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ORIGINAL ARTICLE

The analysis of short shot possibility in injection molding process

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Abstract This paper presents the analysis of short shot possibility in injection molding. The aim of this research is to evaluate process and geometric parameters which increase the possibility of short shot in an injected part based on the proposed method. The analysis of short shot possibility was conducted via SolidWorks Plastics and Taguchi method for orthogonal array experiment of L18 to find the significant process and geometric parameters. Finite element method (FEM) is employed in SolidWorks Plastics for simulation. To validate the simulation result, an experimental study was conducted for two circular flat polypropylene of 1-mm thickness. Filling time, part cooling time, pressure holding time, and melt temperature were selected as process parameters, and gate type was selected as a geometric parameter. A new method of analysis for short shot defect is proposed herein to predict the possibility of short shot in injection molding before it occurs. The significance rate of each parameter in both experiments and simulation result was very close together which signifies the robustness of proposed method in evaluation of short shot possibility. *Melt temperature* was the most influential parameter with a contribution of 74.25 and 75.04%, and *filling time* with a contribution of 22 and 20.19% followed by *gate type* with a contribution of 3.69 and 3.93% for simulation and experimental results, respectively. Hence, based on response table of S/N ratio, the optimum levels of each parameter which leads to reduction in possibility of short shot are *gate type at level 1*, *filling time at level 3*, and *melt temperature at level 3*. Finally, *melt temperature*, *filling time*, and *gate type* considered as significant parameters which affect the possibility of short shot in injected parts.

Keywords Injection molding · Short shot · Process parameter · Geometric parameter

1 Introduction

Injection molding is the most significant process for manufacturing plastic products. Injection molding is considered for mass production of the complex geometry plastic products which requires accurate dimensions [1]. Some of the key points of this industry are the advantages such as short product cycles, good mechanical properties, low cost, and light weight [2]. Injection molding process is unstable repeated work, consisting of filling, packing, and cooling phases. During the filling stage, a hot polymer melts quickly to fill the cold cavity. During the packing stage, the pressure of molten plastic for injection is increased to ensure that the cavity filled properly. Finally, during the cooling stage, the molten plastic cools down and solidifies adequately so that the final product is stable for ejection from the cavity [3–6].

The final quality of an injected part is related to different factors which are part design, mold design, material, and process parameters [7–9]. Different factors cause different defects of the products like warpage, weld line, and sink mark during the manufacturing process, but short shot causes the most highly defects in plastic parts. The evaluation of short shot in injection molding is very complicated [2, 10, 11]. In general, when insufficient material which was injected into the mold cannot fill the cavity, a

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short shot occurs [12]. It is caused by different factors such as wrong plastic material selection, incorrect processing parameters, incorrect mold design, and part design. Hence, because of the complexity of melt flow process, it is critically significant to have control over the factors of influence during the injection molding process [10, 13]. The formation of short shot is a plastic defect which eliminates the overall success of the injection molding process. There are different physical causes for incomplete filling such as small shot volume, venting problems, insufficient injection pressure, low injection speed, wrong temperature control in mold, etc. The effects of process and geometric parameters on the formation of short shot on the injected parts need to be understood in order to control the processing conditions to reduce the flaw [10].

There are a few articles which determined optimum levels and the impact of different parameters in creating different plastic defects in injection molding, like weld lines, sink mark, and warpage in injection molding [1, 14–16]. Weld lines decreases the strength and appearance quality of injected part. Different process parameters such as melt temperature, injection speed, and injection pressure and mold design parameters such as gate design lead to weld lines [17, 18]. Sink marks is another type of defect which reduce the final quality of the injected part. Optimum process parameters and mold design to reduce sink marks are needed to improve the part quality [1, 19].

However, to the best of the author's knowledge based on the literature survey, there is not enough study to show the effect of different geometric and process parameters on short shot defect. Also, there is no study to evaluate different process and geometric parameters for the possibility of short shot before they occur through the injection process. Most of the studies are based on the evaluation of different plastic defects when it occurs.

Among four essential factors, namely *mold design*, *part design*, *material*, and *process parameters*, *mold design* and *process parameters* are clearly the essential factors which lead to different defects; therefore, they are used herein for the analysis of short shot possibility. Since the design of the part is based on customer requirement, it is not possible to cover all issues in part design. So, the part design is not considered herein. So is the material type because more than 17,000 plastic materials are used through the world and therefore is not possible to conduct experiments on all of them. Injection molding process is a nonlinear and multivariable procedure. Conventional trial-and-error method can improve the part quality, but it is so expensive and time-consuming [1]. With the advancements in *Computer Aided Engineering* (CAE) technology, simulation of the injection molding process is now an influential tool to support engineers and meets these challenges as a replacement for conventional method. The CAE technique and *Taguchi* method are jointly employed herein to investigate the impact of different parameters on short shot index of injected parts with the aim of reducing this defect. Also, orthogonal array experiment of L18 (based on the number of parameters and their levels) is selected to find the optimum levels of process and geometric parameters and evaluate their significance in reducing the possibility of short shot for two thin shell plastic samples via the *Signal to Noise ratio (S/N)* and *Analysis Of Variance (ANOVA)*. To ensure that other factors such as the size of runner and gate do not affect the simulation and experimental results, the selection of the right size for runner and gate is conducted via simulation and manufacturing of mold tools.

In this paper, based on two different feeding systems of injected parts and Taguchi method, different process parameters, short shot is analyzed via SolidWorks Plastics. The significance and the contribution percentage of each process and geometric parameters on possibility of short shot are determined via *signal to noise ratio* and *analysis of variance*. Finally, to validate the simulation result, a real case study is conducted.

2 Taguchi

Taguchi techniques were established by Taguchi and Konishi. The Taguchi method is a comprehensive quality strategy that conducts minimal number of experiments using orthogonal array and forms robustness into a process during its design stage [1, 2, 20]. An orthogonal array makes the independent mathematical assessment of the effect of all parameters possible. The quality evaluation of injected parts which is affected by many parameters is important. Therefore, studying task which is required to perform by CAE can be remarkable. Hence, *design of experiment* (DOE) is a reasonable method to decrease the number of numerical experiments and also acquire enough information which is used in real experiments [1]. Taguchi is a technique to predict the significant and insignificant parameters and also optimum level of the design parameters by running a series of experiments.

