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Optimization of Melt and Coolant Temperature on Defects of Injection Molded Toothbrush Handle

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ABSTRACT

The toothbrush handle is an injection molded product that rejects up to 10%. One of the factors that cause defects is the injection molding process settings, namely melting and cooling temperature. The purpose of this optimization is to obtain the optimum value of melt and cooling temperature parameters on product quality (minimum defects) of toothbrush handles using RSM. The methods used include simulation using ANSYS to obtain mold temperature, Autodesk Moldflow to obtain product defects and quality prediction based on input parameters of melt temperature (190^o , 200^o , and 210^o C) and coolant temperature (22^o , 24^o , and 26^o C), and Minitab 19 for RSM optimization. The simulation results that cooling temperature and melt temperature that are too low and high result in high defect values (weld line and shrinkage) in the product, resulting in low quality prediction values. Based on the results of the optimized simulation, the best injection molding setting is at a melt temperature of 200^oC and a cooling temperature of 24^oC which obtains a *toothbrush handle* product quality response variable of 78.04% with a minimum *weld line* value of 0.0277^o and a minimum *shrinkage* depth of 0.009 mm.

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Keywords: Optimization, Toothbrush Handle, Injection Molding, RSM.

1. Introduction

Optimization is a method to get the best results related to given parameters [1]. Optimization is one of the manufacturing processes used to ensure optimum results [2]. Some methods used to optimize a number of parameters include Taguchi and RSM methods [3]. Taguchi and RSM methods are statistical concepts used to improve the quality of a product [4]. The weakness of the Taguchi method is that if the experiment is carried out with many factors and interactions, there will be an update of some interactions by the main factor which results in the accuracy of the results and affects the observed characteristics [5]. RSM has the advantage that the mathematical model built meets all the inherent statistical assumptions so that the optimization is not biased [6]. RSM is used as a tool to study and optimize industrial processes, ranging from material selection, machine settings, to industrial process parameters [6].

Plastic is a synthetic material that can be deformed and can be maintained and hardened by adding other materials in a composite manner to it [7]. Injection molding is one of the techniques to form plastics into various shapes as desired [8]. Injection molding is a method used to produce a product by injecting liquid melt into a mold or mold which has the advantage of being able to produce products with complex geometric shapes, high accuracy, less material usage, high production capacity, and low cost [9].

Factors that affect the quality of injection molding products include cooling temperature and melt temperature [10], [11]. As in previous research on injection molding simulation, namely process simulation on the rear door of a vehicle that produces the best gating design and cooling system so as to produce mechanical properties of objects that are lightweight, strong, corrosion resistant, and economical [12]. Optimization of polypropylene injection process control parameters resulted in a product defect of 0.0062 with an optimal setting of 275° C injection temperature [13]. In auto lock-part products, the factor that affects warpage is the mold temperature and the parameter that can minimize defects is the melt temperature of 260° C [14]. Melt temperature in polypropylene affects the shrinkage defects of injection molding results. The higher the melt temperature, the more shrinkage defects are found in the product [15]. Melt temperature of 185° C produces 8.2 mm warpage defects and 10.3% shrinkage volume in automotive door panel products [16]. Volume shrinkage of 5.61% and shear stress at the wall of 0.17 MPa were produced in bowl-shaped products with a melt temperature setting of 180° C. Warpage in the product obtained the best value with a melt temperature setting of 260° C.

One of the injection molding products is a toothbrush handle. The reject value on this product reaches 10% which is caused by shrinkage defects during the production process. So, these changes are needed to reduce the reject value in this case which results in reducing losses due to production costs. The solution that can be offered is to simulate the cooling temperature and melt temperature with certain variations and optimize the results to determine product quality. So that a hypothesis formulation can be drawn, namely that there is a significant relationship between cooling temperature and melt temperature in improving product quality. The product quality parameters include quality prediction, weld line, and defects. The purpose of this optimization is to get the optimum value of cooling and melt temperatures that affect product quality using RSM.

