www.arpnjournals.com

OPTIMISATION OF PROCESS PARAMETERS IN LINEAR RUNNER FAMILY INJECTION MOLD USING MOLDFLOW SIMULATION SOFTWARE

Mohd Amran Md Ali, Noorfa Idayu, Mohd Sanusi Abd Aziz, Mohd Hadzley and Sivaraos
Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Melaka, Malaysia
E-Mail: mohdamran@utem.edu.my

ABSTRACT

The optimization of process parameters in family injection mold using moldflow simulation software was studied. Type of runner employed was linear runner layout system. The simulation matrix was planned using Taguchi method and the data were analyzed using Minitab. The family mold that consists of plastic parts such as tensile specimen, impact specimen, flexural specimen and hardness specimen were designed using CATIA. Then, designed plastic parts in CATIA software were imported into Moldflow software to transform the plastic specimen parts from solid form to mesh form. Feeding system such as sprue, runner and gate including water cooling system was designed inside the mold. Determination of the type of injection molding machine and the type of plastic material in the settings was taking under cool + fill + pack + warp analysis. It was found that the most influential parameters is melt temperature. Based on ANOVA result, all the three responses such as deflection, volumetric shrinkage and residual stress have significantly affected by melt temperature. Melt temperature is an important parameter to determine the deflection, shrinkage and residual stress that can lead to warpage of molded parts. High melt temperature value resulting in lowest value of deflection and in-cavity residual stress. Therefore, by using moldflow simulation software, it can helps manufacturers to predict and prevent any potential manufacturing defects as well as reducing cost and waste of material.

Keywords: simulation, linear runner layout, taguchi method, optimization.

INTRODUCTION

Harper [1] stated injection molding process is a rapid process when comparing with other type of molding processes. Furthermore, after a cycle of the process is completed, feed system such as sprue, runner and gate can be recycled. According to Ghosh [2], this injection machine works by injecting molten thermoplastic into a mold cavity. This process is subjected to high pressure so that the melted thermoplastic is injected by plunger action with the help of plunger system. Harper [3] said plastic injection molding machines composed of three components such as the injection unit, the clamping unit and the control system. In the injection unit section, it will plasticate and inject the polymer melt. At the same time, the clamping unit supports the mold, opens and closes the mold and clamping unit also has the part ejection system. According to Amran *et al.* [4], holding pressure contributed the most significant parameter on quality of flatness of plastic part, then followed by back pressure, clamping pressure and injection time. This was due to the back pressure pushed the volume of cushion area at the end of injection nozzle to compensate solidifying process in cavity area during cooling process.

INJECTION MOLDING

Injection Molding Parameters

Yin *et al.* [5] found that there are five process parameters are selected as the design variables in the mathematical model in order to optimize the optimization of injection molding process. The process parameters are mold temperature, melt temperature, packing pressure, packing time as well as the cooling time. Usually, the upper and lower bounds of the process parameters are set based on the recommended parameters values provided by Moldflow software. Dang [6] said melt temperature also one of the design variables in order to determine warpage, shrinkage, or residual stress. Kwiatkowski *et al.* [7] found a higher mold temperature makes cavity filling more easily. In addition, a decrease in the temperature gradient between the polymer and mold wall will decrease residual stresses in the part. In the research, it was found that when lowering mold temperature values, there was an increase in residual stresses of the part. According to Reddy *et al.* [8], during production of the plastic parts, quality problems such as warpage, shrinkage, weld and meld lines, flow mark, flash, sink mark and void were affected from manufacturing process conditions such as injection time. In 2005, Kurtaran *et al.* [9] found that warpage is directly proportional with cooling time and inversely proportional with mold temperature, melt temperature, packing pressure and packing pressure. Azaman *et al.* [10] found the effect of different cooling times that occurs at the centre of the surface of the thin-walled parts from 10 seconds to 50 seconds on the residual stresses showed no obvious change.

