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Optimisation of Pipe Fitting in the Injection Moulding Process Using the Taguchi Method

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ABSTRACT

This paper presents the optimisation of the injection moulding process on a pipe fitting using the Taguchi method. This study optimises the injection moulding parameters that yield minimum sink marks and volumetric shrinkage in the injected pipe fitting. Five parameters: cooling time, melting temperature, packing time, packing pressure, and injection pressure, were considered in the simulation. Taguchi method with L27 Orthogonal array was employed to construct the Design of Experiment (DOE) for the simulation analysis. The main responses are sink marks and volumetric shrinkage. The main effect and ANOVA analysis were also studied. The results revealed that melting temperature was the most significant factor influencing sink mark response. However, packing pressure crucially affects the volumetric shrinkage of the injected pipe fitting part. The optimal injection moulding process can be achieved with a cooling time of 26.52 s, a melt temperature of 218 ℃, an injection pressure of 36.23 MPa, a packing pressure of 60 MPa and a packing time of 5 s.

Keywords: Injection moulding, Taguchi method, Optimisation, Simulation

1. INTRODUCTION

Thermoplastic is commonly used in injection moulding to produce various plastic parts in daily life [1]. Polyvinyl chloride (PVC) is a 'contested' versatile material used in construction. PVC is one of the most important plastic materials used worldwide in various phases of the construction industry, such as pipes, fittings and gutters, window profiles and doors, ceiling tiles, various furniture and upholstery applications and coatings for electrical cables. It is mainly because of its economy, durability, and assembly ease [2]. PVC softens if heated and hardens as it cools. It can be processed using conventional plastics processing techniques, such as extrusion, calendering, injection and blow moulding. PVC is one of the significant low-cost, high-volume commodity resins used today due to its economy and its excellent chemical and mechanical properties [3]. PVC can be processed into a wide variety of short-life or long-life products. With increasing consumption in recent years, the number of used PVC items entering the waste stream is gradually increased. There is considerable public concern about plastic waste, specifically PVC [4].

The injection moulding method is vital for providing plastic components with complex geometries [5]. The injection moulding process typically utilises the single-screw extrusion machine [6]. Forming the standard product with the injection moulding method depends on the material aspects, mould design, and method condition. For example, the housing of the mobile phone has a thin wall. These products shall become an agent and lighter for client comforts. However, the injection moulding operation goes to be robust if the wall thickness of plastic

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becomes agent due to the various warpage defects that are about to appear. To avoid these defects occurring, a testing procedure for that influential factor is required [7]. Thus, the proper controlling of the injection moulding parameters crucially affects the final result of the injected part.

The thermoplastic is injected into the mould until it forms the desired plastic part in the filling phase. The injection pressure and injection temperature are the factors that need to control in this phase. When through the packing phase, the shrinkage occurs on the injected part [8]. Thus, it needs to continue introducing the polymer into the mould to fill empty spaces. In the packing phase, the packing pressure and packing time is the parameters that should be controlled. Lastly, to achieve the ejection temperature of the part, the cooling phase is necessary to complete the process [9]. In this case, the parameters to control in this phase are mould temperature and cooling time. Besides, further data about injection moulding, mould basis and computer modelling can be found in the technical literature [10]. Thus, the control of the injection moulding process parameter can be achieved by using the optimisation methods, such as response surface methodology [11] and Taguchi Orthogonal array [12].

The objective of Taguchi is to improve control variables and lessen the affectability of building plans to wild elements (clamours). Taguchi proposed augmenting the S/N proportion because of lessening item differences around the objective esteem [13]. The quality trademark in the S/N proportion examination is that the smaller, the better. Taguchi technique was additionally utilised as a part of a few different attempts to locate the most influencing components on warpage and shrinkage [13]. Besides, the Taguchi strategy combined with principal component analysis (PCA) was used to recognise the impacts of preparing parameters and on the different mechanical properties of composites from virgin-reused Polypropylene (PP) mixes in different creations [14]. This approach maintained a strategic distance from expanding fillers and fragile aggravating strategies. Trials were conveyed to upgrade handling conditions, and the advanced mixes of preparing parameters were checked. The L9 Taguchi OA was used as a trial outline for the four controllable infusion forming methods: dissolve temperature, shape temperature, pressing weight, and infusion speed. The outcomes were figured as S/N proportions and then plotted and examined to locate the ideal conditions for infusion forming [14]. Therefore, the defects on the injected part can be minimised using the Taguchi method.

