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OPTIMIZATION OF INJECTION MOULDING PARAMETERS IN REDUCING CAVITY PRESSURE USING TAGUCHI METHOD

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ABSTRACT: This research focuses on optimization of injection moulding process parameters on cavity pressure that plays an important role not only limited to the quality of the moulded products but also for monitoring, optimizing and controlling the injection moulding process. The implementation of cavity pressure sensor can improve the product quality and reduce cost by eliminating waste. However, the parameters setting variation can increase the cavity pressure inside the mould during the injection moulding process that can affect the quality of plastic products. It is very important that the effect of injection moulding parameters on cavity pressure during the injection moulding process are to be determined. Therefore, the objective of this paper is to optimize the injection moulding parameters on cavity pressure using Taguchi method of polypropylene (PP). The selected parameters are temperature of mould (MoT), temperature of melt (MeT), time of injection (IT) and time of cooling (CT). The experiment is conducted using Taguchi method and analysis of variance (ANOVA) to determine the most significant parameter. During cavity pressure monitoring, the location of the pressure sensor installations is located near the gate and at the end of the cavity inside the mould. The experimental result shows that the optimal combination of injection machine parameters near the gate are MoT with 50°C, MeT with 310°C, IT with 0.7s and CT with 15.4 s. The similar set of optimum parameter setting for the cavity pressure at the end of the cavity is obtained except for MoT with 56°C. The improvement of reducing cavity pressure for both near the gate and end of the cavity is 1.18% and 1.30%, respectively. Thus, by using Taguchi optimization, the improvement of reducing cavity pressure can be achieved.

KEYWORDS: *Cavity Pressure; Injection Moulding; Taguchi Method; Analysis of Variance*

1.0 INTRODUCTION

Plastic injection moulding process is a process to produce a variety of thermoplastic products and it has many advantages. Plastic products with excellent surfaces and complex shapes can be created in short production cycles [1]. Selvaraj et al. [2] stated that plastic injection moulding is used in the application of a high production rate with excellent surface finish, especially for complex shape products. It is important that controlling and modifying process parameters is an efficient way to eliminate plastic product defects in the plastic injection moulding business. However, there are many injection machine characteristics that must be considered including the injection rate, melt pressure, mould temperature, filling time, packing time, holding time, cooling time, melt temperature [3-4]. In addition, gate position, plastic type, and product structure are other factors that need to be taken into consideration as these factors might cause product shrinkage. Different gate locations affect how the polymer chains are oriented and crystallize, which has a significant impact on how much plastic parts shrink [5]. Therefore, it is clear that during the production of plastic products, the optimization of the process parameters aims to eliminate final product defects.

Trial and error were frequently employed, however, it was highly difficult and time-consuming to determine the ideal process parameters through an experiment [6]. This conventional trial-and-error approach, which mainly relied on the machine operators' experiences and was unable to tackle the challenges of globalization. In addition, Ali et al. [7] claimed that DOE was a highly helpful method for analyzing challenging industrial design challenges and understanding the characteristics of the processes. Based on statistical concepts in the DOE, investigations on how parameter inputs affect the outcome can be conducted. When compared to other DOE techniques, the Taguchi approach only required a small number of experimental runs for process optimization [8]. By using this Taguchi method, trial-and-error methods can be avoided, and the experimental costs required to produce a reliable and high-quality process can be reduced. To understand the influence of each process parameter, ANOVA is employed to determine the most significant parameter contributing to the experimental conditions [9-10]. Therefore, the implementation of ANOVA is important to obtain the total percentage of contribution of each parameter and determine the statistically significant parameters influencing the quality characteristics. The higher percentage of contribution indicates the more important of a factor.

In general, different groups have carried out investigations focused on the characterization of injection moulded polymers by process parameters. A variety of methods have been used, including cavity pressure monitoring. In 2018, Farotti and Natalini [11] performed experiments to determine how input parameters affected mechanical qualities, such as the tensile test of polypropylene (PP). In order to collect data on the temperature and cavity pressure, sensors are installed next to the mould. Melt temperature, mould temperature, packing pressure, and cooling time were selected as process parameters. Through the application of ANOVA, they discovered that the mould temperature and packing pressure are the most significant parameters. Additionally, the cavity pressure needs to be monitored to prevent plastic part defects like flash and to collect relevant data for process monitoring [12-13]. There are some reasons for choosing two different locations to install the pressure sensors. From this, the different values of cavity pressure inside the mould can be obtained when cavity pressure values that located far from the gate is smaller than near gate due to the pressure loss as the melt attempts to overcome the resistance along the filling path as mentioned by Huang [14]. In addition, flash defect which one of the most common defects in injection moulding can be avoided. It was stated that processing conditions such as injection speed, melting temperature and injection pressure can cause flashing [15-16]. This is also supported by Trotta et al. [17] when lower pressure in the mould cavity is crucial in order to reduce the likelihood of producing product with flash. Hence, in order to achieve identical parts that can be manufactured consistently, pressure sensors are necessary to measure cavity pressure inside the mould cavity.

