Optimization of Injection Molding Process Control Variables using Taguchi Approach for a Thermoplastic Polymer Material

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Abstract: Polymer injection molding is a mass production technology for economic generation of components of varying geometry. One of the main challenges associated with the process is to minimize residual stress which directly affects quality and geometric accuracy of injection molded components. Therefore, it is important to select injection molding control variable settings for obtaining the minimum residual stress. Taguchi approach was used to investigate the effect of control variables on residual stresses and to optimize the process. Optimum injection molding variables for machining the polymer were obtained as time for filling 1.5 s, temperature of melt 180°C, temperature of mold 50°C, volume filled 100%, holding time at pressure 15 s, pressure for holding 60 MPa and coolant in temperature 20°C. Analyses of variances and analyses of means methods were used to see which variable has significant effect on the residual stress. The results indicate that pressure for holding, melt temperature and time for filling are the most significant injection molding variables affecting the enticement of residual stress. Regression equation was developed to model the residual stress as a function of the molding process control variables.

Keywords: Plastic injection molding, Residual stress analysis, Taguchi methods, Analysis of means, Analysis of variance, Process optimization

1. Introduction

The last two decades has seen a speedy growth in the novel applications of injection molding of thermoplastic materials. In the process, polymer in the molten phase is injected into a mold cavity and further shaped under high pressure. Injection molding has several advantages such as quick processing times, simplicity of operation, excellent flexibility, corrosion resistance and capability to produce parts of complex geometric configurations [1]. The injection molding process however has limitations including occurrence of defects such as shrinkage, sink marks and warpage. These defects are caused by variations in temperature and pressure that causes inducement of residual stresses on the part surfaces.

Several research studies have been performed worldwide aiming at experimental analysis or numerical simulations to identify the reasons behind injection molding defects. A number of new investigations have emerged, offering significant findings in the area of injection molding [2-9]. The residual stresses in injection molding are caused due to the following: i) thermally induced stress during cooling and ii) viscoelastc flow of the polymer during filling and post filling phases [2]. The geometry of the part is influenced by the injection molding control variables. The holding pressure is found to significantly influence the part geometry as well as the residual stresses induced in it [3]. Furthermore, injection speeds, mold temperature, melt temperature and packing pressure are found to have a direct effect on the residual stresses [4, 5]. The residual stresses on injection mould could be minimized by attaining an effective control over the injection molding process variables. However, because of the complex phenomena of injection molding process and large number of control variables, process optimization still remains as a challenge [6]. One of the approaches to minimize residual stresses was by a selection of optimum wall thickness of the parts, which was attempted in [7]. Tang et al. [8] developed a numerical model for the temperature distribution to calculate thermal residual stresses in the plastic injection molding. They have considered the effect of uneven cooling of the part to obtain thermal residual stresses at various sections of the mold. A hybrid method using advanced soft computing tools involving genetic algorithm and artificial neural network was used to calculate the residual stresses in plastic injection molding at various sections of the part in [9]. The method involved selection of optimum process control variables for the minimum residual stresses on the part represented as a quality indicator of the surface defects as a result of three-dimensional shrinkage effect. However, the method failed in predicting the residual stress levels at different conditions and instances of injection molding. A similar approach was followed in [10] using global optimization genetic algorithm and back propagation neural network to correlate the responses and the process control variables. Five variables were observed to be dominant in controlling the injection molding process. The variables were packing pressure, packing time, mold temperature, melt temperature and cooling time.

2. Injection molding process control variables

In injection molding process, the properties of the thermoplastic material, design of the feeding system and the process control variables determine the inducement of residual stresses in the products. Table 1 shows a summary indicating various defects in the injection molded products.

Table 1. A summary of common defects in injection molded products

Sl. No.	Type of defect	Reason for occurrence	Possible solutions and recommendations	Reference
1	Brittleness	Thermal degradation of the melt	Increase in injection speed and injection pressure, a decrease in residual stresses in the part	[8,11]
2	Warpage and shrinkage	Positions of the gates, process settings for the mould	Selection of gate positions, orientations and lower residual stress levels	[2, 5,7,12,13]
3	Weld lines	Insufficient mixing of two streams of molten plastic	Enhancement of interface temperature and pressure, venting at such positions	[8,11,13]
4	Flash lines	Greater injection forces, excess feed, overheating	To remove the residual stresses and locked in strains	[7,8,11]
5	Material discoloration	Melt stagnation, flow over sharp edges	Remove excessive residual stress induced by ejection system	[5,11-13]

The occurrence of defects in injection molding process is primarily due to residual stresses accumulated during the period after the filling. The residual stresses induced in the part are controlled by the injection molding variables, material of the mold and the geometry of the mold [14].

