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Computational Study of Injection Molding Parameters to Minimize Shrinkage and Warpage Using the Taguchi Method

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Abstract: Injection molding is one of the processes for forming products from plastic materials using heat treatment and applying pressure into the mold (mold). The results products of injection molding must be of good quality with minimal shrinkage and warpage. The quality product of the injection molding process is affected by the parameters of the injection speed, injection pressure, injection time, and temperature on the barrel. The Taguchi method is one of the optimization methods that can be used to improve product quality. In Taguchi's robust design, a product will be designed to be strong and resistant to noise factors. This study aims to reduce shrinkage and warpage using Autodesk Moldflow simulation and the Taguchi method. In this study, there are 4 parameters with 3 levels each using the fractional factorial L9 Orthogonal Array Taguchi method and 4 times repetitions with consideration of the noise factor, the derivative of the sample also aims to determine fluctuations of data and obtain standard deviation values. The results of the study get the minimum shrinkage and warpage on the product, where the product resulting from optimization provides an increased (gain) S/N ratio between the initial design and the robust design. The optimization strategy found that I_S= 50 cm/s, I_P = 40 kg/cm², I_T = 5.5 seconds, T_{OB} = 190°C, give the optimum *shrinkage* with -7.922 in S/N ratio or improve 0.736 compared from initial design, and give the optimum *warpage* with 3.718 in S/N ratio or improve 0.854 compared from the initial design.

Keywords: Injection Molding, Shrinkage, Taguchi Method, Warpage.

Abbreviations: Injection Speed (I_S), Injection Pressure (I_P), Injection Time (I_T), Temperature on Barrel (T_{OB}), Deviation Temperature on Barrel (D_{ToB}), Deviation Injection Time (D_{IT})

Introduction

Consumption of thermoplastic has grown in line with the demand for innovative products such as spare parts, components for the automotive, household items and furniture industries (Miranda and Nogueira 2019). Injection molding is one of the processes for forming products from plastic materials with certain shapes and sizes by using heat treatment and pressure is given by injection into the mold (Rajalingam and Vasant 2016). Polypropylene is a thermoplastic polymer that is widely used because it is rigid, translucent, fatigue resistant, heat resistant, chemically durable (Farotti and Natalini 2018). The process of injection molding has several parameters that can be varied including injection speed, injection pressure, injection time, and temperature on the barrel. Errors of the factors of the injection molding process can cause product defects including shrinkage and warpage. Shrinkage causes a discrepancy between the dimensions of the mold and the resulting product so that it can affect the function of a product (Humbe and Kadam 2014). Warpage is a product defect that occurs in the form of convexity or curvature on the surface of the product (Koslowski and Bonten 2019).

Most of the production process by injection molding uses the trial and error method to find the best combination of parameters, the trial and error

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method requires high costs and takes a long time (Humbe and Kadam 2014). Autodesk Moldflow is software used fthe or visualization and simulation of plastic molding processes (Erdem 2017). Several methods that can be used to find the best parameters combination for maximum product quality are optimization methods. One method that can be used in optimization is the Taguchi method, the method can produce an optimum combination of parameters and improve the quality of products that are resistant to noise (robust design), the Taguchi method takes into account the response obtained from the mean, standard deviation & fluctuations that occur to produce S /N ratio Taguchi'sTaguchi method also uses the S/N ratio as a comparison of signal and noise to produce robust design (Su 2013). The S/N ratio has several categories for optimizing a processa or product design, namely: Smaller the Better, Nominal the Best, Large the Better (Bhargavkumar 2020).

Related research to reduce injection molding product defects has been carried out by Othman et al. (2017) about the experimental injection molding process and optimization using the Taguchi method with a response to the minimum warpage, this study resulted in the optimum combination of parameters for minimum warpage, namely temperature on barrel 175˚C, 40% packing pressure, 35% screw speed and 2s filling time. Another study by Sateesh et al. (2019) using a simulation method in the injection molding process of Water Meter Component products with deflection output response, shrinkage volumetric, cycle time and quality prediction result in the optimum combination of process parameters for minimum shrinkage percentage, namely melt temperature 280˚C, mold temperature 80˚C, and injection time 1.2s. Mukras (2020) doing research using optimization methods (CCD and Kriging Model) to minimize warpage & shrinkage from prthe oduct in the injection molding process experimentally with a combination of parameters injection speed, injection pressure, cooling time, packing pressure, mold temperature, packing time, melt temperature generated cycle time, warpage and volume shrinkage at 6.7%, 3.2%, and 8%.