Injection Mold

Basically, molds are differentiate according to the number of cavities inside them. One cavity is called as single-cavity molds and if the molds contain several parts, they are considered as multiple cavity molds or family mold [11]. Mold is embedded with water cooling for stabilizing the mold temperature at appropriate

www.arpnjournals.com

temperature at longer running time. Amran *et al.* [12] mentioned that mold having good distribution cooling produced low shrinkage. Injection mold appropriately using thermoplastic materials as compare with thermoset materials. Chemical properties of thermoplastics remain the same after molding process. It is mean after molding process, thermoplastics can be reused by chopping or cutting them into smaller size and remelting them. Meanwhile, for themosets plastics, it cannot be remolded due to the changes or alterations in its chemical properties from their raw forms [13].

Design of Experiments (DOE)

DOE using Taguchi approach attempts to extract maximum important information with minimum number of experiments. Taguchi techniques also are experimental design optimization techniques which use standard Orthogonal Arrays (OA) for forming a matrix of experiments. Taguchi design will recognize not all factors that cause variability can be controlled. The uncontrollable factor is called noise factor. Hence, this method will identify controllable factor that will minimize the effect of the noise factor. Mohd *et al.* [14] stated that in the Taguchi experimental design, S/N ratio is the ratio of signal-to-noise, where signal represents the desirable values. For example is the mean for the output characteristic. Meanwhile noise represents the undesirable value such as the square deviation for the output characteristic. Other than that, Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available depending on type of characteristic such as lower is better, nominal is better and higher is better. Amran *et al.* [15] mentioned that analysis of variance (ANOVA) on the collected data from the Taguchi design of experiments can be used to select new parameter values to optimize the performance characteristic. In addition, without the use of ANOVA, no significant parameters and each of input parameter contribution to the response cannot be calculated. In 2014, Kim *et al.* [16] used Autodesk simulation Moldflow software to study about imbalance filling of multicavity mold. Further, Amran *et al.* [17] stated that optimized runner system can be done in family mold even having different volume by optimized the filling time using mold flow software. This project optimizes injection molding parameters suggestion from moldflow software to the responses such as deflection, volumetric shrinkage and cavity residual stress using Taguchi method.

EXPERIMENTAL

Specimens such as tensile test specimen, hardness test specimen, impact test specimen and flexural test specimen are drawn by using CATIA V5 as shown in Figure-1. Each of the part is drawn based on their ASTM standard. Each part has the same thickness of 3 mm. Autodesk Simulation Moldflow® Insight software is used for injection molding simulation analysis. The family mold plastic part drawings are imported to moldflow environment and meshed with triangular elements.
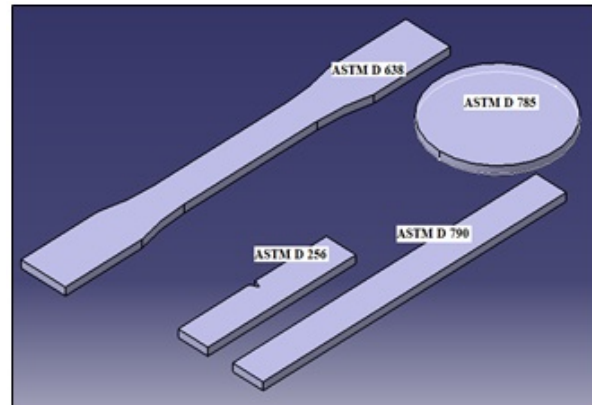

Figure-1. Family mold parts are drawn by using CATIA software

Linear Runner Layout System

Linear runner layout system was employed in this study as shown in Figure-2.
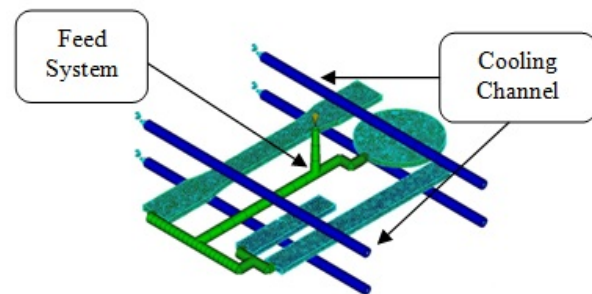

Figure-2. (a) Linear runner layout

After the model is successfully generated, the details of the family mold can be obtained in the moldflow software. The mesh match percentage of this model is 99.9% which is higher than 85% allowable value. This is important in order to determine whether elements of different surfaces are corresponding with each other. The simulation model was performed by using set analysis called as (Cool +Fill + Pack + Warp).

