Investigation of Simulation Injection Moulding Process using Response Surface Methodology (RSM)

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ABSTRACT

Plastic injection moulding simulation is one of the methods that can be used in the improvement of the quality of plastic goods hence minimizing the manufacturing costs. Defects may arise during the injection moulding process that could degrade the quality of the plastic product. Although the defects are impossible to eliminate, they can be minimized by optimizing the parameters in the injection moulding process. This study aims to identify the suitable parameters for the injection moulding process of an ABS material product for a car door handle storage box by using simulation. The Response Surface Methodology (RSM) through the Box-Behnken technique is employed to optimize the process parameters as well as improve the quality and productivity of moulded parts. The tools that were used in this study are Catia V5 for designing the part model and Moldex3D for the simulation of the injection moulding process. The injection moulding process parameters, in terms of mould temperature, melt temperature, injection pressure and cooling time and the output responses such as warpage and shrinkage of moulded parts are further analysed using Analysis of Variance (ANOVA) in Design-Expert software. Results show that the significant parameters in this study are melt temperature and cooling time. The optimal parameters were achieved at 220 °C melt temperature, 40 °C mould temperature, 64 MPa injection pressure and 22 s cooling time producing the warpage of 1.609mm and shrinkage of 6.379%. The confirmation test with error does not exceed 10% for warpage and shrinkage verified the validity of the model.

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1.0 Introduction

Injection molding can be considered as the popular and usual method of plastic processing as it is the most outstanding for native businesses to manufacture various goods like home appliances, electronics or electrical and lots of additional [1] [2] [3]. It is calculable that the method uses 32% of all plastics. The method is frequently utilized in both business and consumer goods mass production. Its monumental quality stems from a range of aspects, as well as its dependability and capability to manufacture complex shapes in an exceedingly single step with excellent tolerance [4]. Injection-molded plastic products have outgrown in popularity as a result of their lightweight, low price [5] and speed of shape formation, making them more popular than metallic products. The quality standards of injection molded products have become more firm as a result of enhanced plastic applications, increasing customer demand, and the speedy rise of the worldwide marketplace [6] [7]. Figure 1 below shows the example of automatic parts that are produced from the injection moulding process.



Figure 1: Application of injection moulding in automotive industries

Vishwakarma *et al*. [8] investigated the characterization of ABS material in their paper. ABS has many good properties which include lightweight, easy formability, etc. The focus of this research setup by Gurrier *et al*. [9] was to categorize and simulate the compunction impact in thin-wall molded cavities with a sloped geometry which comprised a variety of process parameters such as filling configurations and several kinds of material such as ABS and PP. A study on remote control covers by Kamber *et al*. [10] has been done to observe the forming responses of the polymer material of ABS. Processing temperature plays a significant role in this paper as high processing temperature causes a large amount of shrinkage and warpage. Optimization has been done in the previous study [11] [12] [5] to improve the

quality and productivity of molded parts. As a result, variable parameters such as mold temperature, melt temperature as well as output responses of shrinkage and warpage have been optimized. The parameters that could affect the warpage in the study of auto lock parts are mold temperature, followed by packing pressure [13]. Another researcher, [14] looked at the filling time to observe if it could help to reduce the molded part defects. It has been found that the longer the injection time is the most significant parameter that affects filling time.

Computer-aided analysis and engineering software (CAE) are being used to meet a competitive need for generating faster and less expensive injection moulded parts [15]. Current CAE systems used in injection molding process simulations and structural analysis of plastic components accept solid models as geometric inputs. By using simulation, Moldflow CAE software [13] [14] [16] can be used to estimate, improve as well as optimize the product design and manufacturing parameters for plastic by use of simulation. Maria *et al* [17] [18] did a simulation using the software package Moldflow plastic insight (MPI; Moldflow Autodesk, Autodesk, Inc.) used to evaluate the molding of a detachable front plate of a camera and a car bumper. Another researcher, Peter *et al* [19] did a combination of the iARD-RPR (Improved Anisotropic Rotary Diffusion Model with Retarding Principal Rate Model) which later has been implemented in Moldex-3D to predict fibre orientation within fibre-reinforced thermoplastics. Apart from the Hybrid mesh, Moldex3D offers another two additional mesh types which are eDesign and BLM meshes. All-inclusive, Hybrid mesh is much more outstanding for its accuracy of prediction compared to eDesign and BLM meshes.