Several factors access the artefact appearance, such as the temperature of the mould and the melt temperature [15]. Assorted defects can be created during the injection moulding action if the abnormal ascendancy of the action parameter [16]. These defects frequently action during the accomplishment action in the assembly of the product. This is because the polymer is calmly accessible to the surrounding temperature, which affects the acknowledgement of the polymer composition. Proper processing parameters control is significant in injection moulding to ensure the injected part is free from unintended defects [17]. Therefore, this research concentrated on optimising injection moulding parameters for a pipe fitting product. The injection moulding software was applied in this study. In the simulation, polyvinyl chloride (PVC) was utilised as the material. Five processing parameters were considered in the design of the experiment using the Taguchi method. The sink marks and volumetric shrinkage of the injected pipe fitting were optimised according to the optimal control of processing parameters. The most influential factor to the sink marks and volumetric shrinkage was also studied.

2. MATERIAL AND METHODS

In this research, the pipe fitting product was constructed using Solidwork software. Figure 1 shows a three-dimensional pipe fitting model. The detailed dimensions are shown in Figure 2. The pipe fitting dimension is 3.6 cm in width and 3.2 cm in height. In the 3D modelling, the pipe fitting model is built as a solid part and then exported to the injection moulding software using the Initial Graphic Exchange Specification (IGS) format. Then, the model was imported into the injection moulding software, and the mesh elements were generated (Figure 3). The average aspect ratio of the mesh is 1.52, the match percentage is 90.2%, and the reciprocal percentage is 92%. The minimum requirement for the aspect ratio is below 3:1, and the minimum match and reciprocal percentage is 85%. The aspect ratio, match and reciprocal percentage of the pipe fitting model met the requirement in the software. Thus, the simulation model is reliable, and no error occurs in the simulation. The software suggested the gate location. The most suitable gate is located at the centre of the pipe fitting, as shown in Figure 3. The location of the sprue was specified at the best surface of the model. Direct sprue was used as a gate to know how the melt material flows into the model. A direct sprue gate is commonly used for single-cavity moulds. The direct sprue feeds material rapidly into the cavity with minimum pressure drop.

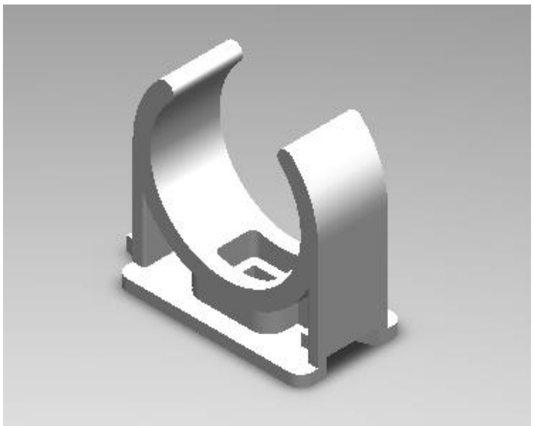
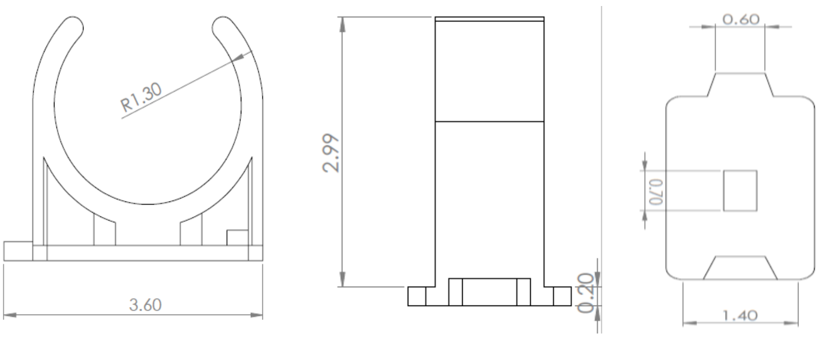


Figure 1: 3D pipe fitting model.



