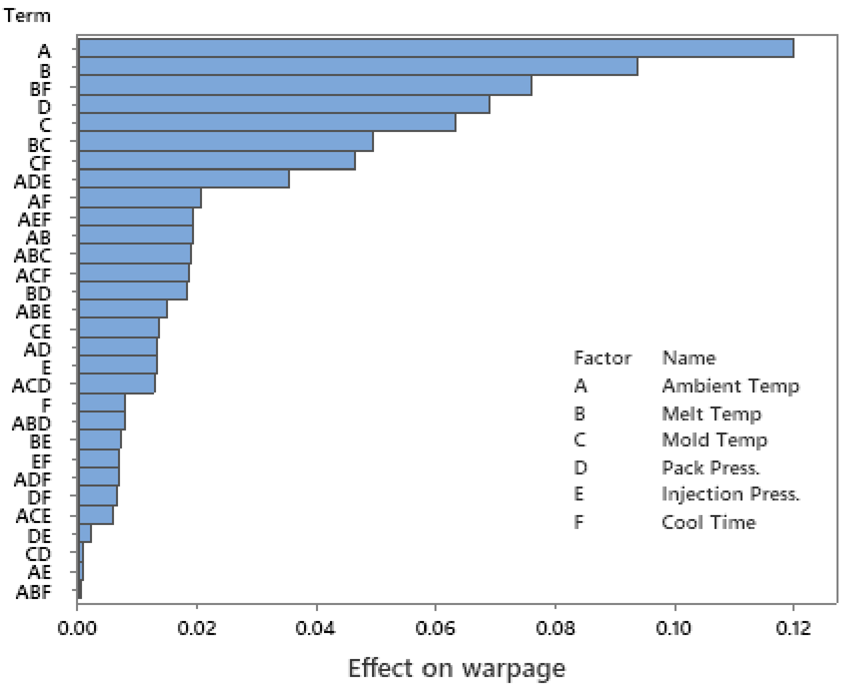


Fig. 6 Pareto plot of mains effects and interactions

Mains effects and interaction effect sizes were computed based on a difference of means approach. Some of these effect sizes are illustrated on Table 3 and mains effects are illustrated on Figure 7. Ambient temperature has a decreasing effect on warpage while melt temperature has an increasing effect on warpage. The interaction effect between melt temperature and cooling time has a decreasing effect on warpage while that between melt temperature and mold temperature has an increasing effect on warpage.

Higher melt temperatures accelerates shrinkage when the material cools to room temperature and thereby induces warpage [2]. The effect of ambient temperature is more pronounced during post-mold warpage stage where higher ambient temperatures helps to maintain a uniform post-molding cooling rate which reduces internal stresses hence resulting to low warpage. Ambient temperature also contributes to the temperature range between the polymer melt as it enters the mold and room temperature which influences the polymer melt thermal contraction and crystallization [18].

As a result of plastic compressibility, the amount of packing pressure during the packing stage affects polymer material molecular alignment, polymer chains orientation and hence internal stresses. Increasing the packing pressure enhances molecular alignment and orientation of polymer chains which significantly reduces internal stresses and warpage. Studies by Chen & Zhu [19] and Singh et al. [20] obtained similar trends in terms of a decrease in warpage at higher packing pressure.

Higher mold temperature and cooling time slows down the rate of cooling and promotes more stress relaxation hence increasing part shrinkage and warpage. An increase in injection pressure results to a difference in molecular orientation which induces residual stress and lead to warpage [2].

Table 3 Computed mains and interaction effects

Parameter	Effect Size	Parameter	Effect Size
A	-0.12	BC	0.05
B	0.09	CF	-0.05
D	-0.07	ADE	-0.04
C	0.06	AF	0.02
E	0.01	AEF	0.02
F	0.008	AB	-0.02
BF	-0.08	ABC	-0.02