2. Materials and Methods

2.1. Materials

The material used in the toothbrush handle is polypropylene with properties of specific gravity 0.89417 g/cm3, thermal conductivity 0.1731 W/m°C, and specific heat 2887 J/Kg° C [17].

2.2. Simulation

2.2.1. Pre-Processing

Pre-processing is the initial stage of simulation which consists of toothbrush handle design, parameter set-up in ANSYS and Moldflow. The toothbrush handle was designed using Autodesk Inventor with dimensions and specifications based on company standards to avoid deviations shown in Figure 1.

The boundary conditions in ANSYS include setting the coolant temperature (22°C, 24°C, and 26°C) and melt temperature (190°C, 200°C, and 210°C). The result obtained is the temperature on the mold. Autodesk Moldflow Adviser with varied mold temperature and melt temperature, injection time of 2 seconds, and injection pressure of 10 MPa. The results obtained in this second simulation include quality predictions, weld lines, and product defects.

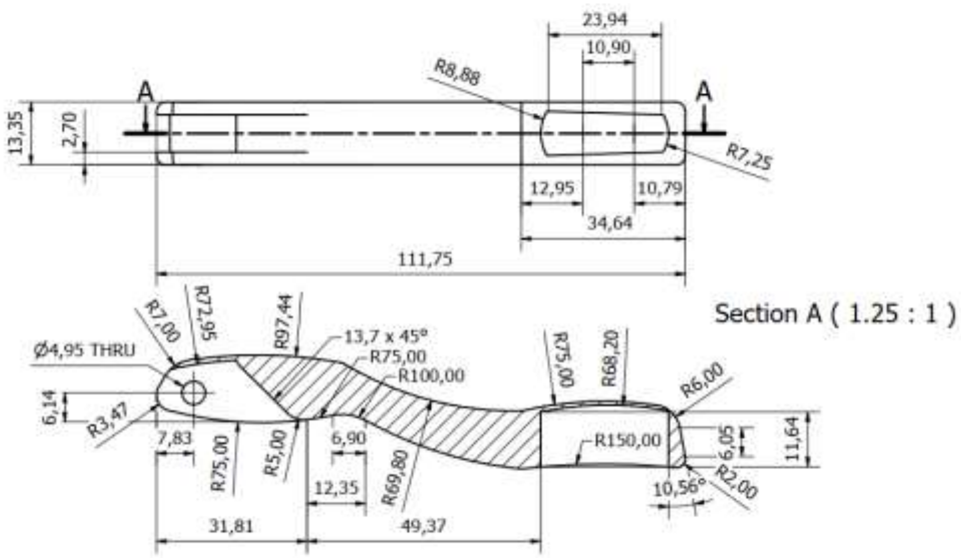


Figure 1. Toothbrush Handle Design

2.2.2. Processing

Processing is the calculation stage performed by the computer based on the conditions given in pre-processing.

2.2.3. Post-processing

Post-processing displays the results of the simulation process. ANSYS simulation obtained mold temperature results. The results of Moldflow simulation are predictions of quality, weld line, and defects. Optimization is carried out based on simulation data to analyze the optimal parameter variations that affect defects.

2.3. RSM Optimization

RSM optimization is used to analyze problems where several independent variables affect the response variable, and the goal is to optimize the response. The dependent and independent variables are modeled in the form of equations that are built based on experiments. The equation model can be shown as follows [18].

$$y = \beta_0 + \sum_{i=1}^{K} \beta_k \chi_k + \sum_{i=1}^{K} \beta_{kk} {\chi_k}^2 + \sum_{j=1}^{K-1} \sum_{k-2}^{K} \beta_{jk} \chi_j \chi_k + \varepsilon$$

where y is the dependent variable (product quality), x the independent variable (melt and coolant temperature), b the coefficient, and e the constant. RSM optimization in this study uses ANOVA.