In this work, the authors conducted experiments with simulatiomethodsod to minimize shrinkage and warpage on each sample with 4 repetitions to estimate fluctuations that occur by the combination of process parameters taking into account the noise factor.

Materials and Methods

Study aBirdbath bath products by UD. BINA AA, was used for this research with mold dimensions of 120.75 mm x 75 mm x 43.5 mm and a thickness of 2 mm as shown in (Figure 1). This product is made of polypropylene (PP), polypropylene material has density properties from 0.90-0.91 g/cm3, and has a melt flow index of 10.78 g/10 min.

Figure 1. Cavity Mould and Product Specimen.

Autodesk Moldflow Adviser was used in simulation observed the shrinkage and warpage defect on the plastic product. Simulation processes start with the development of the model using Computer-Aided Design (CAD).

Procedures

The experiment in this study started from the identification of injection molding parameters, formulating the problems encountered in the process of forming products with the injection molding process. Then proceed with the injection molding simulation process to get the shrinkage and warpage values. The results of data collection that have been obtained are then processed in the form of analysis of mean (ANOM), plot effects, result verification, and the last is an analysis of variance (ANOVA). The steps for injection molding simulation using Autodesk Moldflow Adviser software are:

a. ***Geometry Modeling***, geometric models created in CAD software and imported into simulation software.

b. ***Selection of Polymer Material**,* material selection is an important step of the injection molding simulation process which contains detailed information for material properties.
c. ***Setting the Conditions of Molding Process**,* the setting of process conditions is a representation of the actual conditions of the manufacturing process and production equipment, including parameters relative to the process and parameters relative to the machine.
d. ***Numerical Resolving**,* after completing the basic settings then run numerical calculations. The results will be displayed as graphics, text, animation, etc.

Data analysis

Design of experiment is a technique to find optimized process designs by studying their effects on performance and solve production problems by laying out investigative experiments. For this studythe, experiment is designed by using the Taguchi method. The range of parameters and noise factors used in the injection molding process at each level can be seen in (Table 1) and (Table 2). For the study of 4 process parameters with 3 levels, selected L9 orthogonal array and combined with noise factor so that it becomes a crossed array design.

Table 1. Injection Molding Control Parameters.

Parameters	Level 1	Level 2	Level 3
Injection Speed (I_S), cm/sec	40	45	50
Injection Pressure (I_P), kg/cm^2	40	45	50
Injection Time (I_T), seconds	3.5	4.5	5.5
Temperature on Barrel (T_{OB}), ^oC	190	200	210

Table 2. Noise Factor and Their Level.

Parameters	Level 1	Level 2
Deviation Temperature on Barrel *(D_{TOB})*, ^oC	+1	-1
Deviation Injection Time *(D_{IT})*, seconds	+0.1	-0.1

This study uses 4 times repetitions to determine the average fluctuation and estimation along with the standard deviation that occurs in each sample of the product, and this study used the smaller the better type S/N ratio which aims to minimize shrinkage and warpage. So the mathematical equation S/N ratio used in this study can be seen in Equation 1.

e. $$S/N_{STB} = -10.\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \approx -10.\log_{10}\left(y^2 + s^2\right) \quad (1)$$

Results and Discussion

Shrinkage and Warpage

The results of the shrinkage and warpage in this study use an orthogonal array L9 which can be seen in (Table 3) and (Table 4). Mean and stanthe dard deviation is obtained based on the results of 4 repetitions carried out on each sample from the injection molding process.

Table 3. Summary of Result Shrinkage.