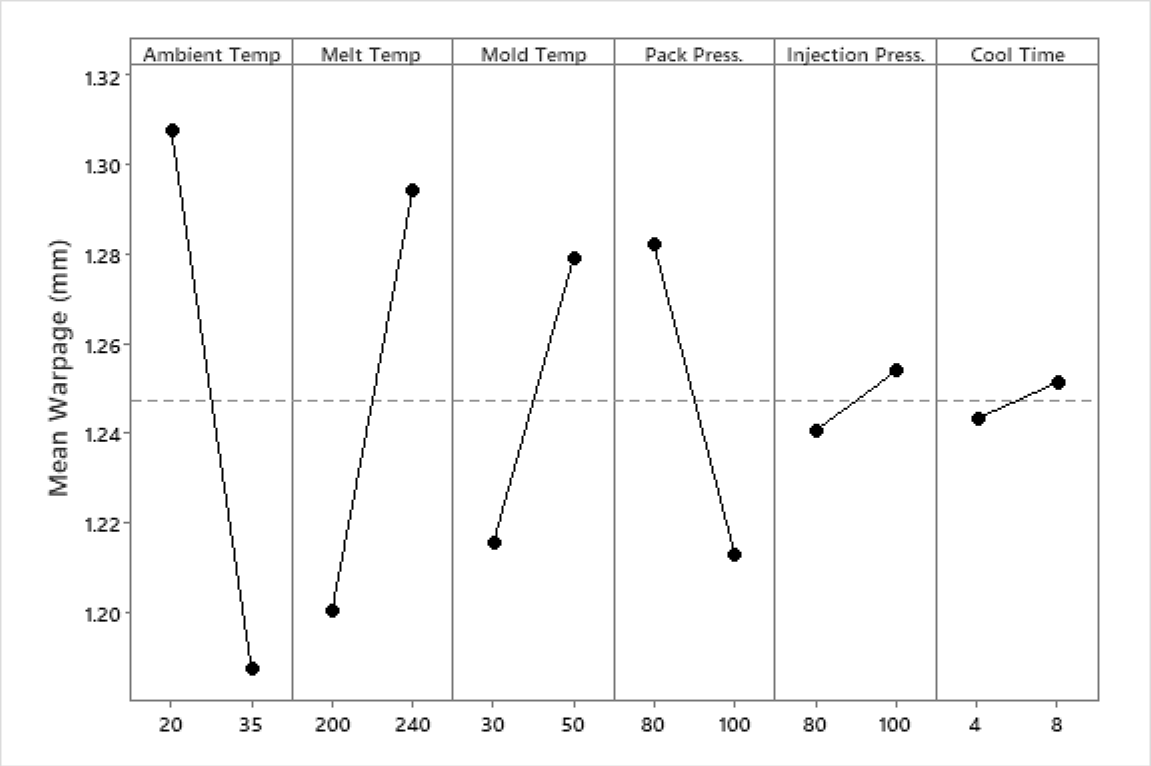


Fig. 7 Statistical mains effects

To determine the statistical significance of the effects, an ANOVA was carried out at 95% significance level. Table 4 presents ANOVA of the mains effects and interaction effects. Of the six inputs, injection pressure (P=0.084) and cooling time (P=0.250) were statistically insignificant. However, interactions between these parameters and other parameters were statistically significant. Mains effects had a contribution of 68%, two-way interactions had a contribution of 25% while three-way interactions had a contribution of 6%. Ambient temperature and melt temperatures had the largest individual contributions to warpage of 30.6% and 18.7% respectively.

Model metrics for an initial ANOVA carried out with mains effects only were R-squared of 68.4%, adjusted R-squared of 60.7% and predicted R-squared of 48.1% whereas model metrics for a final ANOVA with interaction terms yielded R-squared of 99.6%, adjusted R-squared of 97.5% and predicted R-squared of 83.5%. The increase in adjusted R-squared with the addition of interaction terms implied an improvement to the model and the smaller difference between R-squared and predicted R-squared for the model with interaction terms implied minimal chances of model overfitting.