In Taguchi method, system design using the scientific and engineering information required for producing the part is the target, tolerance design, the evaluation and analysis of tolerances for optimum combination of process parameters are the key points, and for determination of optimum levels of process parameters to improve the quality characteristics, parameter design is significant. In this section, parameter design is employed to attain the optimum levels of process parameters which in turn lead to a reduction of short shot possibility during the production of thin-shell plastic part [2].

Table 1 Three levels of selected parameters

Parameters	Level 1	Level 2	Level 3
Gate type, A	1	2	–
Filling time, B (s)	0.2	0.6	1
Part cooling time, C (s)	3	3.9	5
Pressure holding time, D (s)	1	2	3
Melt temperature, E (°C)	200	230	280

An effectual way to evaluate the effect of a number of factors all together is to utilize the orthogonal arrays to organize matrix experiments [1]. According to the selected orthogonal array, Taguchi technique decreases the number of experiments which leads to a reduction in time and cost. This special design of orthogonal array covers whole parameters with a small number of experiments and allocates control parameters and design variables to the columns of an array and transfers the integers in the array columns into the real setting of parameters [1, 2]. Taguchi proposes S/N ratio to determine the quality characteristics considered for any problems in engineering design. S/N ratio has three categories: *the smaller the better*, *the nominal the best*, and *the higher the better* [2]. In this study, *the smaller the better* quality characteristic is selected to reduce short shot defect through the optimal level of each process and geometric parameters. Also, analysis of variance (ANOVA) is applied to evaluate the effect rate of process and geometric parameters on short shot. Hence, the optimum level of each parameter is determined.

Table 2 L18 orthogonal array

Experiment	A	B	C	D	E
1	1	1	1	1	1
2	1	1	2	2	2
3	1	1	3	3	3
4	1	2	1	1	2
5	1	2	2	2	3
6	1	2	3	3	1
7	1	3	1	2	1
8	1	3	2	3	2
9	1	3	3	1	3
10	2	1	1	3	3
11	2	1	2	1	1
12	2	1	3	2	2
13	2	2	1	2	3
14	2	2	2	3	1
15	2	2	3	1	2
16	2	3	1	3	2
17	2	3	2	1	3
18	2	3	3	2	1

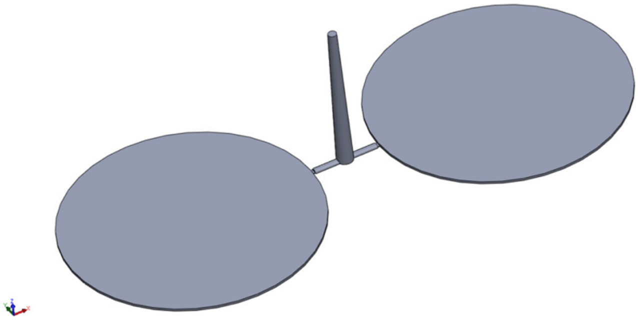

Fig. 1 3D design of plastic parts with sprue, runner, and gate system

3 Experimental set-up

3.1 Molding machine and molding materials

Injection molding machine is required for the injection of plastic product. For selecting the injection machine, it is important to determine the size of the top clamping plate and bottom clamping plate of mold tools. So, based on the need for this research, the injection machine-Poolad-Bch series and plastic material *polypropylene* (PP) were selected.

3.2 3.2Part geometry and mold design

Since, this study is evaluating the effect of different parameters which affect the short shot possibility in injection molding, a round plate plastic part of 100-mm diameter and 1-mm thickness was designed. Some preparations were important to consider for the experiment. In manufacturing the mold tools, computer numerical control (CNC) milling machine, grinding machine, and drilling machine are the main machines to fabricate different components of the mold tools namely *top clamping plate*, *core and cavity plates*, *side plates*, and *bottom clamping plate*. Other components of the mold tools such as sprue bush and guide bush were purchased separately.

4. Process of experiment design

4.1 Selection of the parameters

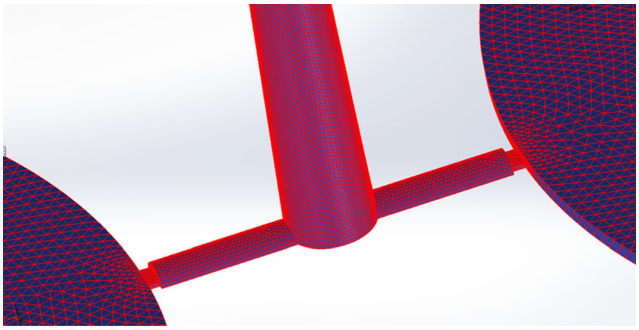

Fig. 2 Finite element analysis for 3D part design

Table 3 Different level of parameters based on L18 orthogonal array

Experiment	Gate type	Filling time	Part cooling time	Pressure holding time	Melt temperature
1	1	0.2	3	1	200
2	1	0.2	3.9	2	230
3	1	0.2	5	3	280
4	1	0.6	3	1	230
5	1	0.6	3.9	2	280
6	1	0.6	5	3	200
7	1	1	3	2	200
8	1	1	3.9	3	230
9	1	1	5	1	280
10	2	0.2	3	3	280
11	2	0.2	3.9	1	200
12	2	0.2	5	2	230
13	2	0.6	3	2	280
14	2	0.6	3.9	3	200
15	2	0.6	5	1	230
16	2	1	3	3	230
17	2	1	3.9	1	280
18	2	1	5	2	200

There are several process and geometric parameters which can affect the short shot defect in a thin plate sample namely *filling time*, *cooling time*, *pressure holding time*, *melt temperature*, *mold temperature*, *gate geometry*, *material type*, and *part design* [10]. Since the design of the part is based on customer requirement, it is not possible to cover all issues in part design. So, the part design is not considered herein. So is the material type because more than 17,000 plastic materials are used through the world and therefore is not possible to conduct experiments on all of them. As a result, five parameters were selected which are *filling time*, *part cooling time*, *pressure holding time*, *melt temperature*, and *gate type.*