To streamline experiments in building equations, one approach is needed through Central Composite Design (CCD), which has been widely used in RSM optimization. This design involves fractional factorials combined with axial points. CCD is an experimental design with a factor consisting of 2 levels that are enlarged by further points that give a quadratic effect [19]. This design starts with the same levels as design 2^k , plus an additional level consisting of *center points* and *star points* (α). The total combination of levels contained in the CCD is $2^k + 2^k + 1$, where k is the number of factors. In this study, the number of factors is 2 (cooling temperature and melting temperature) so that the number of experiments is 9 times. The process variables for the study are shown in Table 1.

Table 1. Process Variable

Factor	Code	Level		
		-1	0	1
Coolant Temp.	x1	22	24	26
Melt Temp.	x2	190	200	210

3. Result and Discussion

3.1. Mold temperature

Mold temperature is the initial temperature of the mold before pouring melted plastic. Setting the coolant and melt temperature for the mold temperature during the molding process will result in a better product. The mold temperature clearance range used for molding PP is 20-80 C. Based on the values in Table 2, the cooling and melt temperature settings for the mold temperature have met the standard. A higher mold temperature will be easier to fill due to its lower viscosity, but economically it will make the cycle time longer [20].

3.2. Quality predictions

Based on the simulation results in Table 2, the highest percentage of product quality prediction is 78.04% and the smallest is 64.5%. The highest percentage is at cooling temperature 24^o C and *melt temperature* 200^o C with *mold temperature* 41.7^o C, while the smallest percentage is at cooling

Table 2. Simulation Results

Coolant Temp.	Melt Temp.	Mold Temp.	Quality Prediction (%)	Shrinkage (mm)	Weld Line	Product Defect
	190	37,8	69,9	0,041	0,7139	WL, B, S
22	200	38,4	72,3	0,012	0,4918	WL, S
	210	39,8	74,5	0,017	0,3826	WL, S
	190	40,9	72,8	0,018	0,1963	WL, S
24	200	41,7	78,04	0,009	0,0277	WL, S
	210	42,5	74,4	0,013	0,1287	WL, S
	190	43,6	72,6	0,019	0,2503	WL, S
26	200	45,9	67,6	0,081	0,789	WL, B, S
	210	47,2	64,5	0,092	0,5948	WL, B, S

WL: Weld Line, B: Bubble, S: Shrinkage

temperature 26^{o} C and *melt temperature* 210^{o} C. The difference in the results of the product quality analysis in the graph above shows the parameters of cooling temperature and *melt temperature* along with the magnitude of the *mold temperature* which both affect the quality of good products. Good product quality is produced by variations in cooling temperature and optimal *melt temperature* because if the cooling temperature and *melt temperature are* too low, it causes more defects to arise and vice versa if it is too high, it causes *bubble* defects to be more dominant and the depth of shrinkage is getting bigger [21] therefore, the selection of optimal *set-up* parameters is needed to produce good product quality.

Figure 2 shows three quality levels: high, medium, and low. The simulation results in this analysis did not find a low-quality level, but there is still a medium quality level. Medium quality is still tolerable if this product is produced. The causes of medium quality are slow cooling and too hot melt temperature. The percentage of imperfect product quality is since there are still points of bubble, shrinkage and weld lines produced during the injection process that cannot close completely. Bubble is caused by melt temperature that is too hot while the cooling process is too fast [22].

3.3. Product Defects

The types of product defects include weld line, bubble, and shrinkage as shown in Table 2 for each coolant and melt temperature parameter. Defects directly affect the quality of the product produced.

The smallest weld line at a cooling temperature of 24^{o} C and a melt temperature of 200^{o} C with a minimum dimension of 0.0277 °, this is because the injected plastic material undergoes a cooling process too quickly while the melt temperature is not hot enough, when the front melt flow of the material meets the two ends of the melt flow of the material, the two ends of the plastic cannot be fused properly because the plastic melt has slowly hardened [21]. Figure 3 below shows the results of product defects in the form of weld lines. Weld lines are caused by two streams meeting, which is inevitable when the flow front splits and merges around the mold cavity or if the part has many gate locations. The presence of weld lines can indicate structural weaknesses or surface defects [23].