Radhwan has mentioned in their paper [20] that the Taguchi methodology has been established to lessen warpage productivity by creating an adequate alternative towards the trial and error technique which leads to wastage. The error rate from the DoE result was minimal with less than 10%, hence the confirmation test was authorized. This paper [21] utilized ABS material in DoE and it has been proven that the experiment runs have been simplified by using the Taguchi technique, similar to the previous one. As previously mentioned by the authors [22] who utilized the RSM approach, a systematically experimental investigation has been conducted to observe the after impacts of factors in the molding along with their behaviour on shrinkage and warpage analysis. By referring to the ANOVA table, a quadratic model for cycle time analysis based on various process modifications has been developed. RSM [23] [24] [25] has been used to obtain mathematical modelling in analyzing optimal injection molding process parameters. It has been evaluated in this study that the output

response observed was warpage shrinkage. According to the study, ANOVA analysis demonstrates the significance of the curvature test for responses.

Nowadays, there are various types of Computer-Aided Engineering (CAE) software like Moldex3D, Catia, AutoCAD that are relevant to be used to perform the designing and simulation processes. These CAE-optimization devices were incorporated to save time and money [26]. For this project, Moldex3D has been utilized to perform various simulations such as meshing, parameter setting and injection molding simulation. The analysis focused on the simulation of the injection molding process of ABS material which uses Moldex3D to analyze the flow behavior of the material. The analysis of the variable parameters as well as the output responses were performed in Design of Expert software [27]. As a result, a 3D model of car door handle storage box is developed, the value of process parameters of injection molding is optimized and the verification runs is obtained. Numerous parameter settings such as melt temperature, mold temperature, injection pressure and cooling time must be thoroughly examine in order to produce a fine finish result. The parameters value changing might result in producing defects like shrinkage and warpage. Most manufacturers' difficulties and goals are to increase the product goods. The fundamental issue that many injection molding process manufacturers encounter is determining on how to control the parameters that consistently affect their goods. Thus, it is essential to find the effect of parameters changing towards the product that could minimize the defect.

2.0 Methodology

This research methodology section includes 3D modelling, experimental design, process simulation and analysis. All of the above mentioned elements insight into the overall research methodologies to execute the objectives of this study.

2.1 3D Design of Product

CATIA V5R20 software was used to model the car door handle storage box as shown in Figure 2 below. The dimension specification are the length of 140 mm, the width of 32mm and the height of 65mm.

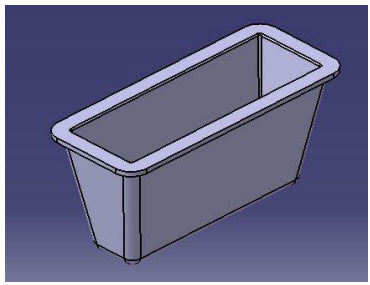


Figure 2: CAD model of a car door handle storage box in CATIA V5R20

2.2 Thermoplastic material

The standard material used for this product is ABS POLYFLAM RABS 90000 UV5 manufactured by A.Schulman in Moldex3D software. The properties of thermoplastic are shown in Table 1 below.

Table 1: Physical and mechanical properties of ABS material

Properties	Value
Melt volume-flow rate (cm^3/10min)	30
Elastic Modulus (MPa)	2.2e10^4
Tensile Modulus (MPa)	2200
Poisson Ratio (v)	0.38
Density (kg/m^3)	1200

2.3 Gating System

Moldex3D R14 software has been used to do the design the gating system of the model as shown in Figure 3. The gate chosen is a single side gate as the model is quite thin. The specification for the side gate is 3mm in diameter.

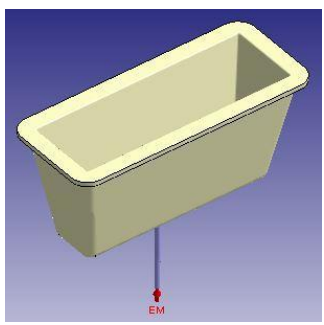


Figure 3: Gating system of the CAD model in Moldex3D R14

2.4 Design of Experiment

The output responses data of warpage and shrinkage can be achieved by selecting the most appropriate setting for the injection moulding process [28]. In this study, Design-Expert software (Version 22.0.6, 2023, Stat-Ease, Inc.MN USA) has been utilized as a tool for experimental design. Box-Behnken Design under Response Surface Method with four process parameters [12] such as melt temperature, mold temperature, injection pressure and cooling time has been chosen as the experimental design. The values of each parameter were from material ABS POLYFLAM RABS 90000 UV5 manufactured by A.Schulman are illustrated in Table 2 below.