Table 4 S/N ratio for simulation results

Trials	A (type)	B (s)	C (s)	D (s)	E (°C)	Simulated inlet pressure/maximum inlet pressure (MPa)	S/N (dB)
1	1	0.2	3	1	200	0.5651	4.957
2	1	0.2	3.9	2	230	0.4848	6.288
3	1	0.2	5	3	280	0.394	8.090
4	1	0.6	3	1	230	0.4185	7.566
5	1	0.6	3.9	2	280	0.3405	9.357
6	1	0.6	5	3	200	0.4879	6.233
7	1	1	3	2	200	0.4738	6.488
8	1	1	3.9	3	230	0.4068	7.812
9	1	1	5	1	280	0.3306	9.613
10	2	0.2	3	3	280	0.4249	7.434
11	2	0.2	3.9	1	200	0.6105	4.286
12	2	0.2	5	2	230	0.5216	5.653
13	2	0.6	3	2	280	0.3628	8.806
14	2	0.6	3.9	3	200	0.5212	5.659
15	2	0.6	5	1	230	0.4469	6.995
16	2	1	3	3	230	0.4308	7.314
17	2	1	3.9	1	280	0.3503	9.111
18	2	1	5	2	200	0.5014	5.996

Table 5 The response table of S/N ratio

	Gate type (dB)	Filling time (dB)	Part cooling time (dB)	Pressure holding time (dB)	Melt temperature (dB)
Level 1	7.378	6.118	7.094	7.088	5.603
Level 2	6.806	7.436	7.086	7.098	6.938
Level 3	–	7.722	7.097	7.090	8.735
|ΔT|	0.572	1.604	0.011	0.009	3.132

3.3 4.2Selection of parameter levels

There are three levels of each selected parameter, each of which is considered using Taguchi method. The reason for selecting three levels (low, medium, high) instead of two levels (low, high) is due to the fact that three levels of each factor give more accurate results in comparison to two levels. Different levels of selected parameters are shown in Table 1.

3.4 4.3Selection of orthogonal array

According to the number of parameters and levels which have been chosen, L18 orthogonal array is selected as shown in Table 2.

4 Simulation

After designing two circular parts as two samples for this application, the next step is to simulate the selected parts via SolidWorks plastic. For simulation, defining the right injection system is necessary. Hence, designing the sprue, runner, and gate based on two circular parts with 100-mm diameter and 1-mm thickness is necessary as shown in Fig. 1. The reason for having two round parts with thickness of 1 mm is to eliminate short shot defect in a critical condition. Also, as mentioned before, one of the selected parameters for this study is the gate type. Finally, the round gate and the modified edge gate were evaluated via SolidWorks Plastics and experiments. Based on the total surface area of the injected parts and material constant, the diameter and length for round gate are calculated. Also, for modified edge gate, based on the total surface area of the injected part, thickness of injected part, and material constant, the width and height of the gate are calculated [21, 22].

In order for the result to be accurate, finite element analysis is applied to the solid models via triangular finite elements as shown in Fig. 2. The selected material for injection is *polypropylene* (P. P). Different sizes have been evaluated for the shell mesh and injection system. Finally, triangle size of 1 mm is selected for the shell mesh of injected parts, and for the injection system which includes *sprue*, *runner*, and *gate*, smaller sizes were applied. Hence, triangle sizes 0.3 mm for sprue and runner and triangle 0.2 mm for gate were selected.

The simulation process is taking place by considering all the parameters into SolidWorks Plastic as shown in Table 3. There are 18 experiments with different combination of five parameters.

5 Result and discussions

5.1 S/N ratio approach

The S/N ratio evaluates the quality characteristic which is deviated from the desired value. The S/N ratio applies the average values to convert the experimental result into the value which is feasible for the evaluation characteristic of

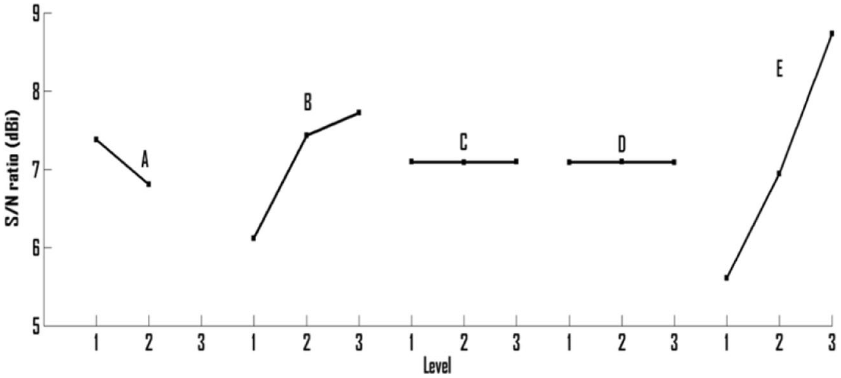

Fig. 3 S/N ratio response diagram based on simulation result

Table 6 Analysis of variance

Factor	*f*	*SS*	*MS*	*F*	*PC (%)*
A	1	1.473472	1.473472	629.3379	3.690974
B	2	8.785992	4.392996	1876.302	22.00847
C	2	0.000412	0.000206	0.088009	0.001032
D	2	0.000328	0.000164	0.070141	0.000823
E	2	29.64202	14.82101	6330.234	74.25178
Pool error	8	0.01873	0.033651	–	–
Total	17	39.92096	2.348292	–	–

an optimum parameter analysis. S/N ratio has three categories: *the nominal-the best*, *the smaller the better*, and *the higher the better* [15, 20]. Since the objective of this study is to reduce the short shot defect in injection molding via optimum level of each parameters, *the smaller-the better* quality characteristic has been selected which is defined by Eqs. 1 and 2:

$$S/N = -10log(MSD) \tag{1}$$

The MSD for the smaller the better quality characteristic can be stated by [20]:

$$MSD = \frac{1}{N}\left(\sum_{i=1}^{n} y_i^2\right) \tag{2}$$

where y_i is the value of short shot defect for that specific test and N is the total number of data points. The proposed method is to calculate the short shot possibility which equals the ratio of *simulated inlet pressure* to *maximum inlet pressure* for a specific injection machine as shown in Eq. 3. The maximum injection pressure for selected injection machine is 100 MPa. By increasing the ratio, the possibility of short shot defect increases. For instance, the simulated inlet pressure to fill the cavities via SolidWorks plastic is 56.51 MPa. Based on Eq. 3, the possibility of short shot for trial number 1 is the ratio of simulated inlet pressure (56.51 MPa) to the maximum inlet pressure (100 MPa). Hence, the smaller the ratio, the better is the objective of this study. The calculated results for short shot defect and *S/N* ratio have been determined and tabulated in Table 4.