Injection Molding Process Parameters

The injection molding machine used is a default setting injection molding machine in the software. Specifications of injection-molding machine are shown in Table-1. Material used is polypropylene (3131 MU7) and its property is shown in Table-2.

Table-1. Specifications of injection-molding machine.

Parameters	Values
Maximum machine injection pressure (MPa)	180
Maximum machine injection rate (cm³/s)	5000
Maximum machine clamp force (tonne)	7000

www.arpnjournals.com

Table-2. Polypropylene (3131 MU7) material properties.

Material properties	Values
Melt Mass-flow Rate (g/10 min)	11
Elastic Modulus (MPa)	1340
Shear Modulus (MPa)	481
Poisson ratio	0.4

The processing parameters are obtained from the Analysis Moldflow software. The software has recommended the parameters such as mold temperature, melt temperature, injection time. For cooling time, the software recommended about 18 seconds for family mold. The process parameters are summarized in Table-3.

Table-3. Recommended process parameter by moldflow simulation software.

Parameters	Values
Recommended Mold Temperature (°C)	32
Recommended Melt Temperature (°C)	210
Recommended Injection Time (s)	0.7
Recommended Cooling Time (s)	18

In the simulation, 3 level designs are used such as low level, medium level and high level. The four factors involve in the simulation are mold temperature (MoT), melt temperature (MeT). Then it is followed by injection time (IT), and cooling time (CT). The process parameters employed in moldflow analysis with both factors and levels are shown in Table-4.

Table-4. Simulation parameters.

Process Parameters	Level		
	low	Medium	high
Mold Temperature (°C)MoT	15	25	35
Melt Temperature (°C) MeT	225	240	255
Injection Time (s) IT	0.4	0.7	1
Cooling Time (s) CT	10	18	26

Taguchi Method using Minitab 17 Software

Taguchi performed the orthogonal array which means that the design is balanced so that factor levels are weighted equally. L9 orthogonal array is chosen because the design is balanced based on the four factors. The L9 orthogonal array is shown in Table-5.

Table-5. The orthogonal array in Taguchi method with 9 runs of simulations.

Run	MoT (°C)	MeT (°C)	IT (s)	CT (s)
1	15	225	0.4	10
2	15	240	0.7	18
3	15	255	1	26
4	25	225	0.7	26
5	25	240	1	10
6	25	255	0.4	18
7	35	225	1	18
8	35	240	0.4	26
9	35	255	0.7	10

RESULT AND DISCUSSIONS

The responses to be studied are deflection, volumetric shrinkage at ejection, and in-cavity residual stress in first principal direction and the results of simulations were summarised in Table-6.

Table-6. Summarize of the simulation results for each run.

Run	Deflection (mm)	Volumetric Shrinkage at ejection (%)	In- Cavity Residual Stress (MPa)
1	0.9354	10.03	30.88
2	0.9230	10.93	29.02
3	0.9043	11.64	27.91
4	0.9457	10.24	30.47
5	0.9279	10.87	28.80
6	0.8917	11.69	28.53
7	0.9508	10.27	30.22
8	0.9137	10.94	29.55
9	0.9000	11.68	28.13

Analysis Results of Deflection

In S/N response for deflection, the smaller the better characteristic arrangement is selected for deflection analysis. Table-7 shows the corresponding S/N ratio for deflection generated from the Minitab 17 software. From the table, the lowest deflection value is 0.8917 mm from run 6 and the simulation result is shown in Figure-3.

Table-7. Corresponding S/N ratio for deflection.