					Noise Factors						
				D D_{ToB}	+1	+1	-1	-1			
				DI_T	+0.1	-0.1	+0.1	-0.1			
Parameter					**Shrinkage (%)**						
I_S	**I_P**	**I_T**	**T_{OB}**	**Exp**	**1**	**2**	**3**	**4**	**Mean**	**Stdev**	**Ratio**
40	40	3.5	190	**1**	2.836	2.859	2.841	2.851	2.847	0.010	-9.087
40	45	4.5	200	**2**	2.922	2.885	2.778	2.864	2.862	0.061	-9.136
40	50	5.5	210	**3**	2.772	2.852	2.755	2.828	2.802	0.046	-8.950
45	40	4.5	210	**4**	2.819	2.865	2.805	2.864	2.838	0.031	-9.062
45	45	5.5	190	**5**	2.485	2.568	2.477	2.487	2.504	0.043	-7.975
45	50	3.5	200	**6**	2.992	2.988	3.005	3.006	2.998	0.009	-9.536
50	40	5.5	200	**7**	2.566	2.641	2.556	2.651	2.604	0.049	-8.313
50	45	3.5	210	**8**	2.977	3.023	2.947	2.928	2.969	0.041	-9.452
50	50	4.5	190	**9**	2.657	2.672	2.644	2.688	2.665	0.019	-8.515

Table 4. Summary of Result Warpage.

					Noise Factors						
				D_{ToB}	+1	+1	-1	-1			
				DI_T	+0.1	-0.1	+0.1	-0.1			
Parameter					**Warpage (mm)**						
I_S	**I_P**	**I_T**	**T_{OB}**	**Exp**	**1**	**2**	**3**	**4**	**Mean**	**Stdev**	**Ratio**
40	40	3.5	190	**1**	0.8148	0.8376	0.8119	0.8247	0.822	0.012	1.699
40	45	4.5	200	**2**	0.8475	0.8475	0.8572	0.8582	0.853	0.006	1.385
40	50	5.5	210	**3**	0.8503	0.8612	0.8602	0.8613	0.858	0.005	1.328
45	40	4.5	210	**4**	0.7878	0.8153	0.7876	0.8026	0.930	0.257	1.955
45	45	5.5	190	**5**	0.6945	0.7062	0.6987	0.6939	0.698	0.006	3.119
45	50	3.5	200	**6**	0.9117	0.9267	0.9031	0.9203	0.915	0.010	0.767
50	40	5.5	200	**7**	0.7129	0.7112	0.7111	0.7128	0.712	0.001	2.950
50	45	3.5	210	**8**	0.8728	0.8839	0.8669	0.8829	0.877	0.008	1.143
50	50	4.5	190	**9**	0.7492	0.7622	0.7320	0.7590	0.751	0.014	2.490

Analysis of Optimal Parameters

Analysis of mean is used to analyze and determine the optimum combination of parameters based on the S/N ratio. The results from ANOM are then applied to an effect plot to determine the optimum combination of parameters to the output which can be seen (Figure 2) for the S/N ratio shrinkage and warpage.

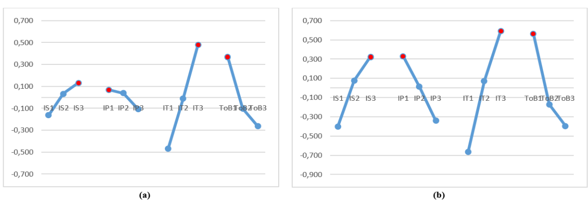

Figure 2. Main Effect Plot For S/N Ratio (a) Shrinkage (b) Warpage.

Based on (Figure 2a), we can see that the optimum combination (robust design) of parameters for shrinkage at injection speed level 3 (50 cm/second), injection pressure level 1 (40 kg/cm^2), injection time level 3 (5,5 seconds), and temperature on barrel level 1 (190 ºC). While in (Figure 2b), the optimum combination for warpage is located at injection speed level 3 (50 cm/second), injection pressure level 1 (40 kg/cm^2), injection time level 3 (5.5 seconds), and temperature on the barrel level 1 (190 ºC).

Verification of Robust Design

The results of the data from the robust design compared to the initial design will give an increase in the value of the S/N ratio on shrinkage and warpage of 0.736 and 0.854, respectively. The results of the comparison between the robust design and the initial design can be seen in (Table 5) for shrinkage and warpage.

Table 5. Summary of Result Verification Shrinkage and Warpage.