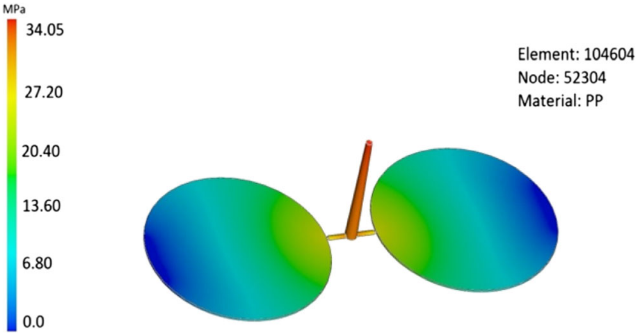

Fig. 4 Pressure at the end of the filling stage for trial number 5

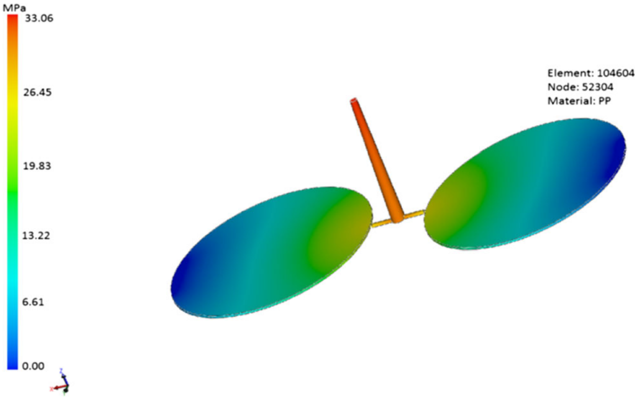

Fig. 5 Pressure at the end of the filling stage for trial number 9

$$\text{Possibility of short shot} = \text{simulated inlet pressure}\Big/\text{maximum inlet pressure} \tag{3}$$

From the data in Table 4, the average *S/N* ratio for response table can be calculated as shown in Table 5. Also, Fig. 3 is plotted using *S/N* response table for the possibility of short shot to determine the optimal levels of four process parameters and one geometric parameter.

Eighteen trials of simulation were taken into account and the result being presented in Table 4. The response table of *S/N* ratio and *S/N* diagram in Table 5 and Fig. 3 was created, respectively. From the S/N response in Table 5, it can be inferred that the larger value of Δ*T*, the more is the significance of each parameter in affecting short shot defect. Based on Table 1, the selected parameters are melt temperature (*E*), filling time (*B*), and gate type (*A*) followed by part cooling time (*C*), and pressure

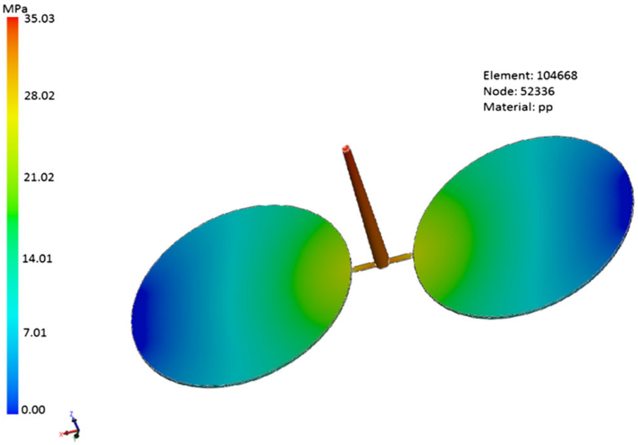

Fig. 6 Pressure at the end of the filling stage for trial number 17

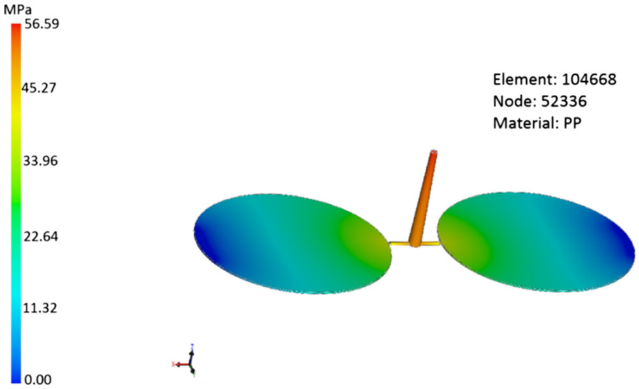

Fig. 7 Simulated inlet pressure for trial number 1

holding time (*D*). The optimum set of parameters can be evaluated from the S/N response diagram in Fig. 3 by selecting the highest level of S/N for each parameter. The result is a combination of A_1, B_3, C_3, D_2, and E_3. As mentioned before, by increasing the ratio of simulated inlet pressure to maximum inlet pressure, the possibility of short shot is increased. By using these sets of parameters in SolidWorks Plastics simulation, the ratio of simulated inlet pressure to maximum inlet pressure is 0.3306 which is the minimum possibility of short shot.

5.2 Analysis of variance

ANOVA can be used to determine the *percentage of contribution* (PC) for each factor. The largest value of PC indicates the most significant factor affecting the system performance. The PC of scheduling factors can be calculated as follows [20]:

1. *Degree of freedom*: The total degree of freedom (df_T), the degree of freedom of factor *A* (df_A), and the degree of freedom for error variance (df_E) are as follows:

$$df_T = (N-1) \tag{4}$$

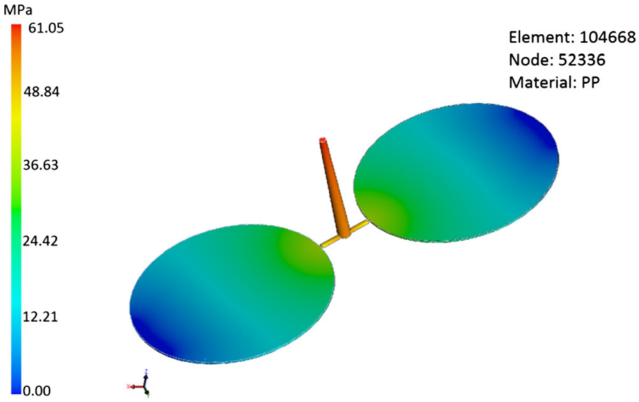

Fig. 8 Simulated inlet pressure for trial number 11

$$df_A = (K_A-1) \tag{5}$$

$$df_E = (df_T - \sum df_{\text{factor}}) \tag{6}$$

where *N* is the total number of experiments.

2. *Sum of squares*: The sum of the square of factor *A* (SS_A), the total sum of square (SS_T), and the sum of the square for error variance (SS_E) are calculated as follows:

$$SS_A = \sum_{i=1}^{K_A}\left(\frac{A_i^2}{n_{A_i}}\right) - \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N} \tag{7}$$

$$SS_T = \sum_{i=1}^{N} {x_i}^2 - \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N} \tag{8}$$

$$SS_A = SS_E = (SS_T - \sum SS_{\text{factor}}) \tag{9}$$

where x_i is a value at level (*1, 2, … N*).
n_{A_i} is the number of levels and.
A_i is a value at level *i* of factor *A*.