(a) Front view (b) Side view (c) Top view

Figure 2: Detailed dimension of the pipe fitting model.

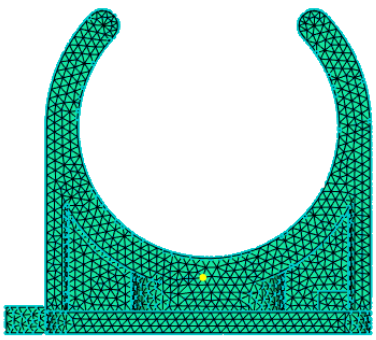


Figure 3: Meshing element and gate location (yellow point).

Polyvinyl chloride (PVC) was selected as the material for the pipe fitting model. With the chemical formula C2H3Cl, PVC is a vinyl polymer composed of repeating vinyl groups (ethenyl), having one hydrogen atom replaced by chlorine on alternate carbon atoms per repeat unit [2]. PVC material was considered due to its characteristics on the impact, chemical resistance and low-temperature resistance for pipe fitting. The methodology parameter was used to recognise their noteworthy by utilising different perspectives to decrease the procedure parameter. The number of levels and the range were chosen based on those parameters. Some levels could be utilised for the outline toward utilising the Taguchi method. In this study, three levels were considered for each factor. That chosen quality of each parameter is low, medium and high. Table 1 summarises the selected factors and levels for the Taguchi Orthogonal Array analysis.

Table 1: Selected factors and levels for Taguchi method.

Column	Factor	Level 1	Level 2	Level 3
A	Cooling Time (s)	26.52	30.06	33.74
B	Melting Temperature (°C)	206	212	218
C	Packing Time (s)	5	10	15
D	Packing Pressure (MPa)	60	80	100
E	Injection Pressure (MPa)	36.23	46.23	56.23

3. RESULTS AND DISCUSSION

The responses appeared after a complete run using the selected parameters from the simulation analysis. A total of 27 trials injection moulding process were completed using the simulation. The process setting was varied based on each trial, as suggested by Taguchi Orthogonal Array (OA). The simulations were performed based on the value of factors (cooling time, melt temperature, filling time, packing and injection pressure). The simulation in every trial gives different results in the response. Two responses, sink mark and volumetric shrinkage, were considered in this study. The Taguchi OA with the value of responses is summarised in Table 2.

The simulation results revealed that the combination of process parameters in trials 10, 11 and 12 yielded the lowest sink mark on the injected pipe fitting. The lowest sink mark value is 5.081. However, the highest sink mark value was spotted on trials 25, 26, and 27, with a value of 5.770. Besides, the lowest volumetric shrinkage (6.564) was noticed in trials 10, 11 and 12, and the highest was in trial 4 (7.894). The results indicated that the changes in the processing parameters crucially influenced the sink mark and volumetric shrinkage. The sink mark and volumetric shrinkage are unintended defects in the injection moulding process. Thus, the minimum value of these responses is preferable.

Main effect analysis generally shows the trend that influences the factors of the product. Main effect analysis was applied in this study by combining the parameter which gives the optimum quality effect on the pipe fitting. Two responses were calculated from Microsoft Excel using the main effect analysis formula. From the values of the responses, the main effect analysis was carried out to identify the optimal parameters that affect the model pipe fitting during the injection moulding. The values of each parameter will appear in the graph based on their selected levels. The highest value represents the most optimum parameter in the main effect graph.

Table 2: Taguchi OA with the value of responses.