It can be seen that process parameters optimization of injection moulding process was mainly conducted to find their effect in the final products. Therefore, cavity pressure measurement plays an important role to determine the quality of the final product. To date, very few research has been conducted on the effect of injection moulding parameters on cavity pressure during the injection moulding process.

The findings of this research will help to optimize the parameters of injection moulding on cavity pressure during the injection moulding process using Taguchi method and to find the most influential parameter using ANOVA.

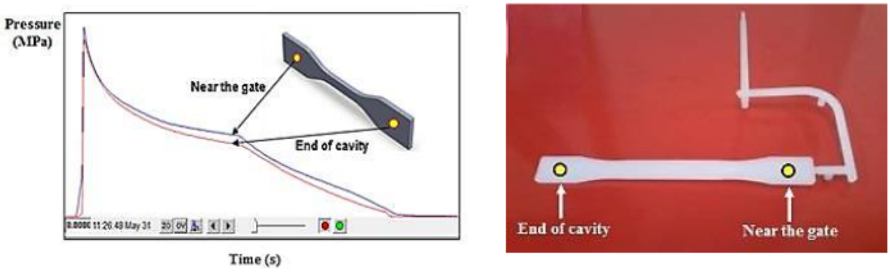
2.0 METHODOLOGY

2.1 Location of Pressure Sensors

The plastic part used of this study was a dumbbell tensile test specimen in accordance with ASTM D638. In this study, polypropylene (PP) having a melt flow index of 4g/10min at 230°C is used. Arburg Allrounder 370 H 600-170 type HIDRIVE was used to inject the dumbbell plastic part. Cavity pressure was monitored by using eDART ® System. The location of the pressure sensor installation was located in two locations. The first location was located near the gate and the second sensor is located at the end of the cavity as illustrated in Figure 1. The reason for the sensor locations was selected to determine the cavity pressure difference and effect of the different sensor locations.

2.2 Plastic Parts Processing Parameters

This research proposes the implementation of Taguchi method to find the optimum process parameters. In order to find the processing parameter for mould temperature, melt temperature, injection time and cooling time, "Moulding Windows" analysis was done by Autodesk Moldflow Insight software. From the analysis, it was found that the suggested parameter for temperature of mould was 56°C, temperature of melt was 280°C, time of injection was 0.7s followed by time of cooling was 14s. These parameters have been set as medium level parameter for the experiment. Three levels involved in the experiment were low, medium and high. Medium values was selected as centre point with reduction and addition 10% from medium value for high and low level. Table 1 shows the injection moulding parameters with three levels. By using this set of parameters, nine experimental runs were performed using Taguchi input variables experimental matrix.



(a) (b)

Figure 1: (a) Image for the location of pressure sensors with cavity pressure profile and (b) moulded dumbbell with feed system

Table 1: Four input variables with three levels

Input variables	Level		
	High	Medium	Low
Temperature of mould (°C)	62	56	50
Temperature of melt (°C)	310	280	250
Time of injection (s)	0.77	0.70	0.63
Time of cooling (s)	15.4	14.0	12.6

2.3 Taguchi Method and ANOVA

In the Taguchi approach, the scatter around a target value is expressed using the signal-to-noise ratio (S/N). A high S/N score indicates that the signal exceeds the random effects of the noise factors by a significant amount [18]. Higher S/N ratio values are preferred because it result in to less product variances around the target value. Hence, "the-smaller-the-better" was employed as the quality characteristic in this investigation. In order to perform S/N ratio analysis for 'the-smaller-the-better' quality characteristic and S/N ratio were calculated from the following equation where n is the number of experiments and y_i the value of response of i^{th} experiment as shown in Equation 1.