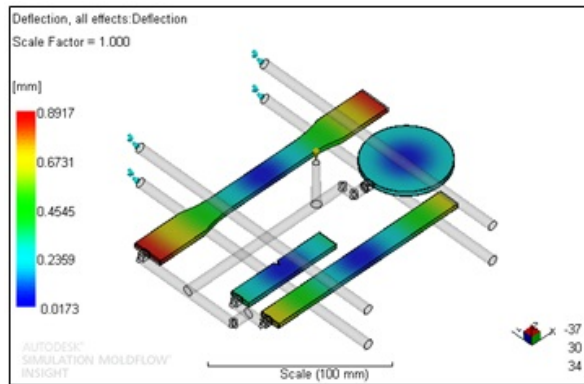| Run	MoT (°C)	MeT (°C)	IT (s)	CT (s)	Deflection (mm)	S/N
1	15	225	0.4	10	0.9354	0.5800
2	15	240	0.7	18	0.9230	0.6959
3	15	255	1	26	0.9043	0.8737
4	25	225	0.7	26	0.9457	0.4849
5	25	240	1	10	0.9279	0.6499
6	25	255	0.4	18	0.8917	0.9956
7	35	225	1	18	0.9508	0.4382
8	35	240	0.4	26	0.9137	0.7839
9	35	255	0.7	10	0.9000	0.9151

www.arpnjournals.com

Figure-3. Simulation result of deflection from run 6 in autodesk simulation moldflow software

The response table of S/N ratio for deflection for all parameters at different levels is shown in Table 8. From the table, deflection is significantly influenced by the melt temperature (MeT). Then it is followed by injection time (IT), mold temperature (MoT) and cooling time (CT). The delta values for the parameters were 0.4271, 0.1326, 0.0064 and 0.0051 respectively.

Table-8. Response table for S/N ratio of deflection.

Level	MoT (°C)	MeT (°C)	IT (s)	CT (s)
1	0.7166	0.5011	0.7865	0.7151
2	0.7102	0.7100	0.6987	0.7099
3	0.7124	0.9282	0.6540	0.7142
Delta	0.0064	0.4271	0.1326	0.0051
Rank	3	1	2	4

Figure-4 shows the signal to noise ratio response graph for deflection. From the graph, it is concluded that the optimum parametric combination were mold temperature 15° C (Level 1), melt temperature 255° C (Level 3), injection time 0.4 s (Level 1), and cooling time 10 s (Level 1). From the graph, it shows that melt temperature significantly affected the deflection values.
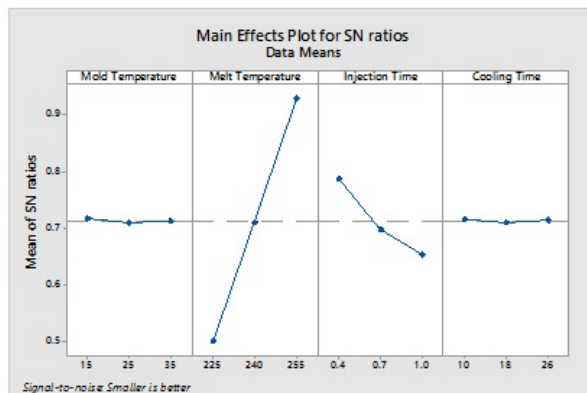

Figure-4. Signal to noise (S/N) graph for deflection.

Analysis of Variance (ANOVA) for Deflection

By using ANOVA, the significance parameter level that affects the deflection can be determined. Table-9 represents the summary of ANOVA result. When considering the p-value of the parameter, if the p-value is very small which less than 0.05, then the parameter has a significant effect on the response. P-value for the melt temperature is 0.001 which is less than 0.05 and it indicates that melt temperature is a significant parameter.

Table-9. One-way ANOVA for deflection.