Trial	Cooling Time (A)	Melt Temperature (B)	Packing Time (C)	Packing Pressure (D)	Injection Pressure (E)	Sink Mark	Volumetric Shrinkage
1	26.52	206	5	60	36.23	5.497	7.671
2	26.52	206	5	60	46.23	5.482	7.385
3	26.52	206	5	60	56.23	5.482	7.385
4	26.52	212	10	80	36.23	5.447	7.894
5	26.52	212	10	80	46.23	5.447	7.090
6	26.52	212	10	80	56.23	5.447	7.090
7	26.52	218	15	100	36.23	5.579	7.060
8	26.52	218	15	100	46.23	5.579	7.060
9	26.52	218	15	100	56.23	5.579	7.060
10	30.06	206	10	100	36.23	5.081	6.564
11	30.06	206	10	100	46.23	5.081	6.564
12	30.06	206	10	100	56.23	5.081	6.564
13	30.06	212	15	60	36.23	5.612	7.194
14	30.06	212	15	60	46.23	5.612	7.194
15	30.06	212	15	60	56.23	5.612	7.194
16	30.06	218	5	80	36.23	5.701	7.672
17	30.06	218	5	80	46.23	5.701	7.672
18	30.06	218	5	80	56.23	5.701	7.672
19	33.74	206	15	80	36.23	5.261	6.746
20	33.74	206	15	80	46.23	5.261	6.746
21	33.74	206	15	80	56.23	5.261	6.746
22	33.74	212	5	100	36.23	5.296	7.014
23	33.74	212	5	100	46.23	5.296	7.014
24	33.74	212	5	100	56.23	5.296	7.014
25	33.74	218	10	60	36.23	5.770	7.697
26	33.74	218	10	60	46.23	5.770	7.697
27	33.74	218	10	60	56.23	5.770	7.697

The main effect results for the sink mark with five parameters are plotted in Figure 4. The best combination of parameters can be determined by selecting the level with the highest value of each factor. The results show that the optimal process parameter combination for pipe fitting is A1, B3, C1, D1 and E1. The value of differences calculated for each parameter determines the most significant factor to the sink mark. Melt temperature (B) with 0.407 of difference value was identified as the most significant factor for the sink mark, followed by packing pressure (D) (0.304). The almost horizontal plot of injection pressure (E) indicated a slight influence on the sink mark. The highest main effect for each factor gave the optimal process conditions, which correspond to a cooling time of 26.52 s, a melt temperature of 218 °C, an injection pressure of 36.23 MPa, and a packing pressure of 60 MPa and a packing time of 5 s.

The main effect analysis was also performed on the volumetric shrinkage. The main effect results are plotted in Figure 5. The results revealed that the optimal combination of process parameters for volumetric shrinkage is similar to the sink mark. The optimal process parameter for pipe fitting is A1, B3, C1, D1 and E1. However, the most significant factor for the volumetric shrinkage is the packing pressure, with a 0.578 difference value. The second significant factor is melt temperature (0.546). According to the plots, other process parameters also affect the volumetric shrinkage. However, those effects are less significant than packing pressure and melt temperature.

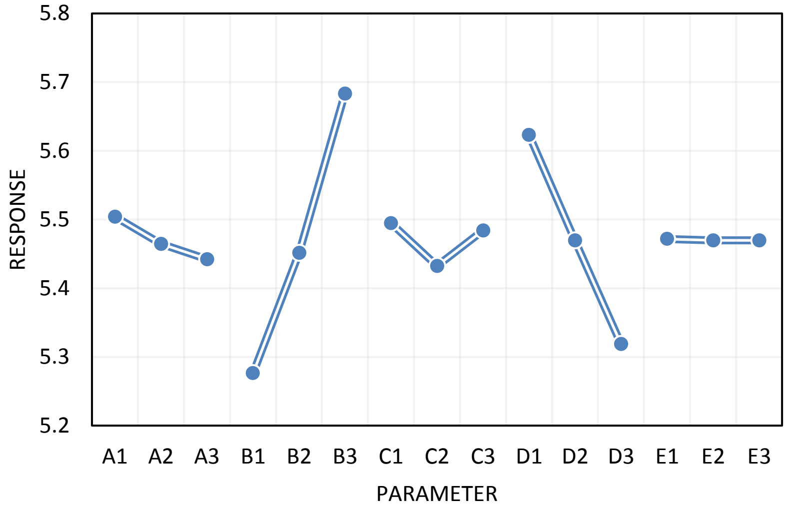


Figure 4: Main effect analysis on the sink mark.