A systematic examination of the results reported in the literature has shown that a number of control variables influence the physics of the injection molding process. Among these control variables, residual stress formation is influenced by number of control variables, see Fig. 1. A statistical approach involving treatment of injection molding process as a multi-objective function was reported in [15] and [16]. The method included analytical hierarchical process, analysis of variance, Taguchi techniques and finite element scheme. Objective functions chosen were warpage, volumetric shrinkage, sink marks, cooling time and residual stresses. However, according to a summary of literature presented in Table 1, residual stress is the dominant objective function and is considered to be an important cause for occurrence of defects. Therefore, in this paper, a single objective optimization of residual stress considering the effect of injection molding control variables is considered. The settings of temperature of melt, temperature of mold, holding pressure, holding time, volume filled and time for filling are selected to obtain the lowest level of residual stress.

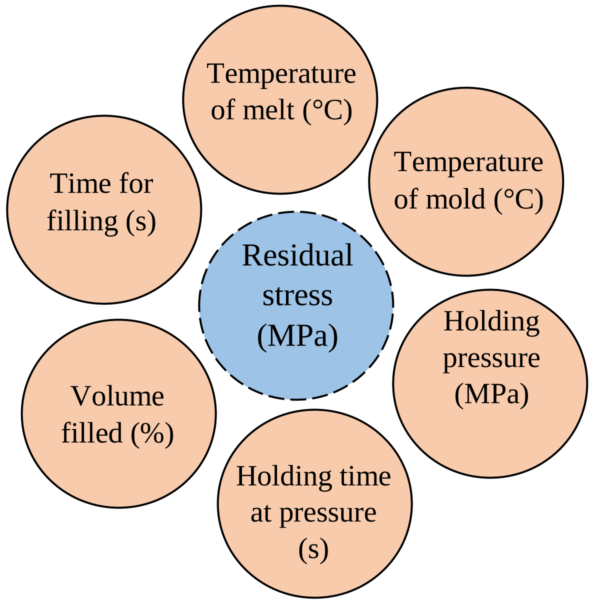


Fig. 1 Identification of the factors influencing residual stress in injection molding

3. Research methodology

For the present investigation, annealed stainless steel is used as the mold, and PVC is used as the material. The properties of the mold and material are shown in Table 2.

Table 2. Governing properties of material and mold

Sl. No	Material: PVC		Mold: Annealed SS grade 420	
1	Allowable shear stress (MPa)	0.19	Specific heat (J/g°C)	0.46
2	Allowable shear rate (s^{-1})	20,000	Thermal conductivity (W/cm°C)	0.25
3	Poisson's ratio	0.38		
4	Thermal expansion coefficient $(°C)^{-1}$	0.00007		

Fig. 2 shows a schematic of the methodology of this research. The data ranges for the control variables are selected and provided as the input for the analysis. Furthermore, the absolute values of the residual stresses (raw data) are collected and are chosen as the process output. The analysis of means and analysis of variance techniques are employed to generate a relationship between residual stress and control variables.