Table 4 ANOVA of the effects

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Model	31	3.75E-01	99.60%	1.44E-02	47.58	0.000
Linear	6	2.57E-01	68.35%	4.29E-02	141.50	0.000
A	1	1.15E-01	30.56%	1.15E-01	379.53	0.000
B	1	7.03E-02	18.69%	7.03E-02	232.13	0.000
C	1	3.19E-02	8.47%	3.19E-02	105.24	0.000
D	1	3.81E-02	10.12%	3.81E-02	125.74	0.000
E	1	1.41E-03	0.37%	1.40E-03	4.64	0.084
F	1	5.12E-04	0.14%	5.12E-04	1.69	0.250
2-Way Interactions	15	9.58E-02	25.45%	6.84E-03	22.58	0.001
A*B	1	2.96E-03	0.79%	2.96E-03	9.79	0.026
A*C	1	1.00E-06	0.00%	1.00E-06	0.00	0.954
A*D	1	1.41E-03	0.37%	1.41E-03	4.64	0.084
A*E	1	5.00E-06	0.00%	5.00E-06	0.01	0.908
A*F	1	3.44E-03	0.92%	3.45E-03	11.37	0.020
B*C	1	1.96E-02	5.21%	1.96E-02	64.71	0.000
B*D	1	2.70E-03	0.72%	2.70E-03	8.92	0.031
B*E	1	4.06E-04	0.11%	4.06E-04	1.34	0.299
B*F	1	4.61E-02	12.24%	4.61E-02	152.05	0.000
C*D	1	8.00E-06	0.00%	8.00E-06	0.03	0.877
C*E	1	1.46E-03	0.39%	1.46E-03	4.81	0.080
C*F	1	1.73E-02	4.60%	1.73E-02	57.11	0.001
D*E	1	3.60E-05	0.01%	3.60E-05	0.12	0.744
E*F	1	3.78E-04	0.10%	3.78E-04	1.25	0.315
3-Way Interactions	10	2.18E-02	5.79%	3.63E-03	11.99	0.008
A*B*C	1	2.89E-03	0.77%	2.89E-03	9.53	0.027
A*B*E	1	1.77E-03	0.47%	1.77E-03	5.84	0.060
A*C*D	1	1.30E-03	0.35%	1.30E-03	4.29	0.093
A*C*F	1	2.81E-03	0.75%	2.81E-03	9.29	0.029
A*D*E	1	1.00E-02	2.66%	1.00E-02	33.05	0.002
A*E*F	1	3.00E-03	0.80%	3.00E-03	9.91	0.025
Error	5	1.52E-03	0.40%	3.03E-04		
Total	31	3.76E-01	100.00%			

Upon the development of the fuzzy inference system (FIS) model, FIS predicted values of warpage response were compared against the initial CAE obtained values. Figure 8 illustrates a comparison between the values predicted by the developed FIS against the numerically obtained values based on CAE. The results were comparable and indicated a satisfactory FIS prediction.

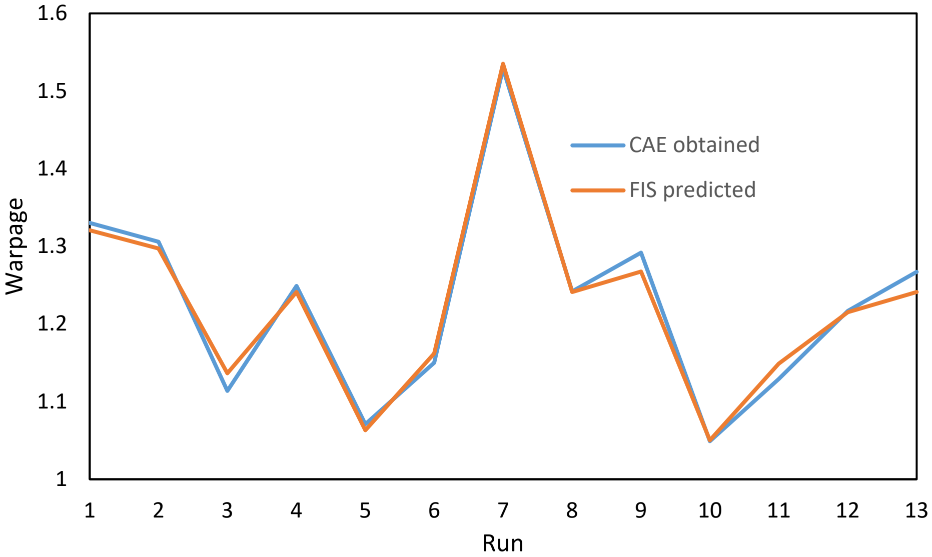
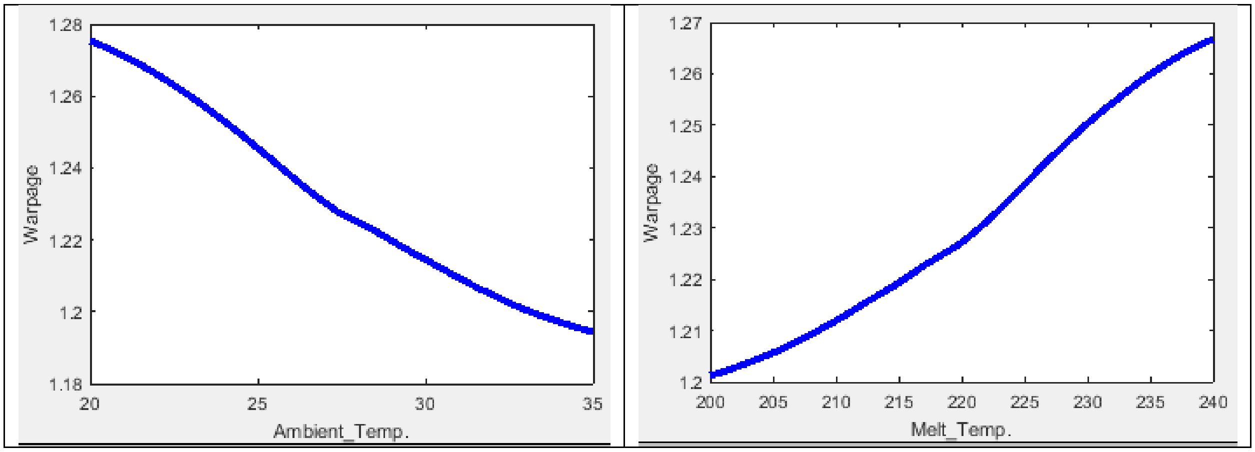