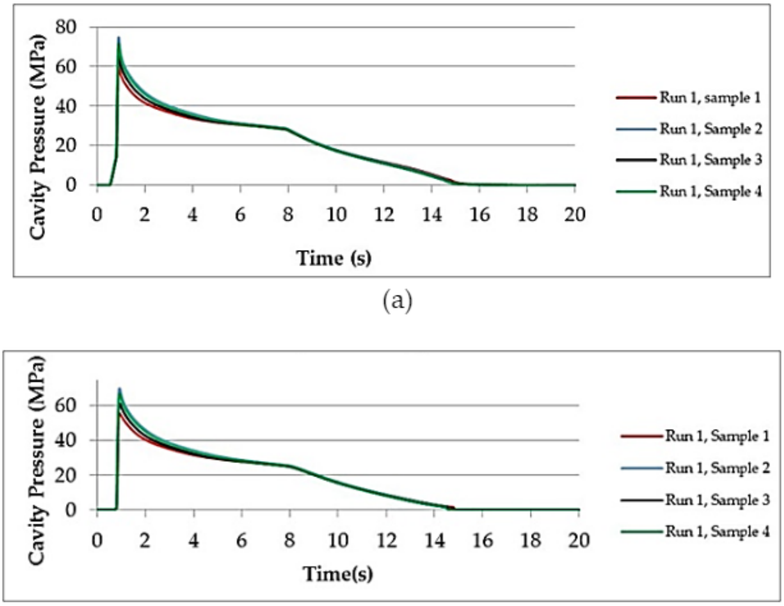
$$\text{S/N ratio} = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \tag{1}$$

To determine which design parameter significantly impacted the quality feature, an ANOVA was carried out. Based on the calculation of the percentage contribution, the aim of the ANOVA is to determine which parameters have significant effects on the performance characteristic. Furthermore, if P-value appears less than 0.05 (95% confidence level) then it can be concluded that the effect of the factor is significant on the selected response.

3.0 RESULT AND DISCUSSION

3.1 Cavity pressure profile

In this study, cavity pressure has been monitored by using process control systems and in-cavity pressure sensors from eDART ® System for injection moulding applications. The pressure sensors were placed in the mould cavity to measure the pressure during the injection process. Figure 2 illustrates the cavity pressure profile near the gate and end of cavity versus time during the injection moulding process for run number 1 with four repetitions. It can be seen that consistency of the injection moulding process in this study is achieved as stated by Kusić et al. [19] when they used cavity pressure measurement to monitor process consistency during the experiments. They stated that a consistent process is achieved if each shot captured with the cavity pressure sensor was identical when using unchanged process parameters.



(a)

(b)

Figure 2: Cavity pressure profile (a) near the gate and (b) end of the cavity

3.2 Taguchi method optimization

Table 2 shows the Taguchi method L9 orthogonal array with 9 experimental runs was generated using Minitab software. It is found the highest cavity pressure values obtained for each run at both locations of sensors are different. It can be seen that cavity pressure near the gate has higher cavity pressure values compared to the end of the cavity for all 9 runs. From the cavity pressure value of both locations, it is found that run 9 has the lowest pressure as supported by Huang [14] that mentioned lower cavity pressure can result in minimizing moulding defects such as warpage, weld line and flashing.

Table 2: Cavity pressure value for both near the gate and end of the cavity of plastic part.

Run	Temperature of mould (°C)	Temperature of melt (°C)	Time of injection (s)	Time of cooling (s)	Cavity Pressure (MPa)	
					Near the gate	End of cavity
1	50	250	0.63	12.6	67.96	63.53
2	50	280	0.70	14.0	63.31	59.7
3	50	310	0.77	15.4	62.14	59.19
4	56	250	0.70	15.4	66.02	61.64
5	56	280	0.77	12.6	63.75	60.06
6	56	310	0.63	14.0	63.61	60.49
7	62	250	0.77	14.0	68.19	63.51
8	62	280	0.63	15.4	64.05	60.28
9	62	310	0.7	12.6	61.93	59.11