3. *Mean squares*: The mean square of factor *A* (MS_A), the total mean square (MS_T), and the mean square of error variance (MS_E) are

$$MS_A = \frac{SS_A}{df_A}, \quad MS_T = \frac{SS_T}{df_T}, \quad MS_E = \frac{SS_E}{df_E} \tag{10}$$

4. *F-ratio*: The value of the *F-ratio* of factor A (F_A) is calculated using the following equation:

$$F_A = \frac{MS_A}{MS_E} \tag{11}$$

5. *PC*: the percentage contribution of factor *A* is calculated using the following equation:

$$PC_A = \frac{SS_A}{SS_T} \times 100\% \tag{12}$$

The short shot data in Table 4 were analyzed via analysis of variance (ANOVA), and the significance rate of factors was evaluated by PC as shown in Table 6. ANOVA computes the quantities such as *degree of freedom (f)*, *sum of squares (SS)*, *mean square (MS)*, *F-statistic (F)*, and *percentage of contribution* (PC). It is clear that the significant factors in comparison with response Table 5 were mostly the same. The percentage weight of *melt temperature* was the most influential factor with a contribution of 74.251%, followed by *filling time* at 22.008%, and *gate type* at 3.690%. The contribution of part cooling time and pressure holding time is very low in comparison with melt temperature, filling time, and gate type.

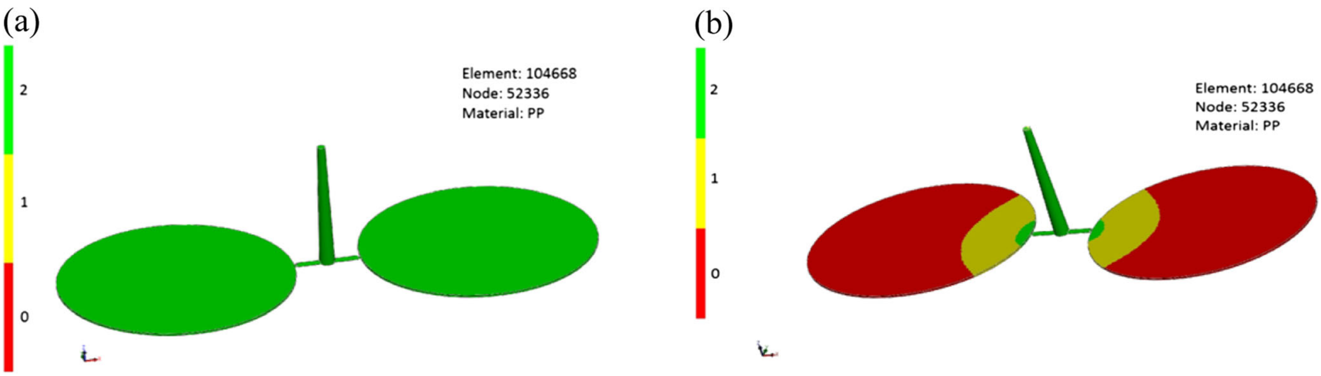

Fig. 9 a Ease of fill with minimum level of each parameters. b Ease of fill with 10% lower than minimum level

The lowest possibility of short shot in Table 4 is for trail numbers 5, 9, and 17. Based on the PC of each factor which is evaluated via analysis of variance, it can be concluded that the reason for having lowest possibility of short shot in trial numbers 5, 9, and 17 is because of *B* and *E* as significant parameters . Although the PC of *C* and *D* is very low in comparison with *A*, *B*, and *E*, the optimum level of each parameter which leads to a reduction in short shot possibility based on response Table 5 is A_1, B_3, C_3, D_2, and $E_{3.}$ The most significant factors which increase the possibility of short shot are *melt temperature* and *filling time* followed by *gate type* based on the *percentage of contribution*. By referring to the F-distribution statistic table, the $F_{0.05,\ 1,\ 17} = 4.45$ for evaluating the level of significant factor that equal to 0.05 (or 95% confidence level). Gate type (*A*) [F-statistic = 629.3379 > 4.45], filling time (*B*) [F-statistic = 1876.302 > 4.45], and melt temperature (*E*) [F-statistic = 6330.234 > 4.45] demonstrate that three parameters were significant to the short shot possibility. The simulated inlet pressure for trial number 5, 9, and 17 is shown in Figs. 4, 5, and 6, respectively.

In trial numbers 1 and 11, it can be concluded that the reason for having highest possibility of short shot is because of B and E being at the minimum level. Hence, any decrease in filling time and melt temperature increase the simulated inlet pressure which leads to an increase in possibility of short shot as shown in Figs. 7 and 8.

Reduction in level of different parameters from their minimum levels leads to difficulty in filling the cavities and finally short shot defect. As shown in Fig. 9a, *ease of filling analysis* for trial number 11 is still in green area which is in its most acceptable level. By reducing the minimum level of each process parameter to 20% for trial number 11, *ease of filling analysis* is in red area as shown in Fig. 9b. The red zone indicates the difficulty of filling the cavities for that zone which increase the possibility of short shot from 0.56 to 0.70 for trial number 11.

Table 7 Material properties of commercial polypropylene

Melt temperature	230°C
Max melt temperature	280°C
Min melt temperature	200°C
Mold temperature	50°C
Melt flow rate	20 cm^3/10 min
Max shear stress	250,000 Pa

6 Experimental set up

In this study, polypropylene has been considered as injected material for the injection of two circular plates with 100-mm diameter and 1-mm thickness. Material characteristics are listed in Table 7. To apply other materials for other applications, the material properties, namely *melt temperature*, *mold temperature*, *melt flow rate*, and *maximum shear stress* are important to consider which affect the injection process. Plastic materials with high viscosity increase the simulated inlet pressure leading to an increase in the possibility of short shot, and plastic materials with lower viscosity decrease the simulated inlet pressure leading to a decrease in the possibility of short shot. Some preparations were important to consider for the experiment. In manufacturing the mold tools, computer numerical control (CNC) milling machine, grinding machine, and drilling machine are the main machines to fabricate different components of the mold tools namely *top clamping plate*, *core and cavity plates*, *side plates*, and *bottom clamping plate*. Other components of the mold tools such as *sprue bush* and *guide bush* were purchased separately. The injection machine - Poolad- Bch series with maximum inlet pressure of 100 MPa was selected.