Fig. 8 Comparison between FIS prediction and CAE results

Figure 9 illustrates the mains effect plots as represented by the developed fuzzy inference system. The plots show an increase in warpage with an increase in ambient temperature and packing pressure and a decrease in warpage with increasing melt temperature, mold temperature, injection pressure and cooling time. These relationships were similar to those obtained statistically. Although statistical responses are obtained at specific input parameter levels, with fuzzy inference system, the mains effects can be varied to explicitly obtain responses at desired input parameter levels.



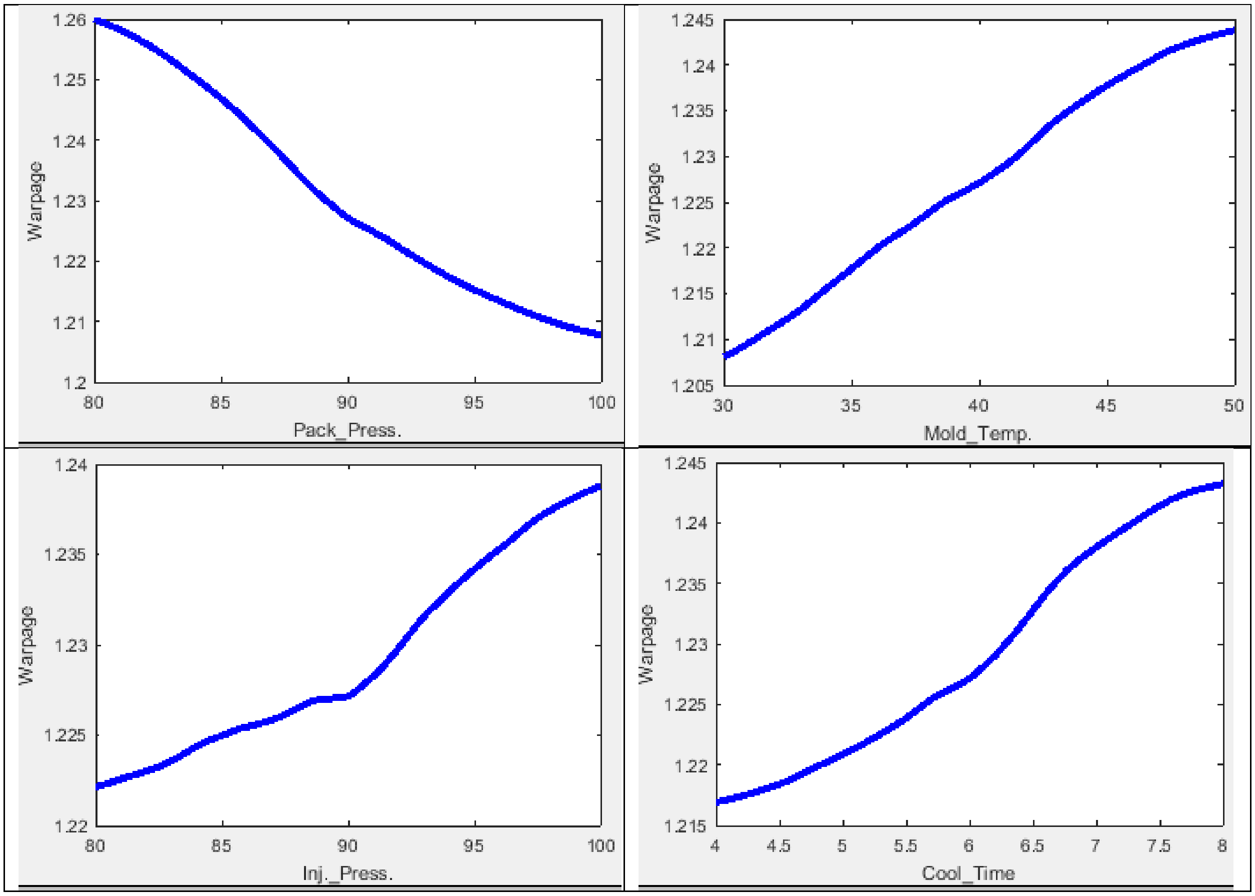


Fig. 9 Fuzzy logic model mains effects

Fuzzy inference system surface plots were utilized to represent the effects of simultaneous variation of process parameters on warpage. This represented the interaction effects between the given variables. Figures 10 and 11 shows the effect of interaction between melt temperature and cooling time on warpage. The lowest values of warpage were obtained at low melt temperature and cooling time while the highest warpage obtained at higher melt temperature and cooling time. The rate of cooling depends on both the melt temperature and specified cooling time and hence