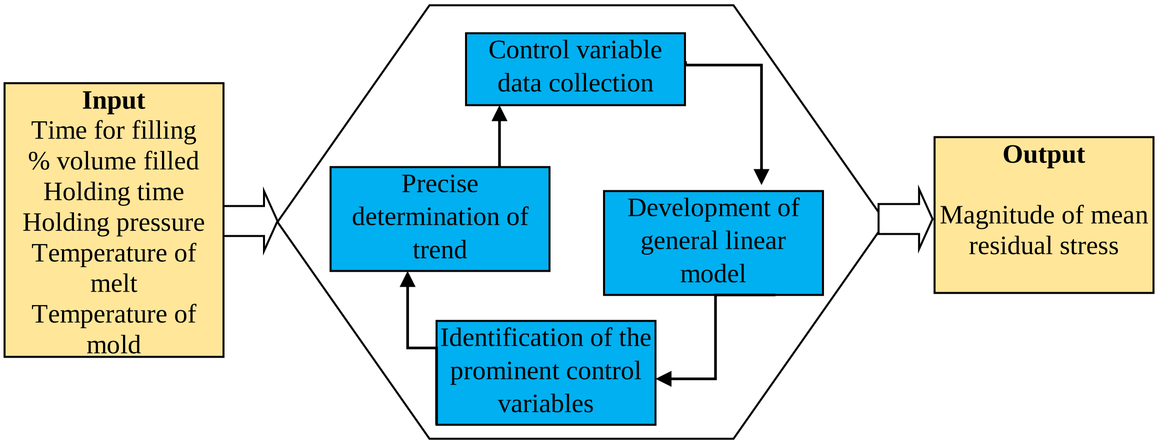


Fig. 2 Schematic of methodology of injection molding investigation

4. Results and discussion

Table 3 shows the results of the general linear model fitting the control variables and the mean residual stress.

Table 3. Results of general linear model – analysis of variance for residual stress

Factor	Type	Levels	Values
Time for filling (s)	fixed	3	1.0, 1.5, 2.0
Melt temperature (deg celsius)	fixed	3	180, 195, 210
Mold temperature (deg celsius)	fixed	3	30, 40, 50
Volume filled (%)	fixed	3	92, 96, 100
Holding time at pressure (s)	fixed	3	5, 10, 15
Pressure for holding (MPa)	fixed	3	60, 80, 100
Coolant in temp.. (deg celsius)	fixed	3	15, 20, 25

Analysis of Variance for Residual stress (MPa), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Time for filling (s)	2	39.799	39.799	19.900	27.06	0.000
Melt temperature (deg celsius)	2	111.116	111.116	55.558	75.56	0.000
Mold temperature (deg celsius)	2	11.350	11.350	5.675	7.72	0.001
Volume filled (%)	2	32.825	32.825	16.413	22.32	0.000
Holding time at pressure (s)	2	29.471	29.471	14.735	20.04	0.000
Pressure for holding (MPa)	2	918.537	918.537	459.269	624.59	0.000
Coolant in temp.. (deg celsius)	2	29.229	29.229	14.615	19.88	0.000
Error	120	88.238	88.238	0.735		
Total	134	1260.565				

S = 0.857506 R-Sq = 93.00% R-Sq(adj) = 92.18%

As evident from Table 1, all the control variables significantly influence residual stress at a confidence level of 95%. The R-sq value of the data is 93%. The p-values in the table show that all the control variables are significant at 95% confidence level. Furthermore, F-value in the table indicates the relative significance of all the control variables. The highest F-value of 624.59 corresponds to the pressure for holding. The next highest F-value of 75.56 corresponds to melt temperature. As seen from Fig. 3, pressure for holding is the most significant variable.

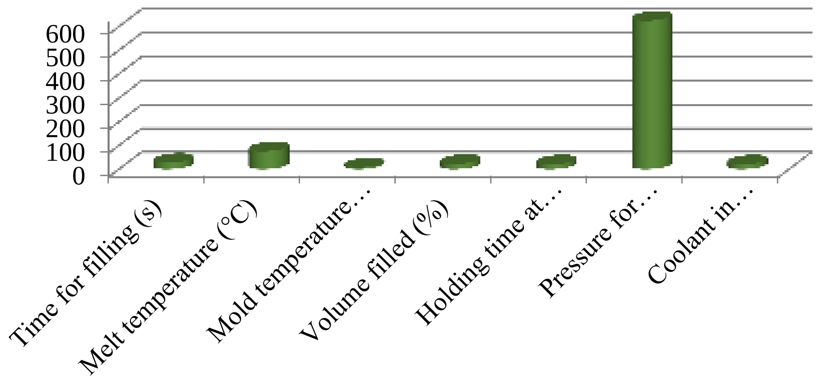


Fig. 3. F-value representing the relative significance of control variables

The analysis of means plots for residual stresses is presented in Fig. 4. The pressure for holding and melt temperature causes an increase in residual stress. The trend of both variables is a linear increase. As the pressure for holding increases from 60 to 100 MPa, the increase in residual stress is by 55%. Similarly, with an increase in melt temperature, the increase in residual stress is only by 17%. The residual stress has shown a decreasing trend with an increase in time for filling from 1.0 to 1.5 s. While the time for filling is increased further to 2 s, increase in residual stress is not observed. This indicates that for polymers, an adequate amount of filling time is necessary to achieve a uniform flow of the material in order to get the lowest residual stress. As the mold temperature increases from 30 to 50°C, a slight decrease in residual stress is observed. This is also evident from Table 3, with the lowest value of F as 7.72. The residual stress decreases by 7% with an increase in the percentage of volume filled from 92% to 100%. A similar trend and effect on residual stress is observed for the holding time at pressure. The lowest value of 13.76 MPa is obtained corresponding to a coolant in temperature of 20°C.