6.1 Mold design

Based on different concept in manufacturing the mold tools, a *two-plate mold* with two cavities and one parting line with runner, gate, and sprue but without ejector system was manufactured. The material for manufacturing core and cavity is steel CK45 with surface hardness 56 HRC. Two cavity plates with two different gate designs were manufactured as

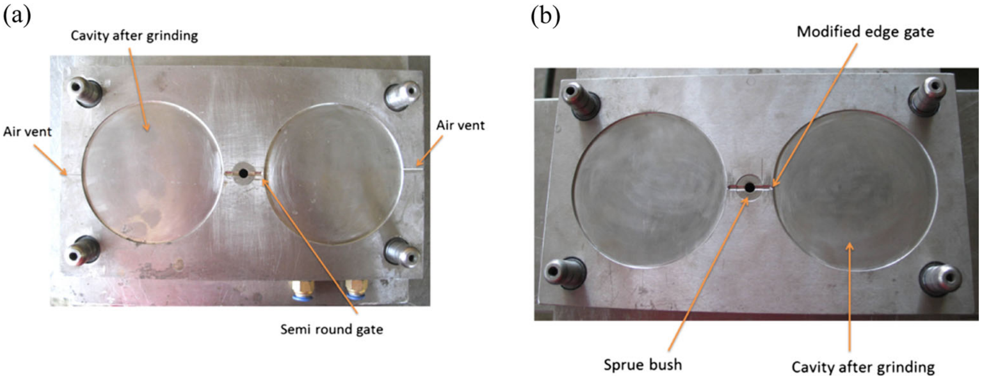

Fig. 10 a Cavity plate with round gate and air vent. b Cavity plate with modified edge gate

shown in Fig. 10. Provision was made for air vent to release the air from the cavity after closing the mold.

Cooling of injected parts happens when the molten plastic is injected into the cavity. The design and mechanism of cooling system are related to the design of the injected parts. Based on two circular plates, the cooling system has been manufactured as shown in Fig. 11a. Also, different components of mold tool namely *core* and *cavity* should be fixed on selected injection machine as shown in Fig. 11b.

6.2 Parameter and orthogonal array selection

Based on the plastic defect and simulation result, five different parameters were chosen in these experiments. Filling time, part cooling time, pressure holding time, and melt temperature were selected as process parameters and gate type as geometric parameter. Finally, based on the number of parameters and number of levels, L18 orthogonal array was used to evaluate the short shot defects in the injected parts. Also, S/N ratio with the definition of the smaller the better was selected.

6.3 Data collection for evaluation of short shot possibility

Eighteen trials were conducted via the injection machine, and the S/N ratio based on the result of short shot possibility was determined as shown in Table 8.

A few samples from 18 different trial numbers of injection process are shown in Fig. 12.

Based on the S/N ratio from Table 8, the average S/N ratio for response table is calculated as shown in Table 9.

The optimal levels of four process parameters and one geometric parameter for short shot defect are plotted as shown in Fig. 13 using S/N response Table 9. Finally, the significant parameters which increase the possibility of short shot are *melt temperature (E)*, *filling time (B)*, and *gate type (A)*. Part cooling time (C) and pressure holding time (D) have lowest PC among the other geometrical and process parameters. The optimum set of parameters can be evaluated from the S/N response diagram by selecting the highest level of S/N for each parameter. The optimum result is a combination of A_1, B_3, C_3, D_2, and E_3.

As mentioned before, using different parameters at levels less than the minimum levels leads to difficulty in filling the cavities and finally short shot defect. As shown

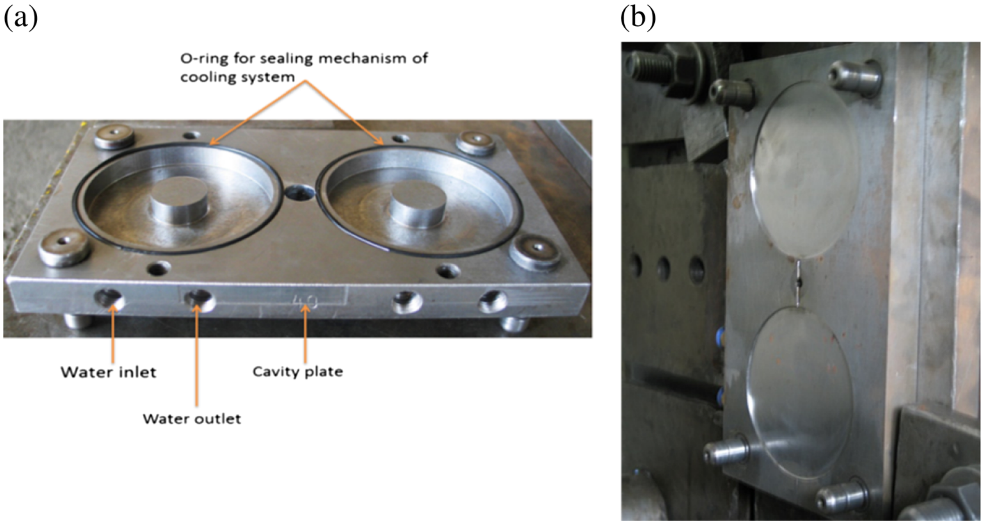

Fig. 11 a Cooling system of cavity plate for solidification of injected parts. b Fixed cavity plate on selected injection machine

Table 8 Determination of S/N ratio based on L18 orthogonal array

Experiment	A (Type)	B (S)	C (S)	D (S)	E (°C)	Simulated inlet pressure/maximum inlet pressure (MPa)	S/N (dB)
1	1	0.2	3	1	200	0.56	5.036
2	1	0.2	3.9	2	230	0.46	6.744
3	1	0.2	5	3	280	0.38	8.404
4	1	0.6	3	1	230	0.40	7.958
5	1	0.6	3.9	2	280	0.32	9.897
6	1	0.6	5	3	200	0.475	6.466
7	1	1	3	2	200	0.460	6.744
8	1	1	3.9	3	230	0.415	7.639
9	1	1	5	1	280	0.320	9.897
10	2	0.2	3	3	280	0.415	7.639
11	2	0.2	3.9	1	200	0.59	4.582
12	2	0.2	5	2	230	0.51	5.848
13	2	0.6	3	2	280	0.355	8.995
14	2	0.6	3.9	3	200	0.51	5.848
15	2	0.6	5	1	230	0.43	7.330
16	2	1	3	3	230	0.42	7.535
17	2	1	3.9	1	280	0.34	9.370
18	2	1	5	2	200	0.49	6.196

in Fig. 14, by reducing the minimum level of each process parameter to 10% for trial number 11, the possibility of short shot increased and short shot happened for the selected part. Uncontrollable factors in experiments lead to a small difference with corresponding ones from simulation, but both simulation results in Table 4 and experimental results in Table 8 validate the ratio of the possibility of short shot for the injected parts.

