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Research on the Effects of Process Parameters on Product Quality in Injection Molding

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Abstract— *Injection molding is a pressure-forming (plastic deformation) process used in polymer material processing (thermoplastics). It is a powerful and unique manufacturing technique that shapes products using molds by injecting molten plastic into mold cavities under high pressure. The substance hardens within the mold, taking on the intended shape as planned, and is subsequently removed as a completed item. Injection molding allows for the creation of intricate designs with great precision and consistency [1]. Therefore, it is widely applied and is considered a core technique in the mold-making industry. Its nature is particularly advantageous for mass production in industrial plants of all sizes. This technique can create complicated forms and supports large-scale manufacturing. Moreover, the short cycle time for each part and the ease of automation make it ideal for mass production [2]. To improve product quality especially warpage, mechanical strength, and product stability we analyzed the impact of various process parameters on product quality in injection molding, and identified suitable parameter sets. To investigate the influence of some processing parameters, an experimental model based on Taguchi L9 was employed [3]. Additionally, ANOVA (Analysis of Variance) was used to determine the influence level of each parameter on warpage. Optimal processing conditions for minimizing warpage were then established and are applicable in real-world production to enhance product quality.*

Keywords— *ANOVA,* Taguchi L9, injection molding, warpage deformation, Warpage.

I. INTRODUCTION

Nowadays, plastic products play an important role in our lives, ranging from basic daily items to high-tech components and devices. Their light weight, durability, and flexibility make them essential in modern living. Therefore, various modern thermoplastic processing technologies such as extrusion, blow molding, and injection molding are widely applied... to manufacture and fabricate plastic components.

Injection molding is one of the technologies widely used in the industrial sector based on the principle of injecting molten plastic material into a mold under high pressure. After that, the material is cooled and solidified, forming a set of parts or plastic products with high precision and detail. This technology has the ability to create complex shapes and large volumes with high accuracy and stable quality. Injection molding brings production efficiency in terms of cost, short cycle time, and minimal material waste, making it a popular choice for mass production of various plastic components. In addition, this process is highly flexible as it can be applied to many different types of plastic materials. In general, injection molding plays an important role in the production of many types of plastic products, from industrial goods to consumer products, making it a key technical process in manufacturing [4].

With the capability to form complex geometries and large volumes with high precision and stable product quality, injection molding requires strict control over numerous input parameters to ensure consistent outcomes. These include process parameters, material types, mold structure design, and their combinations. Inadequate control of these factors can lead to surface defects such as warpage, sink marks, flash, poor surface finish, or scratches, as well as more critical issues affecting durability, safety, performance efficiency, and functional integrity of plastic components [5]. In this study, the influence of mold cavity geometry is excluded. Instead, the focus is placed on investigating the impact of process parameters on product quality particularly on warpage deformation. The objective is to identify the optimal set of process parameters for injection molding that minimizes warpage using the Taguchi method.

Dr. Taguchi from Japan is credited with establishing the basis for the robust design technique and also introduced the experimental approach that bears his name. The objective of the Taguchi method is to design a process (or product) that is less affected by noise factors which cause deviations in quality. The goal is to adjust the parameters to optimize the process (or product) so that it operates stably at the best possible quality level. The Taguchi method uses orthogonal arrays in experimental planning. Therefore, this method allows for the use of a minimal number of experiments while still being able to study the effects of various parameters, making it a suitable choice in situations that require quick process optimization (or product) with fewer trials [3]. With the goal of minimizing defects in injection molding, warpage deformation is considered one of the most important quality indicators. The use of warpage deformation as a quality measure in each case of concern has been repeated many times to ensure that the influence of key technical factors on the process is clearly and accurately reflected.

II. BUILDING AN EXPERIMENTAL CALCULATION PROCESS FOR PLASTIC INJECTION MOLDING PROCESS

During the research process, it was found that the quality of plastic products after injection molding is influenced by many factors. The main factors affecting the injection molding process include raw material preparation, mold installation methods, parameter settings on the injection molding machine, process parameters during injection, part ejection, mold cooling, mold structure, and mold maintenance [5]. The

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quality considered in this study is the warpage deformation of the product after injection molding. There are many parameters that may affect the warpage of a plastic part after molding, such as mold temperature, filling time, pressure packing time, packing pressure, melt temperature, etc. It should be noted that the influence of mold cavity geometry such as cooling channel layout, runner system, and gate design is not considered in this study [6]. The parameters examined in this study include mold temperature, packing pressure, and pressure packing time.

TABLE 1. Experimental parameters when performing plastic injection molding process

Level	Mold temperature (°C)	Packing pressure (MPa)	Pressure packing time (s)
1	80	70	8
2	100	90	12
3	120	110	18

Use the Taguchi method to select the optimal solution based on analysis of variance (ANOVA) and noise ratio (S/N ratio). The influence of factors on output parameters is evaluated through the S/N ratio. This index is determined by formula [3]:

$$(S/N)_i = 10\log\left[\frac{\bar{y}_i^{\,2}}{s_i^2}\right] \qquad (1)$$

In which: $\bar{y}_i = \frac{1}{N}\sum_{u=1}^{N_i} y_{i,u}$ is the signal, $s_i^2 = \frac{1}{1-N}\sum_{u=1}^{N_i}(y_{i,u} - \bar{y}_i)^2$ is the noise, i is the experimental sequence number, u is the sequence number, N_i is the measurement number. The value of the S/N ratio is large (large signal, small noise) when this output parameter is close to the optimal value. In the minimal problem (the smaller the better), formula (1) is expressed as follows [3]:

$$(S/N)_i = -10\log\left[\sum_{u=1}^{N_i}\frac{y_u^{\,2}}{N_i}\right]$$

In this study, the experimental design was established according to the Taguchi L9 (3^3) method, as presented in TABLE 2.