Table 2: Parameters and levels for Design of Experiment

Process Parameters	Minimum	Maximum
Melt temperature, A (°C)	220	250
Mold temperature, B (°C)	40	60
Injection pressure, C (MPa)	50	100
Cooling time, D (s)	16	22

2.5 Response Surface Methodology

Response Surface Methodology (RSM) is one of the methods used to obtain mathematical modeling of regression that assist in optimizing the process parameters. This approach has been commonly utilized and very crucial for analyzing the phase [29]. In addition, this method demonstrates the significant relationship between process parameters and output responses [24].

2.6 Analysis of Variance

The result of the mathematical modelling obtained from RSM regression will later be analyzed using Analysis of Variance (ANOVA) in the Design-Expert software program. ANOVA is used to define the most significant factors among all the process parameters that will affect the output responses of warpage and shrinkage [18][24][30].

3.0 Results and Discussion

3.1 Simulation Analysis

The data results of warpage and shrinkage have been obtained from the simulation analysis in Moldex3D R14 software as tabulated in Table 3 below. The process parameters were set accordingly to DOE which generates a total number of 29 runs.

Table 3: Parameter setting in DOE

Runs	Melt Temperature, A (°C)	Mold temperature, B (°C)	Injection pressure, C (MPa)	Cooling time, D (s)	Warpage (mm)	Shrinkage (%)
1	220	50	75	16	1.679	6.67
2	235	50	100	16	1.843	7.235
3	235	50	100	22	1.792	7.041
4	220	50	75	22	1.629	6.536
5	235	40	75	16	1.843	7.235
6	235	50	75	19	1.82	7.154
7	250	60	75	19	1.991	7.705
8	250	50	50	19	1.991	7.779
9	250	40	75	19	1.99	7.774
10	220	40	75	19	1.657	6.585
11	235	60	75	22	1.794	7.049
12	235	60	75	16	1.847	7.248
13	250	50	75	16	2.016	7.881
14	235	50	75	19	1.82	7.154
15	235	50	50	16	1.851	7.282
16	250	50	75	22	1.96	7.66
17	235	40	100	19	1.821	7.147
19	235	60	100	19	1.821	7.147
20	235	50	75	19	1.82	7.154
21	220	60	75	19	1.656	6.574
22	250	50	100	19	1.983	7.69
23	235	40	50	19	1.819	7.151
24	235	50	75	19	1.82	7.154
25	235	40	75	22	1.791	7.043
26	235	60	50	19	1.819	7.233
27	220	50	100	19	1.657	6.591
28	235	50	75	19	1.82	7.154
29	235	50	50	22	1.795	7.064

Figure 4 and Figure 5 shows Run 4 that when the melt temperature of 220 °C and the mold temperature of 50 °C, warpage and shrinkage were at their minimum values of 1.629 mm and 6.536 %. The warpage and shrinkage were at their maximum values of 2.016 mm and 7.881 % at Run 13 when the melt temperature was 250 °C and the mold temperature was 50 °C as shown in Figure 6 and Figure 7 below.