higher melt temperature and longer cooling time increases the chances of residual stresses which induces warpage. However, the rate of warpage reduction as a result of an increase in one parameter depends on the level of application of the other. At the lowest level of cooling time (4 s) and constant values of the other parameters, increasing the melt temperature from 200°C to 240°C increased warpage from 1.176 mm to 1.255 mm whereas at the highest level of cooling time (8 s) and similar values of the other parameters, a similar increase in melt temperature increased warpage from 1.223 mm to 1.258 mm. This indicated that the mains effect of melt temperature on warpage was magnified at lower cooling time and diminished at higher level of cooling time as the effect of increasing melt temperature was larger at lower cooling time and smaller at higher cooling time. Despite the mains effect of cooling time being statistically insignificant, the mains effect of melt temperature was dependent on the level of cooling time.

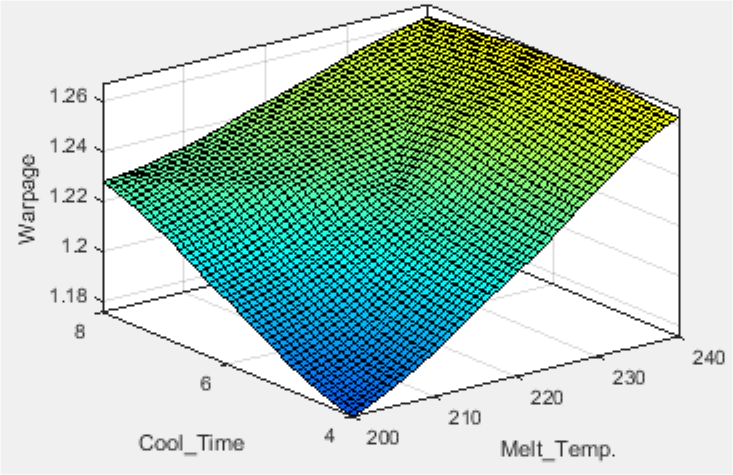


Fig. 10 3D representation of the interaction between melt temperature and cooling time

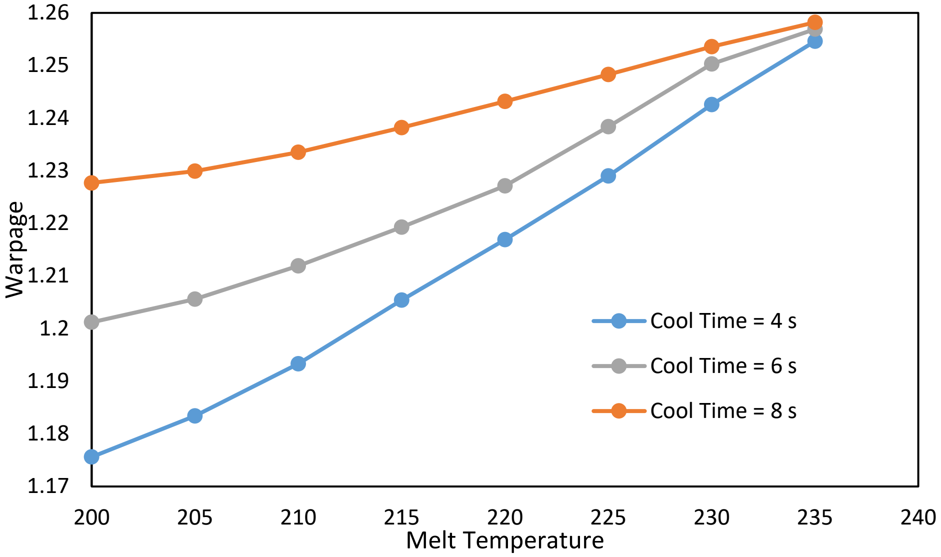


Fig. 11 2D representation of the interaction between melt temperature and cooling time