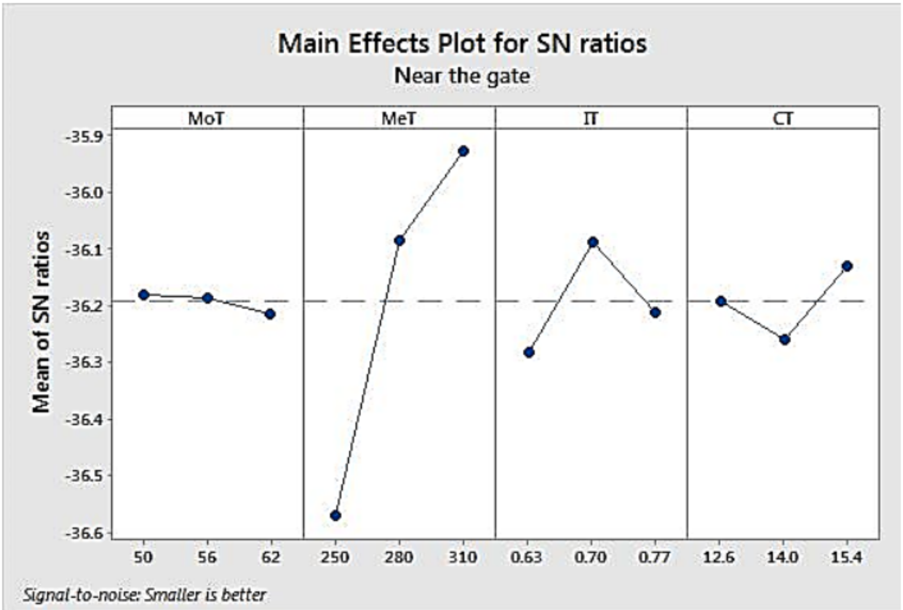
Therefore, to reduce defects in the plastic products 'the-smaller-the-better' characteristic is selected for the cavity pressure value. Equation 2 shows the example of signal-to-noise (S/N ratio) calculation for run number 1 as shown in Table 3.

$$\text{S/N ratio} = -10\log\left[\frac{1}{1}\sum_{i=1}^{1} 67.96^2\right] \tag{2}$$

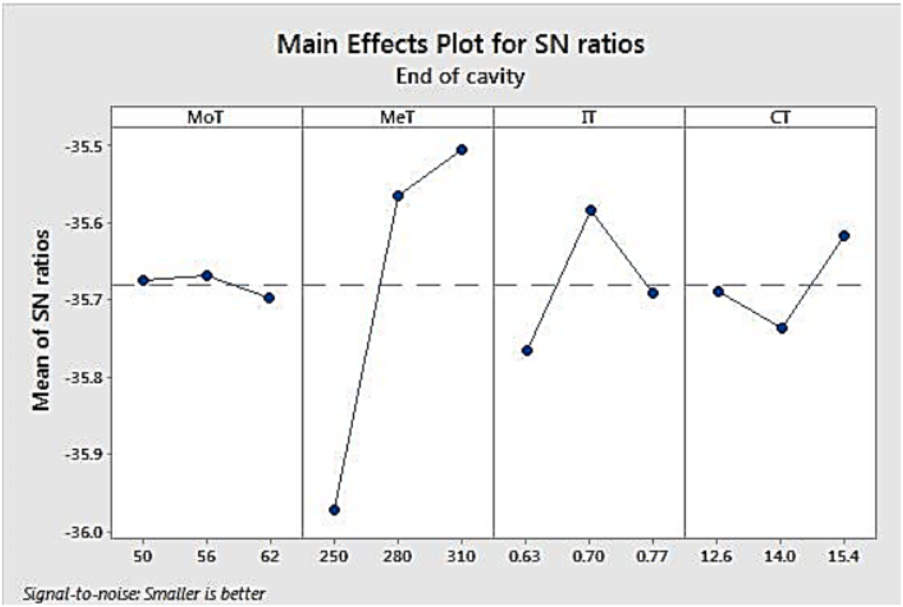
Based on Table 3, S/N ratio response diagram for cavity pressure of both locations is generated as shown in Figure 3. The highest value in each parameter is selected as the optimum level for the parameter. From the figure, the optimum parameters setting for near the gate are temperature of mould 50°C at low level, temperature of melt 310 °C at high level, time of injection 0.7 s at medium level and time of cooling 15.4s at high level. Meanwhile, the optimum parameter setting for the cavity pressure at the end of the cavity are temperature of mould 56°C at medium level, temperature of melt 310°C at high level, time of injection 0.7s at medium level and time of cooling 15.4s at high level.