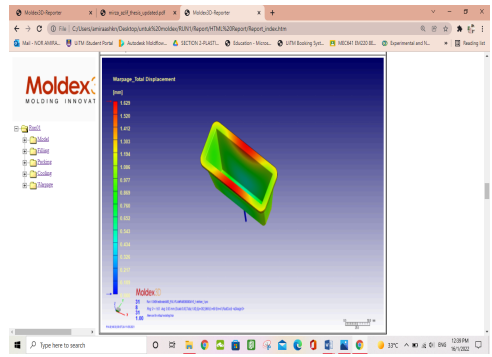


Figure 4: Minimum value of warpage at Run 4

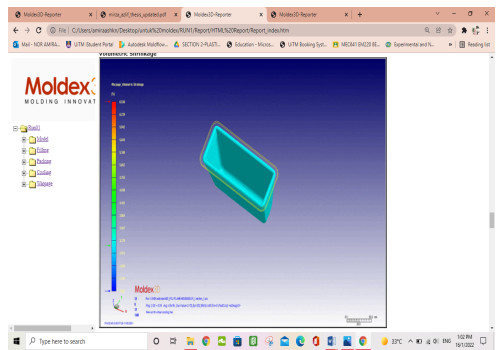


Figure 5: Minimum value of shrinkage at Run 4

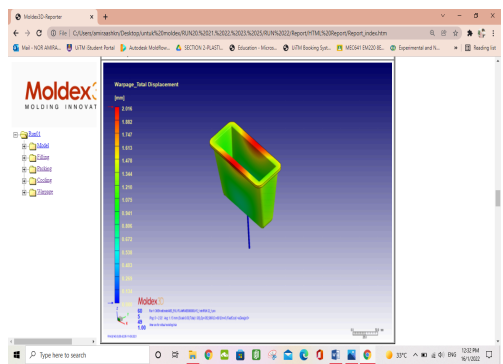


Figure 6: Maximum value of warpage at Run 13

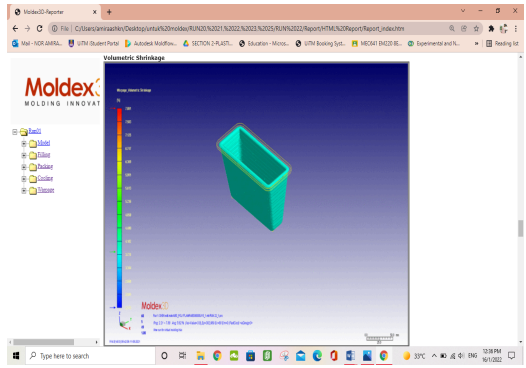


Figure 7: Maximum value of shrinkage at Run 13

3.2 Regression Model Analysis

Regression analysis or mathematical modelling was established as represented in Eq. 1 for warpage and Eq. 2 for shrinkage. This is to study the significant relationship between warpage and shrinkage and all process parameters which are melt temperature (A), mold temperature (B), injection pressure (C) and cooling time (D).

$$Warpage = 1.82 + 0.1666\ A + 0.0006\ B - 0.0009\ C - 0.0265\ D + 0.0005\ AB - 0.0029\ AC - 0.0015\ AD - 0.0002\ BD + 0.0013\ CD + 0.0020\ A^2 + 0.0004\ B^2 - 0.0001\ C^2 - 0.008\ D^2$$

Warpage =1.82+0.1666 A+0.0006 B-0.0009 C-0.0265 D+0.0005 AB-0.0029 AC-0.0015 AD-0.0002 BD+0.0013 CD+0.0020 A^2+0.0004 B^2-0.0001 C^2-0.008 D^2

(1)

Shrinkage=7.15+0.5782 A+0.0017 B-0.0210 C-0.0965 D-0.0145 AB-0.0214 AC-0.0217 AD-0.0205 BC-0.0017 BD+0.0060 CD+0.0148 A^2-0.0037 B^2+0.0042 C^2+0.0029 D^2

(2)

3.3 ANOVA Analysis

Based on the performed simulation analysis in by referring to DOE settings in Table 3, ANOVA has been generated as shown below. Table 4 and Table 5 below indicate that the model of car door handle storage box is significant for both warpage and shrinkage as the probability of P-value obtained is less than 0.05. If the P-value is greater than 0.1, the model is not significant.

It has been found that the melt temperature and cooling time is the significant parameters that lead to warpage and shrinkage. The result obtained is similar to Hazwan *et al*. [24] that discovered the most significant parameters that contributed to warpage is melt temperature, followed by cooling time.