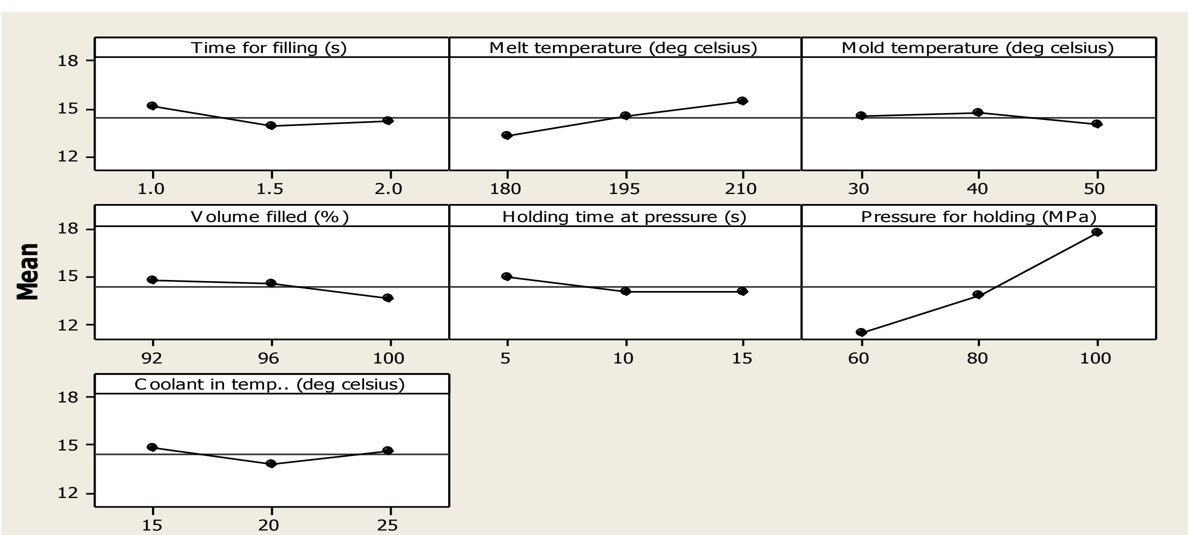
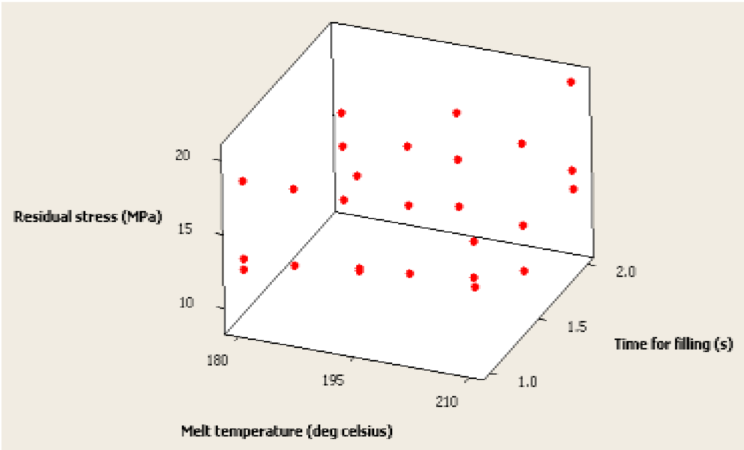