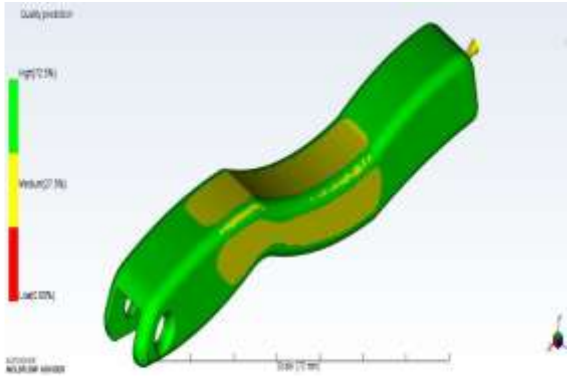


Figure 2. Quality product prediction

The simulation results of product quality analysis predict the occurrence of *bubble* defects in the product so that there are air cavities in the product, this is due to the product cooling process that is too fast. [24]. Product defects in the form of *bubbles* occur at *mold temperature* 37.8 ^{o} C with *melt temperature of* 190^{o} C and occur at *mold temperature* analysis 47.2 ^{o} *C melt temperature of* 210^{o} C obtained the point of greatest *bubble* occurrence which affects the weight of the toothbrush *handle* product. This type of damage is caused by the temperature of the molten plastic that is too hot with the increase in *mold temperature* which causes a greater temperature difference so that the cooling temperature is not able to cool properly in the product cooling process. This damage can be seen directly with the eye on plastic products that have a transparent color [25]. Figure 4 below shows the red-colored dots that indicate the predicted place of defects in the form of *bubbles in the* product, for the others there are not points of occurrence of many *bubbles*. The cooling temperature and *melt* temperature parameters cause differences in the number of *bubble occurrence* points, namely in the initial data analysis obtained cooling temperature data that is too cold so that it is predicted that there will be many *bubble* points found.

Shrinkage or product *shrinkage is* caused by the difference in thickness so that during *solidification the* plastic material will shrink. The analysis process carried out by the author has a very small product shrinkage. Damage that occurs with different shrinkage depths on average, the largest depth is 0.092 mm and the lowest is 0.009 mm. Product shrinkage of 0.092mm is due to suboptimal coolant temperature as the *mold temperature* rises and the *melt* temperature is too hot, namely the coolant temperature of 26° C and the *melt temperature of* 210° C with a *mold temperature of* 47.2° C.