6.4 Analysis of variance

Based on Table 8 and the analysis of variance (ANOVA), the significance of each parameter is evaluated by *percentage of contribution* (PC) as shown in Table 10. The largest value of PC demonstrates the most significant parameter affecting the injection molding process. The procedure of ANOVA consists of four stages to obtain the

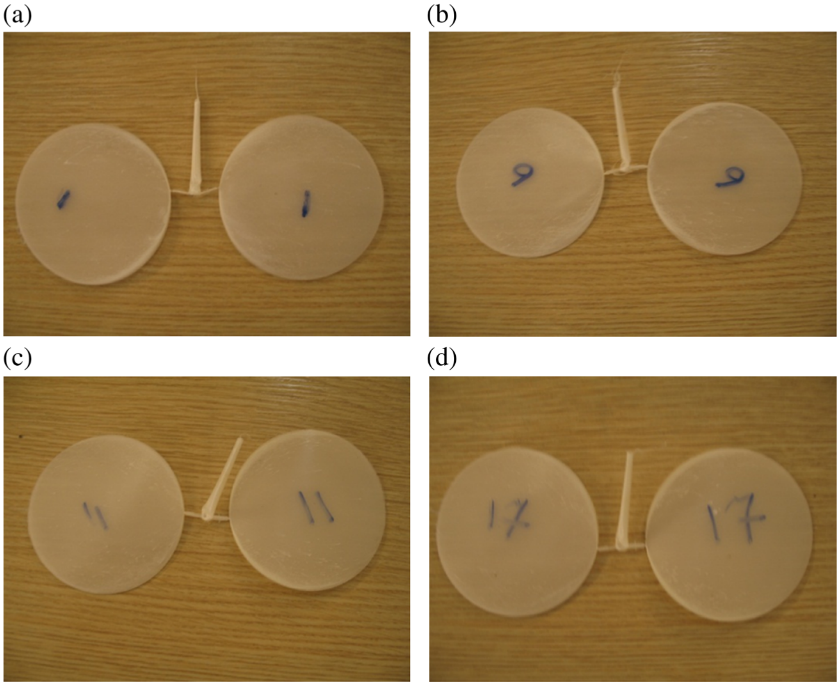

Fig. 12 Injected samples from trial numbers 1, 9, 11, and 17

Table 9 Response table of S/N ratio

	A (dB)	B (dB)	C (dB)	D (dB)	E (dB)
Level 1	7.643135686	6.376001	7.318228	7.362675	5.812474
Level 2	7.038529874	7.749431	7.347143	7.404466	7.176154
Level 3	0	7.897066	7.357127	7.255357	9.03387
Difference	0.604605812	1.521065	0.009984	0.107318	3.221396

contributing scheduling factors: *degree of freedom (f)*, *sum of squares (SS)*, *mean of squares (MS)*, and *percentage of contribution* (PC). All the ANOVA results are based on the calculations using Eqs. 5.7 to 5.12. The percentage weight of *melt temperature* was the most influential factor with a contribution of 75.04%, followed by *filling time* at 20.19%, and *gate type* at 3.93%. The contribution of *part cooling time* and *pressure holding time* is very low in comparison with *melt temperature*, *filling time*, and *gate type*. By referring to the F-distribution statistic Table 10, the $F_{0.05,\ 1,\ 17} = 4.45$ for evaluating the level of significant parameters that equal to 0.05 (or 95% confidence level). Gate type (A) [F-statistic = 48.89257 > 4.45], filling time (B) [F-statistic = 125.4874 > 4.45], and melt temperature (E) [F-statistic = 466.2789 > 4.45] demonstrate that three parameters were significant to the short shot possibility. The following is a sample calculation, using ANOVA equations.

Degree of freedom:

$$df_T = (N-1) = (18-1) = 17$$

$$df_{SR} = (\mathrm{K}_{SR}-1) = (3-1) = 2, \text{ for factor } (A)$$

$$df_E = (df_T - \textstyle\sum df_{\text{factor}}) = (17-(7+2+2+2+2+2)) = 0$$

Sum of squares:

$$SS_T = \left[\left(5.036^2\right) + \left(6.744^2\right) + \ldots + \left(6.196^2\right)\right] - \frac{\left[(5.036) + (6.744) + \ldots + (6.196)\right]^2}{18} = 41.81$$

$$SS_{SR} = \left[\frac{(5.036+6.744+8.404+7.958+9.897+6.466+6.744+7.639+9.897)^2}{9}\right] + \left[\frac{(7.639+4.582+5.848+8.995+5.848+7.330+7.535+9.370+6.196)^2}{9}\right] - \frac{\left[5.036+6.744+\ldots+6.196\right]^2}{18} = 1.645$$

$$SS_E = (41.817-(1.645+8.445+0.004+0.070+31.38+0.269)) = 0$$

Mean squares:

$$MS_T = \frac{41.817}{17}$$

$$MS_{SR} = \frac{1.645}{2} = 0.822$$

Percentage of contribution:

$$PC_{SR} = \frac{1.645}{41.817} \times 100 = 3.934\%$$

Finally, Tables 11 and 12 compare the experiments and simulation result in terms of *percentage of contribution* and *optimal level of each parameter*. It is clear that that PC for simulation results is very close to the experiments. Also, the