Design Parameters	Shrinkage			Warpage		
	Mean	Stdv	S/N Ratio	Mean	Stdv	S/N Ratio
Initial Design	2.716	0.116	-8.685	0.764	0.036	2.324
Robust Design	2.489	0.014	-7.922	0.649	0.004	3.178
Gain			0.736			0.854

Based on (Table 5), we can see that for the values from the mean, standard deviation, and S/N ratio on shrinkage and warpage with the combination of parameters from the initial design at injection speed (I_I) level 2 (45 cm/second), injection pressure (I_P) level 2 (45 kg/cm^2), injection time (I_T) level 2 (4,5 seconds), and temperature on barrel (T_{OB}) level 2 (200 ºC).

Analysis of Variance (ANOVA)

Analysis of variance in this study was used to determine the contribution given by each parameter to the output shrinkage and warpage which can be seen in (Table 6).

Table 6. ANOVA S/N Ratio for Shrinkage dan Warpage.

Parameters	Shrinkage				Warpage			
	SS	DoF	MS	C (%)	SS	DoF	MS	C (%)
I_S	0.138162	2	0.069081	6.35%	0.812829	2	0.406414	14.99%
I_P	0.054741	2	0.027371	2.51%	0.680616	2	0.340308	12.55%
I_T	1.343107	2	0.671554	61.69%	2.414527	2	1.207264	44.53%
T_{OB}	0.641267	2	0.320633	29.45%	1.514312	2	0.757156	27.93%
Error	-	-	-	-	-	-	-	-
Total	**2.177277**	8		100.00%	**5.422284**	8		100.00%

Based on (Table 6), it can be seen that the contribution given by the parameters injection speed, injection pressure, injection time, and temperature on the barrel from the analysis of variance using the S/N Ratio for shrinkage and warpage. The injection time parameter has the highest contribution on shrinkage and warpage.

Discussion

Based on (Figure 2a) and (Figure 2b) it can be seen that the optimum injection speed and injection time values are at level 3, this is because the increasing injection time will reduce product defects because the product is more robust or the product is solid to minimize defects (Wahyudi 2015). In addition, this is in line with the research of Shen et al. (2002) where injection speed has a large contribution on the quality of parts or plastic molding products. For injection pressure and temperature on barrel parameters in (Figure 2a) and (Figure 2b) the optimum value is produced at level 1, is because if the injection pressure is large and if the injection time is small it will produce the product short shot, but if the injection pressure is too small it will also cause the product not complete, therefore setting of the injection pressure parameter is not recommended to be too large and not too small, this is in line with research by Bhargavkumar (2020) showing that injection pressure is a parameter that has a large effect on product defects so that the injection pressure setting must be right. In addition, the high value of the temperature on the barrel will be one of the factors for the occurrence of product defects (Sreedharan and Jeevanantham 2018).

From the result of ANOVA at (Table 6) injection time (I_T) parameter has a significant effect on shrinkage because the longer the injection time, the more perfect the filling of the material, and it can be reduced shrinkage defects. This is in line with research by Wahyudi (2015) where a long injection time it will reduce product defects because it is stronger or there is a tendency for the product to be denser to minimize shrinkage defects. From the result of ANOVA at (Table 6) injection time (I_T) parameter has a significant effect on warpage because the longer the injection time, the more perfect the filling of the material, and it can be reduced warpage defects. This is in line with the research by Sateesh et al. (2019) where a long injection time will minimize the deflection value or warpage defects.

Conclusions

Using a computational method with Autodesk Moldflow Adviser and Taguchi method the optimum combination of parameters for minimal shrinkage and warpage was obtained, namely injection speed (I_S) level 3 (50 cm/second), injection pressure (I_P) level 1 (40 kg/cm2), injection time (I_T) level 3 (5.5 seconds), and temperature on barrel (T_{OB}) level 1 (190˚C). The increased S/N ratio that occurs in the robust design to the initial design for shrinkage is 0.736, and for the S/N ratio warpage is 0.854. The ANOVA table shows that injection time (I_T) has the largest contribution to the injection molding process in reducing shrinkage and warpage, respectively 61.69% and 44.53%, and the injection pressure (I_P) has the smallest contribution, namely 2.51%, and 12.55%.

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