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Original Article

Optimization of Injection Moulding Parameters for Reducing the Shrinkage Using the Taguchi Method

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Abstract - The *injection moulding input factors were optimized employing High-Density Polyethylene (HDPE) plastic material in a two-plate family injection mould. It is well known that non-optimal parameters lead to increased rework time to remove flashing, excessive raw material waste, poor product quality, and higher production costs. Therefore, establishing appropriate injection moulding settings was not easy to ensure minimizing production time, material waste, and cost. This study aims to use statistical methods to optimize the injection moulding input factors to reduce shrinkage. The experimental work was conducted using the Design of Experiments (DOE) approach based on the Taguchi method. The parameters selected were the size of shot, pressure of injection, speed of injection, and force of clamping. Analysis of Variance (ANOVA) was applied to determine the significance of each input factor and to identify the optimal combination. The moulded samples were evaluated based on weight changes to determine the shrinkage percentage. The results show that the size of the shot is the most significant factor influencing shrinkage, followed by pressure of injection, speed of injection, and force of clamping. The optimization process achieved an improvement of 8.4% in shrinkage reduction, where the shrinkage decreased from 30.22% to 27.66%. Therefore, by applying the Taguchi optimization method, the reduction of shrinkage on the moulded parts can be improved, leading to enhanced product quality and manufacturing efficiency.*

Keywords - *Analysis of Variance (ANOVA), High-Density Polyethylene (HDPE), Injection Moulding Parameters, Shrinkage, Taguchi Method.*

1. Introduction

The injection moulding process has advantages in producing mass production of the plastic part, especially for thermoplastic materials. The molten thermoplastic is injected into the mould cavity. The high pressure is applied throughout this operation, where the plunger mechanism is used to inject the melted thermoplastic [1]. In addition, when compared to other moulding methods, the process of injection moulding was the fastest. Additionally, the advantages of injection moulding are in the feeding system, such as runners and sprues, which are easy to recycle after a production cycle is finished [2, 3]. As a result, this method might be seen as one economical process. This injection moulding can also be referred to as a mass production technique, and the products produced must be valuable enough to cover the expenses of fabricating the mould. Additionally, the advantages of the process of injection moulding include that it can create complicated and complex shapes [4, 5]. Nevertheless, despite the advantages of the injection, part weight always parallels the defect of shrinkage.

Various types of defects, such as short shots and flashes, can occur due to improper processing conditions, leading to significant material waste and production costs [6-8]. Further, shrinkage also contributed to the defect on the moulded part. According to Nian et al. [9], shrinkage creates many problems in the application fields, such as plastic part distortions. Besides, it can also cause uneven surfaces due to the reduction in shrinkage. Based to the study by Hopmann et al. [10], temperature fluctuations during the injection moulding process, particularly during heating up and cooling down, can significantly affect thermal shrinkage. This is due to the changes in the specific volume and thermal expansion coefficient of the material. Furthermore, part weight always parallels the defect of shrinkage.

It was found that mould temperature affected the part weight as well as the shrinkage. Therefore, the percentage of shrinkage can be calculated from the difference between the cavity part weight and the injected part weight [11, 12].

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Part shrinkage in injection moulding is influenced by several factors, including human error, material properties, mould design, and, most critically, the moulding parameters. In this study, four key process parameters were selected based on previous researchers and the capabilities of the injection moulding machine, namely the size of shot, pressure of injection, speed of injection, and force of clamping. The size of the shot to inject the raw material in the mould cavity is very important to the part weight as well as shrinkage; therefore, shot size is one of the input parameters. Further, injection speed and pressure affect the part weight as well as shrinkage due to the solidifying process. Clamp force was one of the requirements to ensure a tight mould close [13-15]. When setting parameters to produce a new product, a lot of cost and time are required. Prior to starting the injection moulding process, engineers used trial-and-error procedures that relied on their prior knowledge and perception [16]. According to Zhao et al. [17], trial-and-error methods are expensive and time-consuming, making them unsuitable for complex manufacturing. The Design Of Experiment (DOE) method, such as the Taguchi optimization method, can be used to optimize the injection moulding process to decrease needless losses in manufacturing. DOE is a procedure used in the establishment of a hypothesis or the discovery of an unknown effect while operating under controlled settings. A set of tests or trials was carried out as part of an experiment, which was often done to investigate, estimate, or confirm. When learning about a process or product characteristic, investigation is always a step after data collection [18, 19].