Figures 12 and 13 illustrates the interaction effect of melt temperature and packing pressure on warpage. The highest warpage was obtained at low packing pressure and high melt temperature and the lowest warpage obtained at high packing pressure and low melt temperature. Melt temperature affects material viscosity and flow. At very high melt temperature, the packing process may end before the injection mold gate freezes thereby resulting to backflow of material and accelerated warpage [18]. This explains the effect of increasing melt temperature to 240°C at low packing pressure which results to the largest warpage of 1.285 mm. Increasing the packing pressure at this value of melt temperature therefore reduces warpage as a result of the enhanced delivery of the molten material during packing which compensates for backflow.

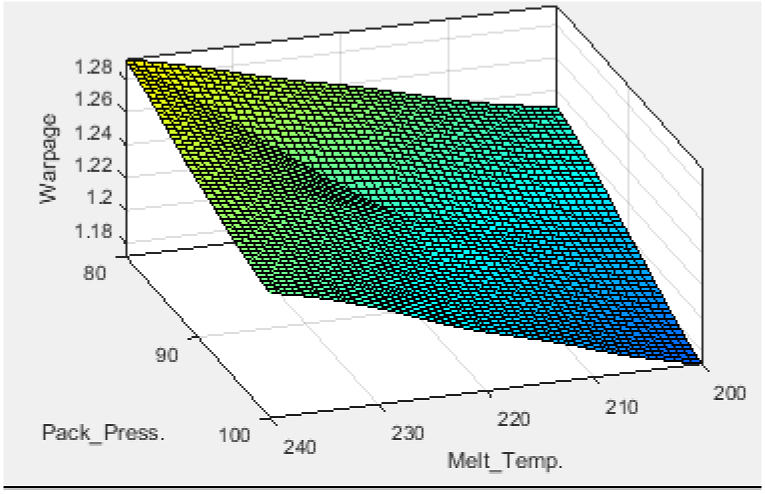


Fig. 12 Interaction between melt temperature and packing pressure in 3D

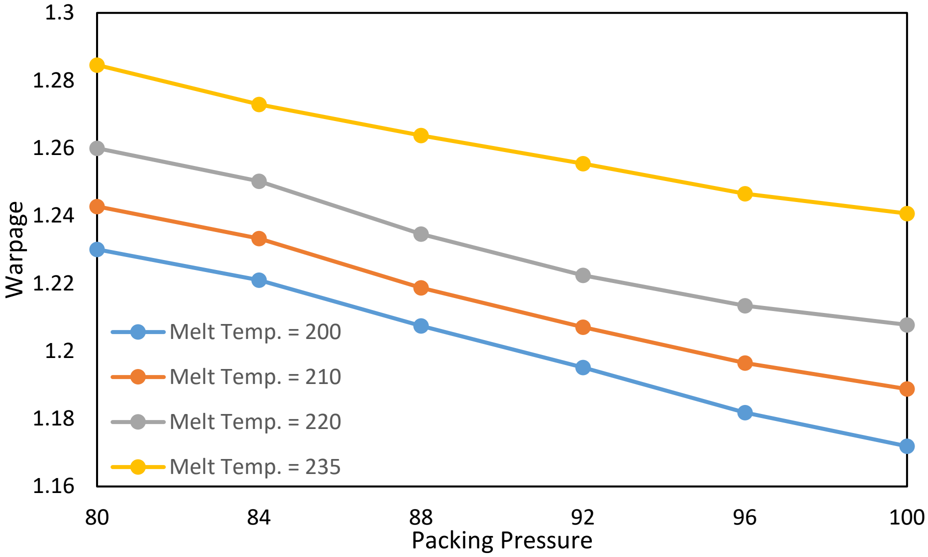


Fig. 13 Interaction between melt temperature and packing pressure in 2D

Figure 14 illustrates the effect of simultaneous changes in melt temperature and mold temperature on warpage. The highest warpage is obtained at the highest values of melt and mold temperatures whereas the lowest warpage is obtained at the lowest melt and mold temperature settings. A difference in the gradients of the curves indicates an interaction effect between melt temperature and mold temperature on warpage. At lower mold temperatures, the curves have lower gradients indicating that an increase in melt temperature at lower mold temperature moderately increases warpage. However, at higher values of mold temperatures, the gradients of the curves are higher indicating a greater increase in warpage as a result of an increase in melt temperature. Melt temperature and mold temperature influences the polymer melt material flow which affects warpage.