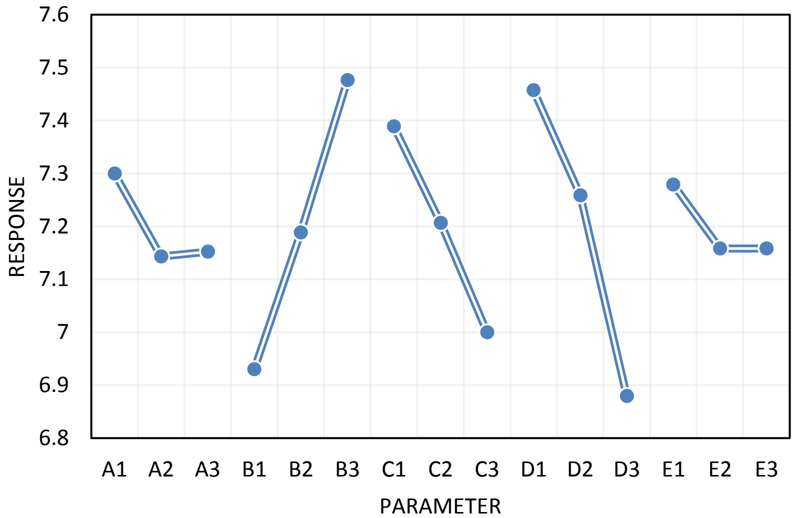


Figure 5: Main effect analysis on the volumetric shrinkage.

The most significant factor was confirmed again in the analysis of variance (ANOVA). In ANOVA, the F-ratio is the variance ratio, denoted as F-ratio in Table 3. F-ratio is used to identify the significant processing parameters by performing a significance test against the desired confidence level's error term. The highest value of the F-ratio will result in a high percentage contribution, indicating the relative importance ranking of the processing parameters in influencing the quality characteristics. In this study, the degree of freedom for the numerator is 2, and the denominator is 16. from the F-table at 0.01 level of significance (99% confidence), the obtained result $F_{(0.01(2,16))}$=6.2262. The ANOVA results indicated that four parameters, including packing pressure, melt temperature, cooling time and packing time, are considered significant because their F-ratios are greater than the values obtained from the F-Table of 99% confidence level. Table 4 summarises the ANOVA results of five processing parameters. Only three parameters, packing pressure, melt temperature and packing time, are considered significant due to their F-ratios higher than the values obtained from the F-Table of 99% confidence level. Besides, the previous study [18] also stated that melt temperature and filling pressure were statistically significant for injection moulding.

Table 3: ANOVA analysis for sink mark.

Parameter	DOF	Sum of Square	Variance	F-Ratio	Percentage
A	2	0.018	0.009	1064.920	1.473
B	2	0.750	0.375	45010.840	62.274
C	2	0.020	0.010	1186.720	1.642
D	2	0.417	0.208	25007.560	34.599
E	2	1.67E-05	8.33E-06	1.000	0.001
ERROR	16	0.0001	8.33E-06		0.011
TOTAL	26	1.205			100

Table 4: ANOVA analysis for volumetric shrinkage.

Parameter	DOF	Sum of Square	Variance	F-Ratio	Percentage
A	2	0.138	0.069	2.783	3.292
B	2	1.344	0.672	27.049	31.998
C	2	0.681	0.341	13.707	16.215
D	2	1.551	0.776	31.224	36.936
E	2	0.088	0.044	1.771	2.0954
ERROR	16	0.397	0.025		9.464
TOTAL	26	4.2			100

4. CONCLUSION

The injection moulding simulation was successfully carried out with 27 trials on the combination of processing parameters. Taguchi's method was utilised to determine the significant processing parameters and control the product's quality, especially manufacturing industry. Five processing parameters were considered in this research. The main effect and ANOVA analysis were studied to identify the most significant factor to sink mark and volumetric shrinkage. The optimal combination of the processing parameters was analysed. The current results found that melt temperature (B) and packing pressure (D) were the most significant factor for sink marks and volumetric shrinkage. The setting of processing parameters at a cooling time of 26.52 s, a melt temperature of 218 °C, an injection pressure of 36.23 MPa, a packing pressure of 60 MPa and a packing time of 5 s can be used to achieve the minimum sink mark and volumetric shrinkage. The current study is expected to be extended on various aspects, such as using different pipe fitting designs and other thermoplastic materials.

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