Furthermore, it involves the manipulation of factors that are within our control in order to not only understand their effects, but also to identify the ideal combination of variables that will produce the intended result. Investigating the best optimum level of resources to generate a product that meets quality characteristics is hence the main objective of DOE [20, 21]. According to Kumar and Bairwa [22], DOE can save material costs rather than relying on trial and error, and it improves a wide range of production processes, including the injection molding process by determining critical parameters and their optimal settings. As a result, it minimizes the number of experiments needed, thus saving time, materials, and effort. Furthermore, it improves process yield, stability, and reduces variability, leading to higher quality and efficiency. This study is to investigate the significant effect of injection moulding input factors in reducing shrinkage, instead of practicing trial and error problem solving, which is costly, time-consuming, and not appropriate for the process of complex manufacturing. Therefore, this study implements a new method of the statistically approved process using ANOVA and the Taguchi method. The High-Density Polyethylene (HDPE) plastic material was employed by being injected into the two-plate injection moulding. The findings of this study can help industrial practitioners to reduce production costs and improve product quality.

2. Methodology

2.1. Injection Moulding Machine

The type of injection moulding machine used was DEMAG Sumitomo SE100EV series, as shown in Figure 1. This new brand of moulding machine, the SE100EV series, was created and planned to use the full potential of zero-moulding. The SE-EV series combines robust software and technology to run the injection moulding machine to perfection in a graceful shape that offers users unmatched potential. The maximum clamping force of the machine was 100 Tons.

Fig. 1 DEMAG Sumitomo SE100EV series injection moulding machine

2.2. Material Preparation and Moulded Part

In this study, HDPE with a density of 0.97 g/cm^3 was selected. The cavity weight of HDPE is 3 g, calculated from part volume multiplied by HDPE density (3.072 cm^3 x 0.97g/cm^3). Figure 2 shows the mould cavity, which consists of four cavities, and only one part in the cavity was investigated in this study. This study focuses on a single cavity rather than a multi-cavity due to the easy monitoring.

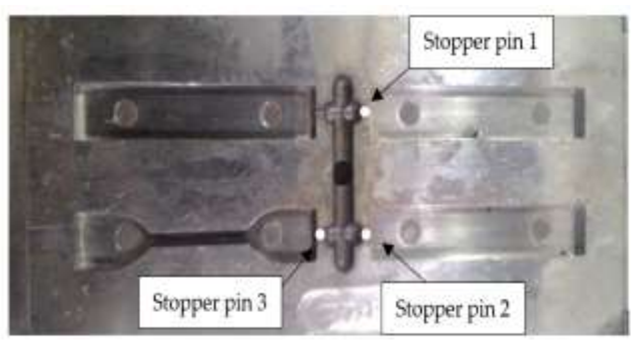

Fig. 2 Three stoppers located at the family injection mould

After the part was injected, it was weighed by using a digital weight scale as shown in Figure 3.

Fig. 3 Weighing of the injected part on a digital scale

2.3. Processing Parameters of Plastic Parts

Table 1 shows the parameter settings of the experiment.

Table 1. Input Process parameter with three levels

Parameters	Lower	Middle	Higher
Shot size (mm)	11	18	23
Injection pressure (kgfmm^3)	1000	1100	1200
Injection speed (mm/s)	90	95	100
Clamp force (Ton)	10	15	20

In this study, for experimental runs, the Taguchi method using an L9 orthogonal array was utilized.

3. Results and Discussion

3.1. Experimental Result of Shrinkage

Table 2 shows the results from the Minitab software created from the orthogonal array with 9 experimental runs of the Taguchi method L9.

Each run was injected with three repetitions, and the average of the part weight was recorded. After that, the shrinkage percentage was calculated by using the Equation 1. Where, symbol of the cavity weight (Cw) and injected part weight (Ipw).