Table 4: ANOVA for quadratic model of warpage

Source	**Sum. of squares**	**df**	**Mean square**	**F-value**	**P-value**	
Model	0.3128	14	0.0223	5166.51	< 0.0001	significant
A-Melt Temperature	0.2777	1	0.2777	64221.09	< 0.0001	
B-Mold Temperature	4.083E-06	1	4.083E-06	0.9443	0.3489	
C-Injection Pressure	8.867E-06	1	8.867E-06	2.05	0.1757	
D-Cooling Time	0.0084	1	0.0084	1948.87	< 0.0001	
AB	1.000E-06	1	1.000E-06	0.2313	0.6386	
AC	0.0000	1	0.0000	4.95	0.0445	
AD	9.000E-06	1	9.000E-06	2.08	0.1728	
BC	0.0000	1	0.0000	0.0000	1.0000	
BD	2.500E-07	1	2.500E-07	0.0578	0.8137	
CD	6.250E-06	1	6.250E-06	1.45	0.2507	
A^2	0.0000	1	0.0000	5.55	0.0348	
B^2	8.299E-07	1	8.299E-07	0.1919	0.6685	
C^2	5.854E-08	1	5.854E-08	0.0135	0.9092	
D^2	3.672E-06	1	3.672E-06	0.8492	0.3736	
Residual	0.0001	13	4.324E-06			
Lack of Fit	0.0001	9	6.246E-06			
Pure Error	0.0000	4	0.0000			

Cor Total	0.3128	27

Table 5: ANOVA for quadratic model of shrinkage

Source	**Sum. of squares**	**df**	**Mean square**	**F-value**	**P-value**	
Model	3.80	14	0.2717	508.81	< 0.0001	significant
A-Melt Temperature	3.34	1	3.34	6260.33	< 0.0001	
B-Mold Temperature	0.0000	1	0.0000	0.0688	0.7972	
C-Injection Pressure	0.0044	1	0.0044	8.29	0.0129	
D-Cooling Time	0.1117	1	0.1117	209.25	< 0.0001	
AB	0.0008	1	0.0008	1.57	0.2316	
AC	0.0011	1	0.0011	2.14	0.1674	
AD	0.0019	1	0.0019	3.54	0.0824	
BC	0.0017	1	0.0017	3.15	0.0994	
BD	0.0000	1	0.0000	0.0229	0.8819	
CD	0.0001	1	0.0001	0.2696	0.6123	
A^2	0.0013	1	0.0013	2.41	0.1444	
B^2	0.0001	1	0.0001	0.1645	0.6917	
C^2	0.0001	1	0.0001	0.1941	0.6667	
D^2	0.0001	1	0.0001	0.0992	0.7578	
Residual	0.0069	13	0.0005			
Lack of Fit	0.0069	9	0.0008			
Pure Error	0.0000	4	0.0000			
Cor Total	3.81	27				

The fit statistics for both output responses of warpage and shrinkage were shown in Table 6 below. It has been found that the value of R^2 for warpage is 0.9998 which is in reasonable agreement with Adjusted R^2 of 0.9996. This is similar to the value of R^2 for shrinkage which is 0.9982, therefore it is in reasonable agreement with Adjusted R^2 of 0.9962. To sum up, as both the value of R^2 for warpage and shrinkage is above 90%, the mathematical model of regression analysis in Eq. 1 and Eq. 2 can be applied to identify the prediction values of the responses limited to the range of the parameters used.

Table 6: Fit statistics for warpage and shrinkage

Warpage		Shrinkage	
Std. Dev.	0.0021	Std. Dev.	0.0231
Mean	1.83	Mean	7.18
C.V. %	0.1138	C.V. %	0.3218
R^2	0.9998	R^2	0.9982
Adjusted R^2	0.9996	Adjusted R^2	0.9962
Predicted R^2	0.9988	Predicted R^2	0.9877
Adeq Precision	253.8017	Adeq Precision	79.7800

3.4 3D Surface Analysis

Design expert software can also be used to study the effect of process parameters on its respective output responses. The model graph of 3D surface response were being demonstrated to investigate the significant relationship between melt temperature, mold temperature, injection pressure and cooling time with respect to warpage and shrinkage as shown in Figure 8 and Figure 9 below. Both the 3D surface graph indicate a linear pattern. Figure 8 shows the highest value of warpage of 2.016 mm when the melt temperature were at 250 °C and the mold temperature at 40 °C. Furthermore, the lowest value of warpage was 1.629 mm when the melt temperature were 220 °C and the mold temperature was 60 °C. Nevertheless, the highest value of shrinkage were 7.881 % with melt temperature of 250 °C and the mold temperature of 40 °C while the lowest value of shrinkage were 6.536 % when the melt temperature was 220 °C and the mold temperature was 60 °C were shown in Figure 9. This can be seen that the higher the melt temperature, the higher the output response of warpage and shrinkage will be.