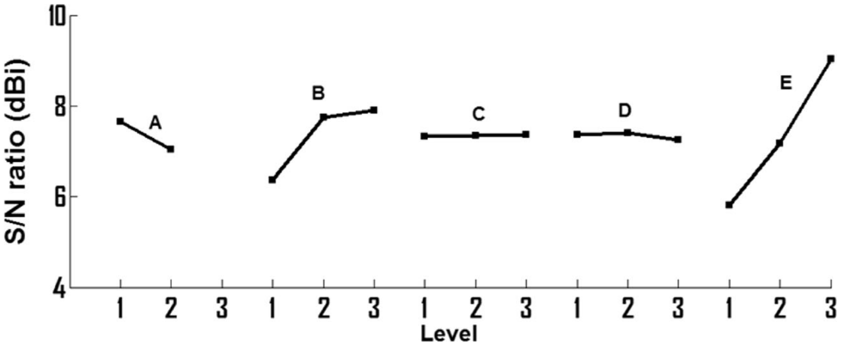

Fig. 13 S/N ratio response diagram based on experimental result

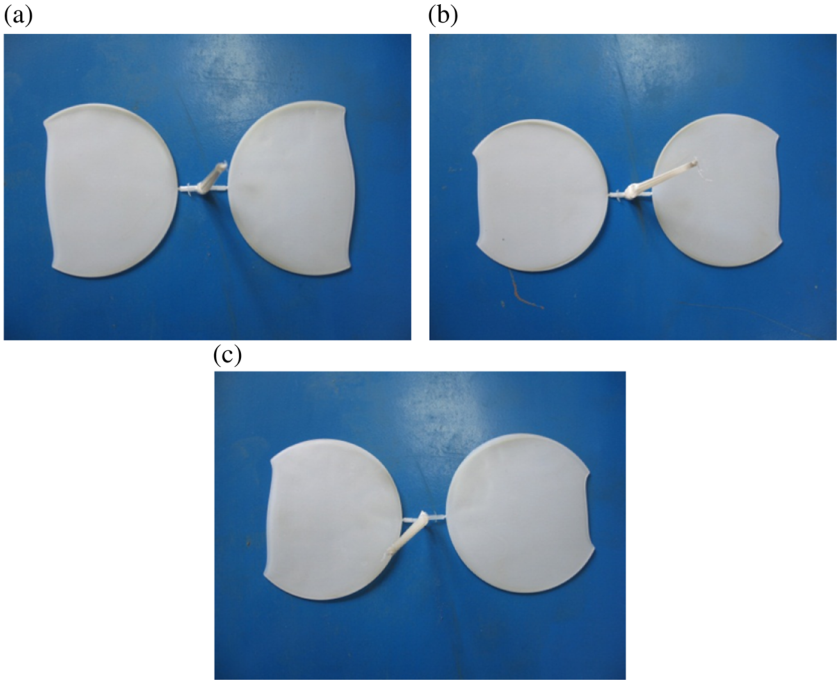

Fig. 14 Short shot defect by reduction in level of a filling time, b pressure holding time, and c melt temperature

optimal level of each parameter for experiments and simulation results is the same. The error margin was calculated by using the following equation:

$$\mathrm{MarginErroe}(\%) = \frac{(\mathrm{Experimentaltest}-\mathrm{Simulation})}{\mathrm{Simulation}} \times 100 \qquad (13)$$

7 Conclusion

The combination of simulation with Taguchi experimental design method offers an efficient and easy approach to determine the significant factors which affect the possibility of short shot in injection molding. The proposed approach for the analysis of short shot possibility based on process and geometric parameters was applied in order to reduce the short shot possibility in injection molding. The analysis of short shot possibility was conducted via SolidWorks Plastics, and finite element method (FEM) was employed in SolidWorks Plastics for simulation. L18 orthogonal array of Taguchi for different levels of each parameter was used based on simulation result. The significant level of each parameter was evaluated via ANOVA and S/N ratio. To validate the proposed method, the experimental setup was conducted for the injected parts.

Based on the simulation results, experiments, and also the statistical analysis of results, the following conclusions can be drawn:

- The significance rate of each parameter in both experiments and simulation result was very close together which signifies the robustness of proposed method in evaluation of short shot possibility. *Melt temperature* was the most influential parameter with a contribution of 74.25 and 75.04%, and *filling time* with a contribution of 22 and 20.19% followed by *gate type* with a contribution of 3.69 and 3.93% for simulation and experimental results, respectively. The percentage of contribution for *part*

Table 10 Analysis of variance

Factor	*f*	*SS*	*MS*	*F*	*PC*
A	1	1.645298	1.645298	48.89257	3.934471
B	2	8.445624	4.222812	125.4874	20.19638
C	2	0.004911	0.002456	0.072976	0.011745
D	2	0.070701	0.03535	1.050491	0.16907
E	2	31.38177	15.69089	466.2789	75.04456
Pool error	8	0.26921	0.033651	–	–
Total	17	41.81752	2.459854	–	–

Table 11 ANOVA for experiments and simulation result

	Experimental result (%)	Simulation result (%)	Error margin (%)
Gate type	3.934471	3.690974	6.59
Filling time	20.19638	22.00847	8.23
Melt temperature	75.04456	74.25178	1.067

Table 12 Optimal level of each parameter for experiments and simulation result

	Experimental result	Simulation result
Gate type	Type 1	Type 1
Filling time	1 s	1 s
Pressure holding time	2 s	2 s
Part cooling time	5 s	5 s
Melt temperature	280°C	280°C

cooling time and *pressure holding time* is very low in comparison with *melt temperature*, *filling time*, and *gate type* which did not consider as significant parameters. Hence, based on response table of S/N ratio, the optimum level of each parameter which leads to reduction in possibility of short shot is *gate type at level 1*, *filling time at level 3*, *part cooling time at level 3*, *pressure holding time at level 2*, and *melt temperature at level 3*. Finally, *melt temperature*, *filling time*, and *gate type* considered as significant parameters which affect the possibility of short shot in injected parts.

- By referring to the F-distribution statistic table of experiments, the $F_{0.05,\ 1,\ 17} = 4.45$ for evaluating the level of significant parameter that equal to 0.05 (or 95% confidence level). Gate type (A) [F-statistic = 48.89257 > 4.45], filling time (B) [F-statistic = 125.4874 > 4.45], and melt temperature (E) [F-statistic = 466.2789 > 4.45] demonstrate that three parameters were significant to the short shot possibility. By referring to the F-distribution statistic table of simulation results, the $F_{0.05,\ 1,\ 17} = 4.45$ for evaluating the level of significant parameter that equal to 0.05 (or 95% confidence level). Gate type (A) [F-statistic = 629.3379 > 4.45], filling time (B) [F-statistic = 1876.302 > 4.45], and melt temperature (E) [F-statistic = 6330.234 > 4.45] demonstrate the robustness of proposed method. Further research in this direction will provide more comprehensive guidelines for designers by evaluating other essential parameters of both process and geometric parameters which affect the short shot possibility in injection molding.

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