Fig. 4 Analysis of means plots for residual stress against control variables

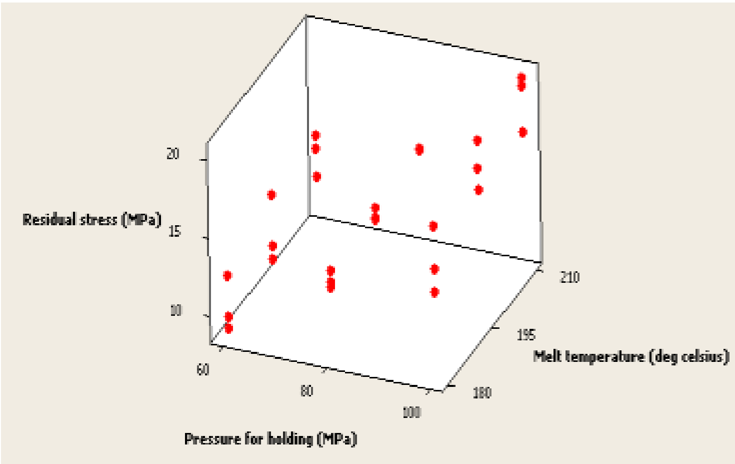
The three dimensional scatter plots of all the control variables with residual stresses are presented in Fig. 5 a-c. Among the seven variables considered in this investigation, only three variables are included in representing relationship using the scatter plots. The variables with the highest values of F values are pressure for holding (F=624.59), melt temperature (F=75.56) and time for filling (F =27.06). According to the analysis of variance, test for lack of fit, comparison of R-squared values and analysis of means, representation of the correlation between residual stress (σ_r) and the control variables is obtained as a general linear regression equation. The equation (1) can be used to predict average residual stress within the area of statistical investigation.

$$\sigma_r = 5.14593 - 0.974444\, t_f\,(s) + 0.0735926\, T_{me}\,(°C) - 0.0236111\, T_{mo}\,(°C) - 0.144444\, V_f\,(\%) - 0.0995556\, t_{hp}\,(s) + 0.158361\, P_h\,(MPa) - 0.0245556\, T_{in}\,(°C) \quad (1)$$

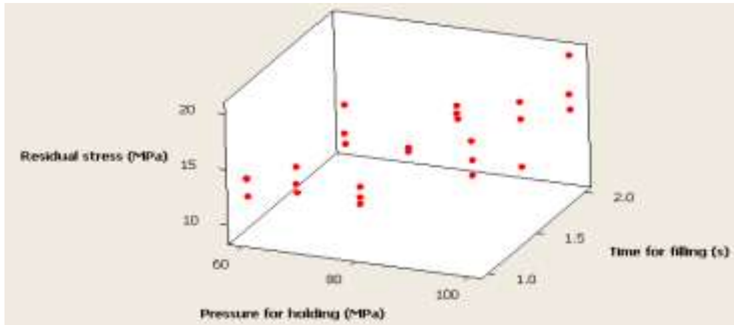
where, t_f is the time for filling in s, T_{me} is the temperature of the melt in °C , T_{mo} is the temperature of the mold °C, V_f is the volume filled in %, t_{hp} is the holding time at pressure in s, P_h is the pressure for holding in MPa and T_{in} is the temperature at the inlet of coolant in °C.



a.



b.



c.

Fig. 5 a-c Three-dimensional scatter plots for combinations of the most significant control variables with residual stress, a. melt temperature × time for filling, b. melt temperature × pressure for holding, c. pressure for holding × time for filling

The optimum injection molding parameters for the minimum residual stress were identified as a result of the performed analysis shown in Table 4.

Table 4 Optimum injection molding control variables

Time for filling (s)	Temperature of melt (°C)	Temperature of mold (°C)	Volume filled (%)	Holding time at pressure (s)	Pressure for holding (MPa)	Coolant in temperature (°C)
1.5	180	50	100	15	60	20

5. Conclusions and Future work

The paper presents a distinct approach for optimization of injection molding process control variables. The objective function was minimization of residual stress in the process. Based on the investigation and analysis, the following conclusions have been arrived at:

- Residual stress is considered to be a major factor influencing the development of defects on injection molded components. Injections molding input settings influence the distribution of residual stresses.
- Due to the complex nature of localized distribution of residual stresses, all the control variables including temperatures, pressures, and time of filling indicate a significant influence. The results of statistical treatment obtained using the general linear model also indicates this effect.
- The control variables, namely, pressure for holding, melt temperature and time for filling are found to be significant. In order to obtain the optimum operating condition, pressure for holding shows the highest significance with the highest 'F' value of 624.59.
- The pressure for holding and melt temperature causes a linear increase in the mean residual stress of the injection molded component. As the pressure for holding increases from 60 to 100 MPa, the increase in residual stress is by 55%. Similarly, with an increase in melt temperature, the increase in residual stress is only by 17%.
- A general expression for linear regression between residual stress and the control variables was established for the range of values selected in this investigation. Three dimensional scatter plots for the prevailing three control variables, viz. pressure for holding, melt temperature and time for filling was developed against residual stress.
- The optimum control variables for the minimum residual stress were obtained for minimum average residual stress: time for filling = 1.5 s, temperature of melt = 180°C, temperature of mold = 50°C, volume filled = 100%, holding time at pressure = 15 s, pressure for holding = 60 MPa and coolant in temperature = 20°C.