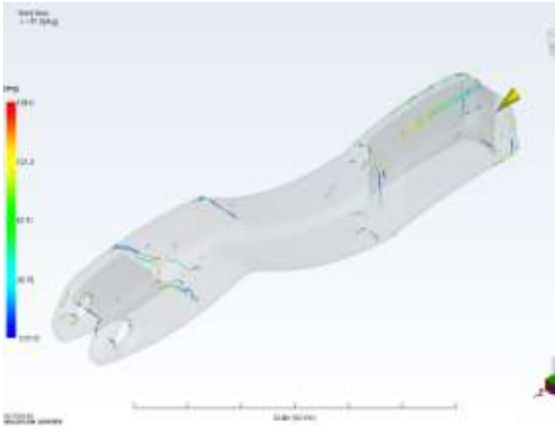


Figure 3. Weld line product

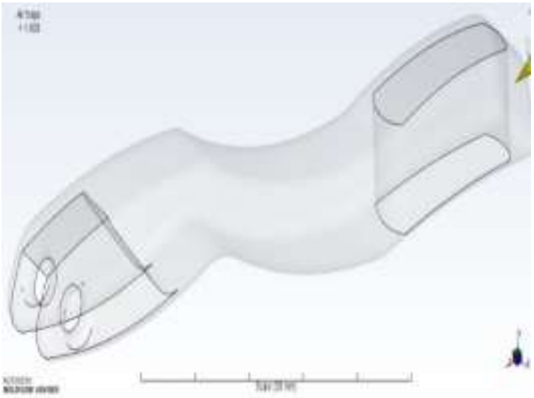


Figure 4. *Bubble defect*

The relationship graph above shows the coolant temperature which is less than optimal. The relationship graph above shows that cooling temperatures that are too low or high and *melt temperatures* that are too hot cause greater *shrinkage* volume, therefore the selection of optimal set-up parameters is needed to produce minimum shrinkage, this is because in hot conditions, the movement of *resin* molecules tends to be faster than cold conditions, which causes greater *shrinkage* when compared to products that come out of the *mold* in cold conditions because the movement of *resin* molecules tends to be slow so that the *shrinkage is* smaller because during the cooling process there is an equal distribution of heat transfer in the product [26].

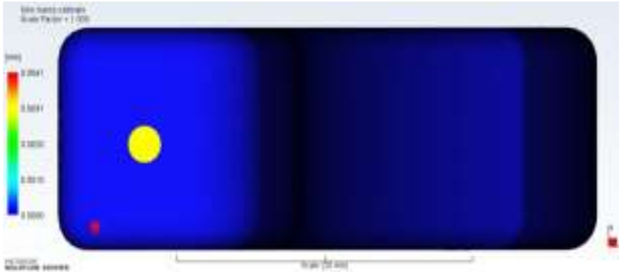


Figure 5. Shrinkage product

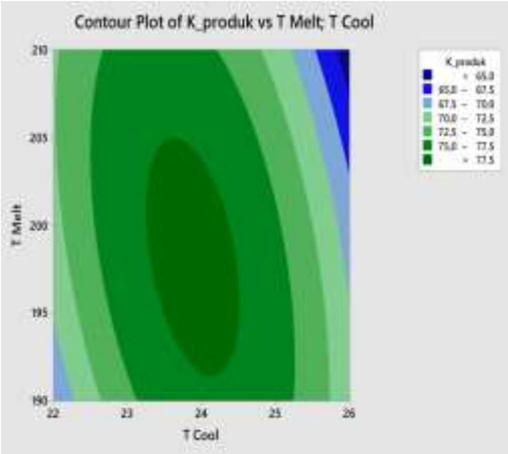
3.4. Product Quality Modelling and Optimization

Product quality modeling was analyzed using ANOVA. ANOVA in Table 3 is a model that is considered suitable for predicting the prediction results of product quality in the optimum *injection molding* process where the coefficient of determination (*R-Square*) value is 88.65% which indicates that the model can describe the quality prediction response data. The value of the cooling temperature response variable does not have a significant effect because the calculated F value is smaller than the F table which means that the cooling temperature does not have a big influence on the prediction of product quality, while the parameter of *melt temperature* has a contribution of 9.34% which means it has an influence on the prediction of product quality because the calculated F value is greater than the F table. The results of this simulation show that product quality does not have a significant influence on the cooling temperature parameter. The quality prediction modeling based on

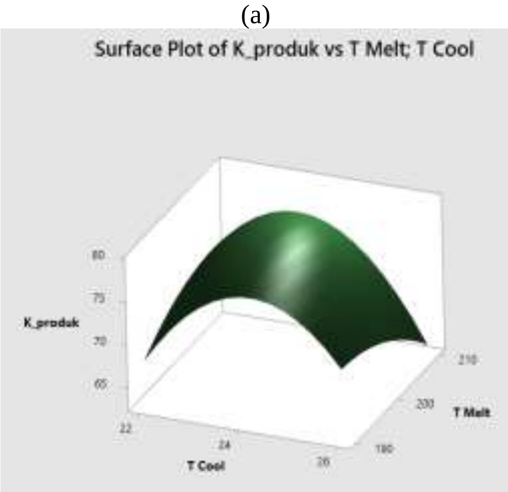
$$(Quality\ Prediction, y\ (\%)) = -1183 + 26{,}84\,x_1 + 9{,}37x_2 - 0{,}256\,(x_1)^2 - 0{,}0192\,(x_2)^2 - 0{,}0725\,x_1x_2$$

Table 3. ANOVA response

Source	DF	Contribution	F-Value	F-Table
Model (R-squared)	4	88,65%	10,94	4,10
Coolant Temp.	(2)	(0,04%)	0,03	4,96
Melt Temp.	(2)	(9,34%)	5,76	4,96
Error	8	11,35%		
Total	12	100%		



(a)



(b)

Figure 6. Quality Prediction (a) Contour Plot (b) Surface Plot

The results of the analysis with *Minitab* 19 *software* produce an image in the form of a *contour plot* graph that shows the RSM model to predict the effect of variables on the response of the quality prediction coefficient, namely cooling temperature and *melt temperature* as shown in Figure 6.