TABLE 2. Experimental design according to Taguchi L9 (3^3) method

S. No.	Combination of factors and levels		
	Mold temperature	Packing pressure	Pressure packing time
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

III. Results of the Analysis on Then Influence of Process Parameters on Warpage Deformation During Plastic Injection Molding

The flow simulation process for the plastic injection molding process on the two-pin power plug housing product is Moldex3D software.

Moldex3D stands out as the premier CAE solution for the plastic injection molding sector globally. Utilizing top-tier analysis technology, Moldex3D enables comprehensive simulations of various injection molding techniques and enhances product design and production efficiency. Furthermore, its exceptional compatibility and flexibility offer users immediate integration with popular CAD systems, creating a dynamic simulation-based design environment.

The experiments were conducted using the Moldex3D simulation software, with the material of the product being PC plastic, and the parameters were varied sequentially according to the experimental table of the Taguchi method L9 (3^3), with the results shown in Fig. 1.

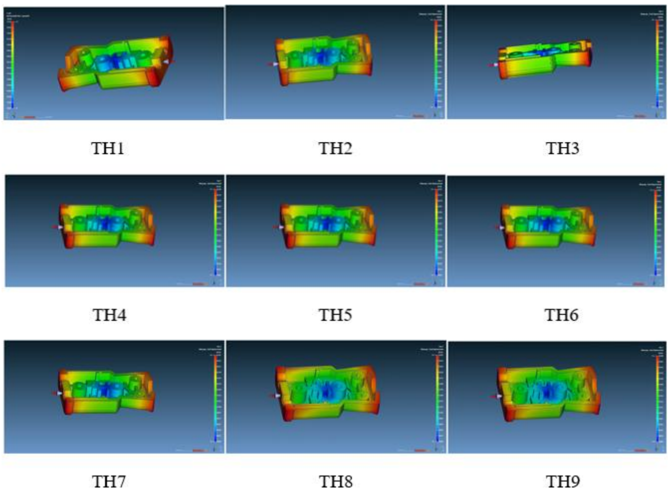

Fig. 1. Results of warpage deformation simulation performed with moldex3d software

The results obtained from the Taguchi L9 (3^3) experimental design in combination with Moldex3D simulations indicate that the warpage deformation of the product is summarized in TABLE 3.

TABLE 3. Results of Warpage Deformation Measurements Under Various Processing Conditions

S. No.	Change code			Warpage Deformation
	Mold temperature	Packing pressure	Pressure packing time	
1	1	1	1	0,273
2	1	2	2	0,256
3	1	3	3	0,246
4	2	1	2	0,260
5	2	2	3	0,251
6	2	3	1	0,286
7	3	1	3	0,261
8	3	2	1	0,293
9	3	3	2	0,280

The results of the Taguchi L9 (3^3) analysis on warpage deformation from the experimental results are shown in Fig. 2. The results show that mold temperature provides the highest S/N ratio (11,764), corresponding to level 1; next is packing pressure with the highest S/N ratio (11,548), also corresponding to level 1; and finally, pressure packing time provides the highest S/N ratio (11,952), corresponding to level 3. The Taguchi L9 (3^3) analysis is used for the process of

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plastic injection molding to determine the optimal solution for minimizing warpage deformation, with the smallest warpage corresponding to case 113 (mold temperature = 80°C, packing pressure = 70 MPa, pressure packing time = 18s).

Element	Average S/N ratio		
	Mold temperature	Packing pressure	Pressure packing time
1	11,764	11,548	10,937
2	11,527	11,501	11,531
3	11,129	11,370	11,952
Average	11,473	11,473	11,473
Max	11,764	11,548	11,952
Best-case	113 (Mold temperature element 1; Packing pressure element 1; Pressure packing time element 3)		

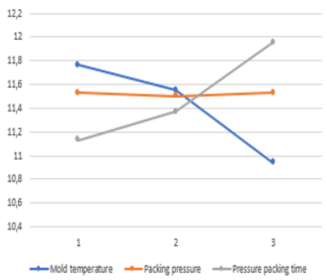

Fig. 2. Results of the Taguchi L9 (3^3) Analysis on Warpage Deformation

TABLE 4. Results of the Percentage Influence of Factors on Product Warpage Deformation in Plastic Injection Molding

Element	Contribution (%)
Mold temperature	27,67
Packing pressure	2,28
Pressure packing time	70,05

The ANOVA analysis results of warpage deformation based on the experimental data are presented in TABLE 4. The results indicate that pressure packing time is the most influential factor on product warpage deformation, accounting for 70.05%, followed by mold temperature with 27.67%, and packing pressure with 2.28%.

IV. Conclusion

From the evaluation of the signal-to-noise (S/N) ratio, conclusions were drawn regarding the trend and extent of the influence of each parameter on the warpage deformation of the product. This helps to quickly identify the parameters and ranges that need to be adjusted to achieve the best injection molding process. At the same time, this also helps to separately assess the influence of each process parameter on the optimization of product quality in detail after injection molding.

From the results of the Taguchi L9 (3^3) analysis and the analysis of variance (ANOVA), conclusions were drawn regarding the influence of the input parameters on the warpage deformation of the product after injection molding of PC plastic.

The results of the Taguchi L9 (3^3) analysis on warpage deformation of the product from the injection molding experiments with PC plastic show that the optimal set of parameters is mold temperature = 80°C, packing pressure = 70 MPa, and pressure packing time = 18s.

The results of the variance analysis (ANOVA) on warpage deformation of the product from the injection molding experiments with PC plastic show that the influence of each parameter on warpage deformation is ranked as follows: pressure packing time has the greatest influence = 70.05%, followed by mold temperature = 27.67%, and finally packing pressure = 2.28%.

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