Table 3: S/N ratio for cavity pressure of both locations

Run	Near the gate		End of cavity	
	Cavity Pressure (MPa)	S/N Ratio	Cavity Pressure (MPa)	S/N Ratio
1	67.96	-36.6451	63.53	-36.0596
2	63.31	-36.0294	59.7	-35.5195
3	62.14	-35.8674	59.19	-35.4450
4	66.02	-36.3935	61.64	-35.7973
5	63.75	-36.0896	60.06	-35.5717
6	63.61	-36.0705	60.49	-35.6337
7	68.19	-36.6744	63.51	-36.0568
8	64.05	-36.1304	60.28	-35.6035
9	61.93	-35.8380	59.11	-35.4332



(a)



(b)

Figure 3: Signal-to-noise response diagram of cavity pressure for (a) near the gate and (b) end of cavity

In Taguchi method, the value of cavity pressure using the optimum process parameter setting can be predicted. The predicted value of cavity pressure near the gate is 61.2MPa while the predicted value of cavity pressure at the end of the cavity is 58.34MPa. Equation 3 shows the formula for improvement percentage of cavity pressure where P_l is the lowest cavity and P_p is the predicted cavity pressure. Both predicted value is lower than cavity pressure obtained in 9 experimental runs as shown in Table 2. Table 4 shows the improvement percentage value of cavity pressure by using the optimum parameter setting. Percentage of improvement for both near the gate and the end of the cavity is 1.18% and 1.30%, respectively.

$$\text{Improvement } (\%) = \frac{P_l - P_p}{P_l} \tag{3}$$

Table 4: Improvement of the percentage value

Optimum parameter setting	Near the gate	End of Cavity
Temperature of mould (°C)	50	56
Temperature of melt (°C)	310	310
Time of injection (s)	0.70	0.70
Time of cooling (s)	15.5	15.5
Lowest Cavity Pressure (MPa)	61.93	59.11
Predicted Value (MPa)	61.2	58.34
Improvement (%)	1.18	1.30

3.3 ANOVA of process parameters

The ANOVA result is represented in Table 5. The most significant parameter that affects the cavity pressure at near the gate and end of the cavity is temperature of melt when the percentage of contribution for both cavity pressures is 88.86% and 83.84%, respectively. These results agree with the findings of other research, in which more melting polymer can fill the cavity at lower pressures when the melt temperature is higher [20].

Table 5: ANOVA of process parameters

Parameter input variables	Near the gate			End of Cavity		
	Sum of Squares	P-value	% of Contribution	Sum of Squares	P-value	% of Contribution
Temperature of mould (°C)	0.1336	0.991	0.31	0.0875	0.989	0.38
Temperature of melt (°C)	38.228	0.001	88.86	19.336	0.004	83.84
Time of injection (s)	3.259	0.790	7.58	2.503	0.708	10.85
Time of cooling (s)	1.402	0.905	3.26	1.137	0.859	4.93
Total	43.022		100	23.0642		100

4.0 CONCLUSION

The purpose of the current study was to determine the optimum process parameter of injection moulding on cavity pressure during the injection moulding process. This research has shown that the optimal injection machine process parameters for near the gate are the combination of temperature of mould 50°C at low level, temperature of melt 310°C at high level, time of injection 0.7s at medium level and time of cooling 15.4s at high level. Meanwhile, the similar set optimum parameter setting is found for the cavity pressure at the end of the cavity except for temperature of mould 56°C at medium level. In addition, the most significant factor that affects the cavity pressure values is obtained from the ANOVA where temperature of melt shows 88.86% and 83.84% contribution for near the gate and end of cavity, respectively. The cavity pressure near the gate is reduced to 61.2MPa which percentage reduction is 1.18%. Meanwhile, at the end of the cavity, cavity pressure is improved from 59.11% to 58.34% where the percentage reduction is 1.30%. Thus, cavity pressure can therefore be one of the indicators used to track, improve, and manage the injection moulding process that results in high-quality plastic products.

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AUTHOR CONTRIBUTIONS

N. Idayu: Investigation, Data collection, Writing-Original Draft, Preparation Methodology; M.A.M. Ali: Supervision, Conceptualization; M.H.F. Md Fauadi: Formal Analysis, Review; Z. Razak: Software, Validation; K.J. Khadim: Writing-Reviewing and Editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

REFERENCES

[1] R. Farooque, M. Asjad and S.J.A. Rizvi, "A current state of art applied to injection moulding manufacturing process - A review", in *Materials Today: Proceedings*, vol. 43, pp. 441–446, 2021.

[2] S.K. Selvaraj, A. Raj, R. Rishikesh Mahadevan, U. Chadha and V. Paramasivam, "A review on machine learning models in injection molding machines", *Advances in Materials Science and Engineering*, vol. 2022, pp. 1-28, 2022.

[3] G. Singh, M.K. Pradhan and A. Verma, "Multi response optimization of injection moulding process parameters to reduce cycle time and warpage", *Materials Today: Proceedings*, vol. 5, no. 2, pp. 8398-8405, 2018.