From the table, the lowest shrinkage percentage value is 30.22 at run numbers 7 and 9. For run number 7, the parameter combination of shot size 23 mm, injection pressure 1000 kgfmm^3, injection speed 100 mm/s, and clamping force 15 Tons.

Meanwhile, for run number 9, the combination of shot size 23 mm, injection pressure 1200 kgfmm^3, injection speed 95 mm/s, and clamping force 10 Tons.

$$\frac{Cw-Ipw}{Cw} x100 = Shrinkagepercentage \quad (1)$$

Table 2. Injection machine parameters and percentage of shrinkage

Run	Shot size (mm)	Injection pressure (kgfmm^3)	Injection speed (mm/s)	Clamp force (Ton)	Shrinkage (%)
1	11	1000	90	10	35.11
2	11	1100	95	15	34.78
3	11	1200	100	20	31.00
4	18	1000	95	20	30.67
5	18	1100	100	10	30.67
6	18	1200	90	15	30.33
7	23	1000	100	15	30.22
8	23	1100	90	20	30.44
9	23	1200	95	10	30.22

3.2. Signal-to-Noise Ratio

After all the part shrinkage is calculated, the signal-to-noise ratio (S/N ratio) is generated using Minitab software. Minimum shrinkage is highly recommended to obtain a good quality of product, and the lower-the-better characteristic of S/N ratio is selected for the shrinkage percentage. The lower-the-better of the S/N ratio calculated using Equation (2.

$$Lowerthebetter = -10\, log(MSD) \quad (2)$$

Where

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\left(y_i^2\right)$$

The mean square deviation is *MSD*, the observation data is *y*, and the number of trials is *n*. From the Equation 2, the S/N ratio for shrinkage is presented in Table 3.

Table 3. Signal-to-noise ratio

Run	S/N ratio for shrinkage
1	-30.9086
2	-30.8266
3	-29.8272
4	-29.7343
5	-29.7343
6	-29.6374
7	-29.6059
8	-29.6689
9	-29.6059

3.3. Response Diagram of S/N Ratio

The response diagram can be constructed by calculating the level 1, level 2, and level 3. The value of level 1, level 2, and level 3 can be determined using the calculation below. The presented calculation below is the shot size factor.

$$\text{Level 1} = \frac{(-30.9086)+(-30.8266)+(-29.8272)}{3} = -30.5208$$

$$\text{Level 2} = \frac{(-29.7343)+(-29.7343)+(-29.6374)}{3} = -29.7020$$

$$\text{Level 3} = \frac{(-29.6059+(-29.6689)+(-29.6059)}{3} = -29.6269$$

Difference = highest value – lowest value

= (-30.5208) – (-29.6269)

= -0.8939

The calculation of shot size can be summarized as shown in Table 4.

However, the calculation of the other factors, such as injection pressure, injection speed, and clamp force, is not presented.

Based on the data of the S/N ratio in Table 4, the data were then constructed into an S/N response diagram in Figure 4.

Table 4. The response table of the signal-to-noise ratio

	Shot size	Injection pressure	Injection speed	Clamp force
Level 1	-30.5208	-30.0829	-30.0716	-30.0829
Level 2	-29.7020	-30.0766	-30.0556	-30.0233
Level 3	-29.6269`	-29.6902	-29.7225	-29.7435
Difference	-0.8939	-0.3928	-0.3492	-0.3395

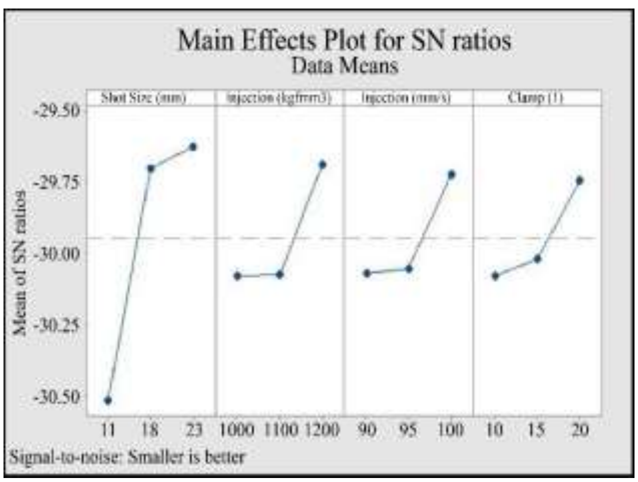

Fig. 4 Signal-to-noise response diagram

From Figure 4, the optimum parameters taking on the upper value of levels on each input parameter were taken. From the figure, the optimum for shrinkage is shot size 23 mm at level 3, injection pressure 1200 $kgfmm^3$ at level 3, injection speed 100 mm/s at level 3, and clamping force 20 Tons at level 3.