The curve plot in Figure 6 shows that the curve obtained is the maximum curve. The combination of the medium level of the cooling temperature and melt temperature factors will cause the maximum (optimum) response. The resulting contour plot consists of various color variations, each of which shows the results of the range of response magnitude where the dark green color on the contour plot shows the maximum condition, and this color range will outline the optimum point of the response variable to the quality prediction coefficient. The quality of toothbrush handle products will be achieved optimally if the coolant temperature is between 22^{o} C to 26^{o} C and melt temperature is between 190^{o} C and 210^{o} C while the mold temperature is at 40^{o} C, with parameter settings at these levels will obtain product quality of less than 65% to 80%.

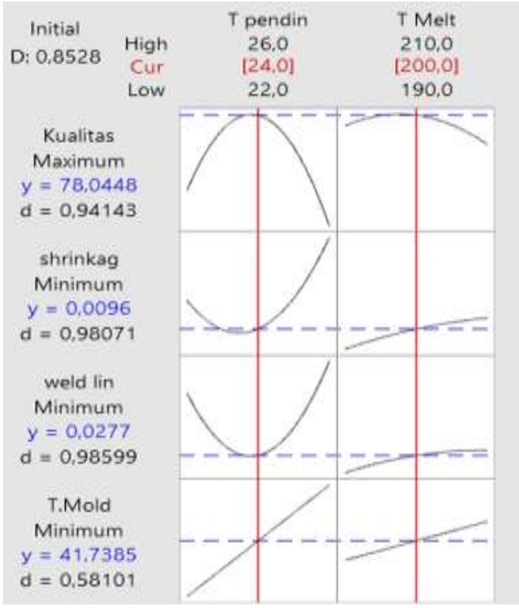


Figure 7. Optimization Response Prediction

The simulated melt and coolant temperatures produce defects in the product that include weld lines, bubbles, and shrinkage. Weld line and bubble are formed due to too high temperature plus too fast cooling process (indicated by low coolant temperature). Visually, weld line defects can be seen in the form of lines and bubbles have a transparent color on the product. Shrinkage is caused by a difference in thickness and temperature (coolant and melt) that is too high so that during solidification the plastic material will shrink. Melt and cooling temperatures that are too high and low tend to produce more dominant defects.

Variations in melt and cooling temperatures result in different quality prediction values. High defects result in lower quality values. Parameter optimization was run to obtain the settings with minimum defects and high predictions. Based on the Optimization Response Prediction graph in Figure 7, the optimal parameter settings of melt temperature 200^{o} C and coolant 24^{o} C were obtained which resulted in a toothbrush handle product quality of 78.04% with a minimum weld line value of 0.0277^{o} and a minimum shrinkage depth of 0.009 mm.

4. Conclusion

The importance of this optimization is to reduce the value of losses or rejections caused by defects.

Defects in the product are minimized by simulation and optimization methods with variations in cooling temperature and melt temperature. Cooling temperature and melt temperature have a significant effect on product defects and quality prediction. The simulation results state that cooling temperature and melt temperature that are too low and high result in high defect values (weld line and shrinkage) in the product, resulting in low quality prediction values. Based on the optimized simulation results, the best injection molding settings at melt temperature 200^{o} C and cooling temperature 24^{o} C resulted in a *toothbrush handle* product quality of 78.04% with a minimum *weld line* value of 0.0277^{o} and a minimum *shrinkage* depth of 0.009 mm.

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