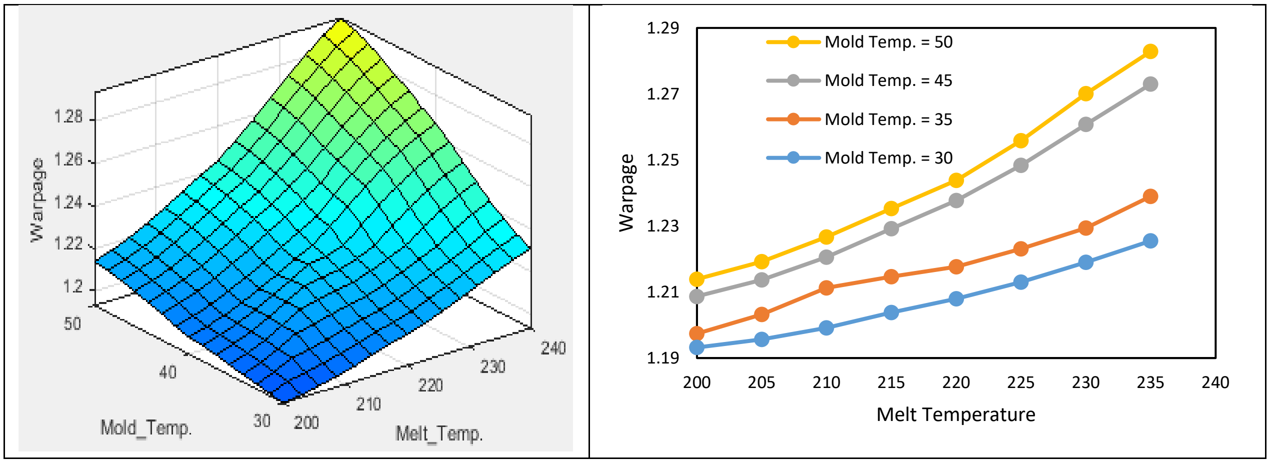


Fig. 14 Interaction between melt temperature and mold temperature

The largest three-way interaction involved ambient temperature, injection pressure and packing pressure. Figure 15 illustrates the effect of simultaneous variation of ambient temperature, injection pressure and packing pressure on warpage. The figure was plotted with results obtained from the fuzzy inference model based on variation of ambient temperature at three levels, packing pressure at three levels and injection pressure at two levels. The lengths of the curves represent the effect of variation of injection pressure from 80 MPa to 100 MPa at given values of ambient temperature and packing pressure. A clear interaction effect among the three parameters is explicitly represented by the difference in the lengths of the curves. For instance, at an ambient temperature of 20°C, an increase in injection pressure at a 90 MPa packing pressure increases warpage by 0.001 whereas the same increase in injection pressure at a 100 MPa packing pressure increases warpage by 0.015. The effect of variation of injection pressure on warpage depends on the levels of the other two parameters. The effect of variation of injection pressure is largest at an ambient temperature of 27°C and packing pressure 100 MPa and smallest at an ambient temperature of 20°C and packing pressure of 90 MPa. The same relationship applies in variation of the other two parameters. Changes in ambient temperature or packing pressure have varying effects on warpage across the levels of the other two parameters.