The results agree with the findings of Zhai and Xie. [23] In which overfilling the plastic component (i.e., using a larger shot size than the cavity) significantly reduces shrinkage. This is because the additional material compensates for the volume loss due to shrinkage. Meanwhile, according to Huang et al. [24], if the clamping force is insufficient, flashing can occur at the parting line. This is because the mould halves may not be held tightly enough, allowing the molten plastic to escape and form burrs or flashes.

3.4. Analysis of Variance (ANOVA)

ANOVA is purposely used to identify the parameter that gives a significant effect on the shrinkage of the part. The summary of the ANOVA result for the average shrinkage of the part is shown in Table 5. The most important consideration in ANOVA is the p-value of the parameter, whereby, if the p-value is less than 0.05, it shows that the parameter has a significant effect on the response. The p-value of shot size was 0.039, which was smaller than the prefixed value of 0.05; this means that the main factor had an influence on the response result, as mentioned by Banh et al. [25]. From the result, the size of the shot is the most significant parameter that affected the shrinkage, followed by the pressure of injection, the speed of injection, and the force of the clamp. The shot size that compact the cavity area, therefore by increasing the volume of the molten plastic inside the cavity area, totally packs as well as reduction of volume minimizes the shrinkage [26].

Table 5. ANOVA result

Process Parameters Run	P-value
Shot size (mm)	0.039
Injection pressure ($kgfmm^3$)	0.641
Injection speed (mm/s)	0.710
Clamp (Ton)	0.748

The equation 3 shows the calculation of improvement after optimization using the optimum parametric combination, where *SL* is the lowest average shrinkage, and *SP* is the optimized shrinkage. Minitab software provides the predicted value of the average shrinkage percentage value for the plastic part based on the optimum parametric combination defined by Taguchi. The new set of optimum parametric combinations of average shrinkage of the plastic part has predicted a shrinkage value of 27.66%.

$$\frac{SL-SP}{SL}X100 = Percentageimprovement \quad (3)$$

From the Equation (3), the difference between the lowest experimental shrinkage of 30.22% and the optimized average shrinkage of 27.66% of the part results in an 8.4% reduction of shrinkage. This improvement proves that the new set of optimum parametric combinations has minimized the percentage value of shrinkage. Further, validation of optimization parameters shows there are only small differences in shrinkage from the optimum result. Warpage and mechanical properties should be considered for further investigation for multi-response optimization. However, the effort of the research requires more cost and time. Grey Relational Analysis (GRA) with the Taguchi method is widely considered one of the best approaches for multi-objective optimization because it effectively converts multiple, conflicting objectives into a single, optimized solution [27].

4. Conclusion

This study targets optimizing the process of injection moulding machine input factors, such as the size of the short, pressure injection, speed of injection, and force of clamping, towards the goal of reducing the percentage of shrinkage.

Based on the result gained from this experiment, through the Taguchi method and ANOVA analysis, S/N ratio results proves that to get the lowest shrinkage percentage value of the part, the parameters should be set to size of shot 23 mm, pressure of injection 1200 $kgfmm^3$, speed of injection 100 mm/s, and force of clamping 20 Tons which all levels located at level 3. This optimum parametric combination provides an improvement in reducing shrinkage by 8.4%.

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Author Contribution

Wan Noor Azrina Wan Azhari conducted the experiments and drafted the initial manuscript. Mohd Amran Md Ali conceived and designed the research and wrote the final manuscript. Subramoniam Sivarao analyzed the data, while Mohd Najib Ali Mokhtar reviewed and edited the manuscript.

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