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References

[1] Schafer, H., Pretschuh, C., Bruggemann, O. (2019), Reduction of cycle times in injection molding of PLA through bio-based nucleating agents, *European Polymer Journal*, v115, n1, pp. 6-11.

[2] Gu, Y. X., Shen, C. Y. (2001), Numerical simulation of thermally induced stress and warpage in injection-molded thermoplastics, *Advanced Polymer Technology*, v20, n1, pp. 14-21.

[3] Attia, U. M., Alcock, J. R. (2010), Optimizing process conditions for multiple quality criteria in micro-injection molding, *International Journal of Advanced Manufacturing Technology*, v50, n5-8, pp. 533-542.

[4] Nagahanumaiah, Ravi, B. (2009), Effects of injection molding parameters on shrinkage and weight of plastic part produced by DMLS mold, *Rapid Prototyping Journal*, v15, n3, pp. 179-186.

[5] Erzurumlu, T., Ozcelik, B. (2006), Minimization of warpage and sink index in injection-molded thermoplastic parts using Taguchi optimization method, *Materials and Design*, v27, n10, pp. 853-861.

[6] Bensingh, R. J., Machavaram, R., Boopathy, S. R., Jebaraj, C. (2019), Injection molding process optimization of a bi-aspheric lens using hybrid artificial neural networks (ANNs) and particle swarm optimization (PSO), *Measurement*, v1354, n1, pp. 359-374.

[7] Lee, B. H., Kim, B. H. (1995), Optimization of part wall thickness to reduce warpage of injection-molded parts based on the modified complex method, *Polymer Plastics Technology Engineering*, v34, n1, pp. 793-811.

[8] Tang, S. H., Kong, Y. M., Sapuan, S. M., Samin, R., Sulaiman, S. (2006), Design and thermal analysis of plastic injection mould, *Journal of Materials Processing Technology*, v171, n2, pp. 259-267.

[9] Shen, C. Y., Wang, L. X., Li, Q. (2007), Optimization of injection molding process parameters using combination of artificial neural network and genetic algorithm method, *Journal of Materials Processing Technology*, v183, n2-3, pp. 412-418.

[10] Yin, F., Mao, H., Hua, L. (2011), A hybrid of back propagation neural network and genetic algorithm for optimization of injection molding process parameters, *Materials and Design*, v32, n6, pp. 3457-3464.

[11] Tran, N. T., Gehde, M. (2019), Creating material data for thermoset injection molding simulation process, *Polymer Testing*, v73, n1, pp. 284-292.

[12] Lakkanna, M., Kumar, G. C. M., Kadoli, R. (2016), Computational design of mold sprue for injection molding thermoplastics, *Journal of Computational Design and Engineering*, v3, n1, pp. 37-52.

[13] Huang, C. T., Hsu, Y. H., Chen, B. S. (2019), Investigation on the internal mechanism of the deviation between numerical simulation and experiments in injection molding product development, *Polymer Testing*, v75, n1, pp. 327-336.

[14] Zhou, H., Li, D. (2005), Residual stress analysis of the post-filling stage in injection molding, *International Journal of Advanced Manufacturing Technology*, v25, n7-8, pp. 700-704.

[15] Sorgato, M., Babenko, M., Lucchetta, G. and Whiteside, B. (2017), Investigation of the influence of vacuum venting on mould surface temperature in micro injection moulding, *International Journal of Advanced Manufacturing Technology,* v88, n1-4, pp. 547-555.

[16] Alkaabneh, F. A., Barghash, M., Mishael, I. (2013), A combined analytical hierarchical process (AHP) and Taguchi experimental design (TED) for plastic injection molding process settings, *International Journal of Advanced Manufacturing Technology*, v66, n5-8, pp. 679-694.