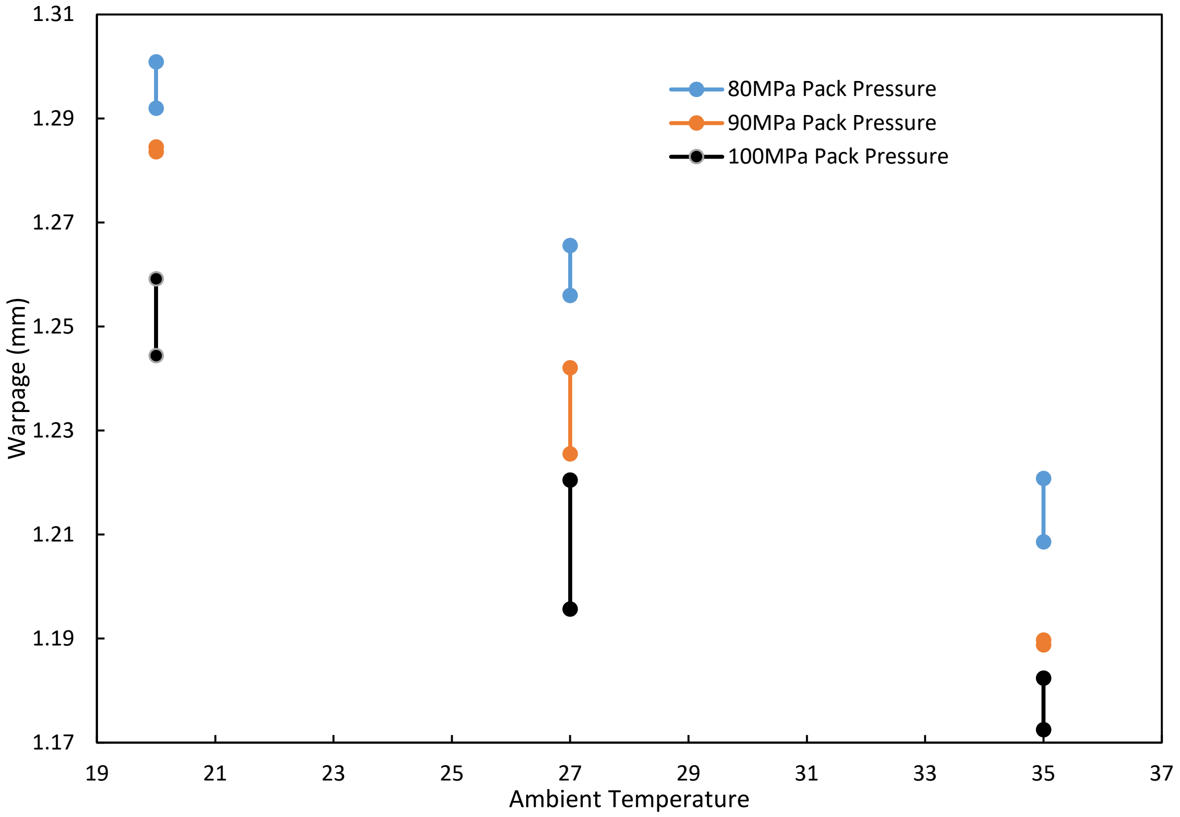


Fig. 15 Interaction between ambient temperature, packing pressure and injection pressure

4 Conclusion

The purpose of this study was to evaluate the effects of interactions among major process parameters on warpage defect. These were determined both statistically and through fuzzy logic. The following conclusions were made from this study;

1. Variations in ambient temperature and melt temperatures have the greatest contribution to warpage defect whereas cooling time has the least contribution to the defect. Ambient temperature has an individual contribution of 30.6%, melt temperature has a contribution of 18.7% whereas cooling time has a contribution of 0.1%.
2. The largest two-way interaction affecting warpage involves melt temperature and cooling time, which has a contribution of 12.2%. Shorter cooling time magnifies the mains effect of melt temperature on warpage while longer cooling time diminishes the mains effect.
3. The largest three way interaction involves ambient temperature, packing pressure and injection pressure with a contribution of 2.7%.
4. Despite cooling time having the least mains effect, most interaction terms with greater effect on warpage involved cooling time and melt temperature.
5. Compared to statistical methods, fuzzy inference system provides a robust means of determination of the detailed effects of process parameter interactions on warpage defect

This study has demonstrated that interactions among major process parameters have a significant effect on warpage defect. The study demonstrates that it is not feasible to consider only the mains effects in the evaluation of the effects of process parameters to warpage defect as some parameter mains effects are magnified or diminished by significant interaction terms. The results from this study could form a basis for process parameter screening and in the warpage defect minimization through targeted process parameter control and setting. The findings of this study could build up onto further studies entailing the evaluation of the effects of interactions among other variables such as mold design features, part geometric features and injection molding machine features.

Statements and Declarations

Conflicts of interest: The authors declare no known conflicts of interest in the method and results adopted in the study

Consent for publication: The authors consented to this publication

Data availability: This paper has provided all the data obtained from the study and adopted in the analysis

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