[4] J.C. Chen, G. Guo and W.N. Wang, “Artificial neural network-based online defect detection system with in-mold temperature and pressure sensors for high precision injection molding”, *The International Journal of Advanced Manufacturing Technology*, vol. 110, no. 7–8, pp. 2023–2033, 2020.

[5] X. Fangcheng, C. Lei and W. Xiao, “Calculation of shrinkage rate for injection molding based on moldflow,” in Proceedings of the FISITA 2012 World Automotive Congress: Volume 8: Vehicle Design and Testing (II), Berlin Heidelberg, 2013, pp. 1501–1510.

[6] C.J. Lin and Y.C. Li, “Lung nodule classification using Taguchi-based convolutional neural networks for computer tomography images”, *Electronics*, vol. 9, no. 7, pp. 1–9, 2020.

[7] M.A.M. Ali, N. Idayu, M.S Salleh, S. Sivaraos and M. Yamaguchi, “Optimization of injection machine parameters on high tensile strength of polypropylene/fibreglass”, *Journal of Advanced Manufacturing Technology*, vol. 16, no. 3, pp. 71-80, 2022.

[8] N.I.M. Ali, M.A.M. Ali, M.S. Salleh, S. Subramonian, M.I.H.C. Abdullah and M. Yamaguchi, “Optimization of compression moulding parameters on mechanical properties of stainless steel 316L”, *Journal of Advanced Manufacturing Technology*, vol. 17, no. 1, pp. 47–58, 2023.

[9] Q.M. Usman Jan, T. Habib, S. Noor, M. Abas, S. Azim and Q.M. Yaseen, “Multi response optimization of injection moulding process parameters of polystyrene and polypropylene to minimize surface roughness and shrinkage’s using integrated approach of S/N ratio and composite desirability function”, *Cogent Engineering*, vol. 7, no. 1, pp. 1-30, 2020.

[10] B. Ravikiran, D.K. Pradhan, S. Jeet, D.K. Bagal, A. Barua and S. Nayak, “Parametric optimization of plastic injection moulding for FMCG polymer moulding (PMMA) using hybrid Taguchi-WASPAS-Ant Lion optimization algorithm”, *Materials Today: Proceedings*, vol. 56, pp. 2411–2420, 2022.

[11] E. Farotti and M. Natalini, “Injection molding. Influence of process parameters on mechanical properties of polypropylene polymer. A first study”, *Procedia Structural Integrity*, vol. 8, pp. 256–264, 2018.

[12] M. Kariminejad, D. Tormey, S. Huq, J. Morrison and M. McAfee, “Ultrasound sensors for process monitoring in injection moulding”, *Sensors*, vol. 21, no. 15., pp. 1-22, 2021.

[13] Y. Ding, M.H. Hassan, O. Bakker, S. Hinduja and P. Bártolo, “A review on microcellular injection moulding”, *Materials*, vol. 14, no. 15, pp. 1-25, 2021.

[14] M.S. Huang, “Cavity pressure based grey prediction of the filling-to-packing switchover point for injection molding”, *Journal of materials*

processing technology, vol. 183, no. 2–3, pp. 419–424, 2007.

[15] A. Bagalkot, D. Pons, D. Clucas and D. Symons, "A methodology for setting the injection moulding process parameters for polymer rapid tooling inserts," *Rapid Prototyping Journal*, vol. 25, no. 9, pp. 1493–1505, 2019.

[16] I. Mawardi, A. Jannifar and H. Lubis, "Effect of injection temperature on defect plastic products", *IOP Conference Series: Materials Science and Engineering*, vol. 536, pp. 1-6, 2019.

[17] G. Trotta, S. Cacace and Q. Semeraro, "Optimizing process parameters in micro injection moulding considering the part weight and probability of flash formation", *Journal of Manufacturing Processes*, vol. 79, pp. 250–258, 2022.

[18] R.K. Roy, *A Primer on the Taguchi Method*. Society of Manufacturing Engineers, 2010.

[19] D. Kusić, T. Kek, J.M. Slabe, R. Svečko and J. Grum, "The impact of process parameters on test specimen deviations and their correlation with AE signals captured during the injection moulding cycle", *Polymer Testing*, vol. 32, no. 3, pp. 583–593, 2013.

[20] Q. Wang, X. Zhao, J. Zhang, P. Zhang, X. Wang, C. Yang, J. Wang and Z. Wu, "Research on quality characterization method of micro-injection products based on cavity pressure", *Polymers*, vol. 13, no. 16, pp. 1-13, 2021.