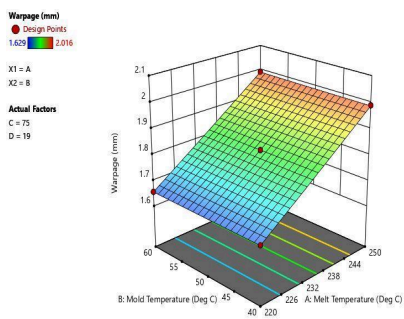


Figure 8: 3D surface of warpage

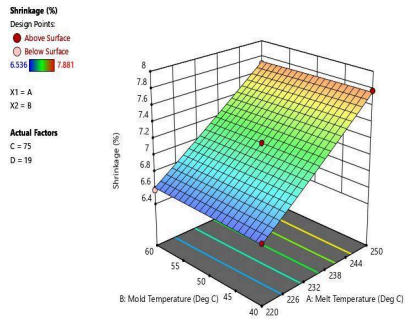


Figure 9: 3D surface of shrinkage

3.5 Optimization of Process Parameters

The objective of this study needs to be achieved which is to optimize the process parameters in the injection moulding process. Therefore, an optimization phase is very crucial to minimize the responses as well as to improve the quality of the moulded parts.

The most ideal parameters have been obtained by utilizing the point prediction in Design Expert. The DOE have suggested a few parameter setting runs but the most selected run is 220 °C melt temperature, 40 °C mould temperature, 64 MPa injection pressure and 22 s cooling time. This optimized parameter values has produced the warpage of 1.609 mm and shrinkage of 6.379 % as shown in Figure 10 and Figure 11 below.

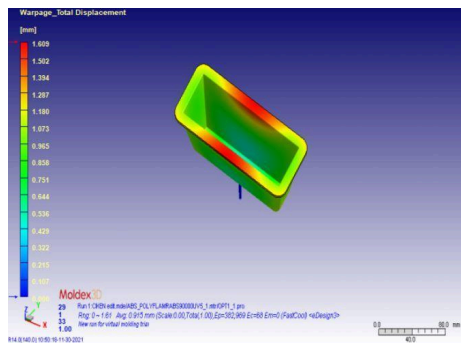


Figure 10: Optimized warpage value at the most optimal run

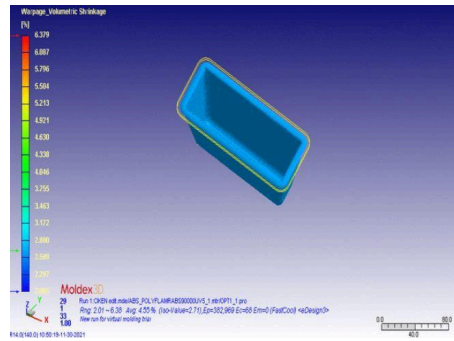


Figure 11: Optimized shrinkage value at the most optimal run

3.6 Percentage Error

The percentage error for the most optimal run of 220 °C melt temperature, 40 °C mould temperature, 64 MPa injection pressure and 22 s cooling time have been calculated using Eq. 3 below. The result obtained was 1.2 % for warpage and 1.8 % for shrinkage.

$$Percentage\ error = \frac{Predicted\ value - Actual\ value}{Predicted\ value} \times 100\% \quad (3)$$

4.0 Conclusion

This research summarizes that the most optimal parameters for minimum warpage and shrinkage were at 220 °C melt temperature, 40 °C mould temperature, 64 MPa injection pressure and 22 s cooling time. The simulation of the confirmation run with these optimal parameters produced warpage of 1.609mm and shrinkage of 6.379%. The confirmation test with error does not exceed 10% for warpage and shrinkage verified the validity of the model. Thus, the result obtained is acceptable and the objectives of this study have been successfully achieved. In a conclusion, the results obtained in this study can be very helpful in the manufacturing industry to reduce the defects thus improving the quality of molded parts. Response Surface Methodology (RSM) has been done in Design-Expert software is proven to be the optimization technique to achieve the optimal setting parameters and minimise the warpage and shrinkage. By using RSM, a significant mathematical model or regression analysis can be generated to forecast the warpage and shrinkage value with reasonable accuracy.

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