Input parameters	MoT (°C)	MeT (°C)	IT (s)	CT (s)
R-Sq (%)	0.03	90.87	9.07	0.03
R-Sq (adj) (%)	0.00	87.83	0.00	0.00
p-value	0.999	0.001	0.752	0.999
Rank	3	1	2	4

Validation of Parameter for Deflection

The optimum parameter combination of the injection molding process were mold temperature 15° C (Level 1), melt temperature 255° C (Level 3), injection time 0.4 s (Level 1), and cooling time 10 s (Level 1). This setting of parameters should lower deflection value than 0.8917 mm. In Minitab software, Taguchi can predict the result of response for these optimal parameters setting. It means that by using predict Taguchi result, the software can determine the signal to noise ratios as well as response characteristics for selected new factor settings. The result of prediction by using optimum parameter setting is 0.8901 mm. Equation 1 shows example of percentage error calculation.

$$\text{Error } (\%) = \frac{|\text{Lowest deflection} - \text{optimize deflection}|}{|\text{Lowest deflection}|} \quad (1)$$

$$\text{Error } (\%) = \frac{|0.8917 - 0.8901|}{|0.8917|} = 0.18\,\%$$

From the calculation, the difference between lowest simulation value of deflection and optimize deflection is only 0.18%. The result is acceptable and proves that the verification result correlates with the verification test. Therefore, in order to achieve the lowest deflection value, the optimum parameter for deflection is considered valid.

Analysis Results of Volumetric Shrinkage at Ejection

The smaller the better quality characteristic has been selected for determination of S/N ratio for volumetric shrinkage at ejection. Table-10 shows the corresponding S/N ratio for volumetric shrinkage at ejection and the lowest value is 10.03% from run 1 and the simulation result is shown in Figure-5.

www.arpnjournals.com

Table-10. Corresponding S/N ratio for volumetric shrinkage at ejection.

Run	MoT (°C)	MeT (°C)	IT (s)	CT (s)	Vol. Shrinkage (%)	S/N
1	15	225	0.4	10	10.03	-20.0260
2	15	240	0.7	18	10.93	-20.7724
3	15	255	1	26	11.64	-21.3191
4	25	225	0.7	26	10.24	-20.2060
5	25	240	1	10	10.87	-20.7246
6	25	255	0.4	18	11.69	-21.3563
7	35	225	1	18	10.27	-20.2314
8	35	240	0.4	26	10.94	-20.7803
9	35	255	0.7	10	11.68	-21.3489
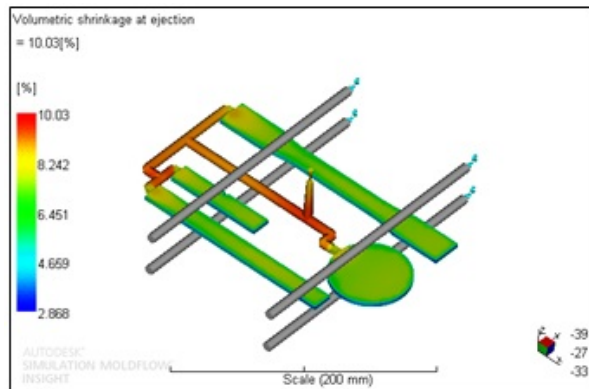
Figure-5. Simulation result of volumetric shrinkage at ejection from run 1 in Autodesk Simulation Moldflow software.

The response table of S/N ratio for volumetric shrinkage at ejection for all parameters at different levels is shown in Table-11. From the table, volumetric shrinkage at ejection is significantly most influenced by the melt temperature (MeT). Then it is followed by cooling time (CT), mold temperature (MoT) and injection time (IT). The delta values for the parameters were 1.19, 0.09, 0.08 and 0.05 respectively

Table-11. Response table for S/N ratio of volumetric shrinkage at ejection.

Level	MoT (°C)	MeT (°C)	IT (s)	CT (s)
1	-20.71	-20.15	-20.72	-20.70
2	-20.76	-20.76	-20.78	-20.79
3	-20.79	-21.34	-20.76	-20.77
Delta	0.08	1.19	0.05	0.09
Rank	3	1	4	2

Figure-6 shows the signal to noise ratio response graph for volumetric shrinkage at ejection. From the slope of graph, it is concluded that the optimum parametric combination were mold temperature 15° C (Level 1), melt temperature 225° C (Level 1), injection time 0.4 s (Level

1), and cooling time 10 s (Level 1). It is found that, the optimum parameters were the same with parameter of run 1 of the simulation. From the graph, it shows that melt temperature significantly affected the deflection values.
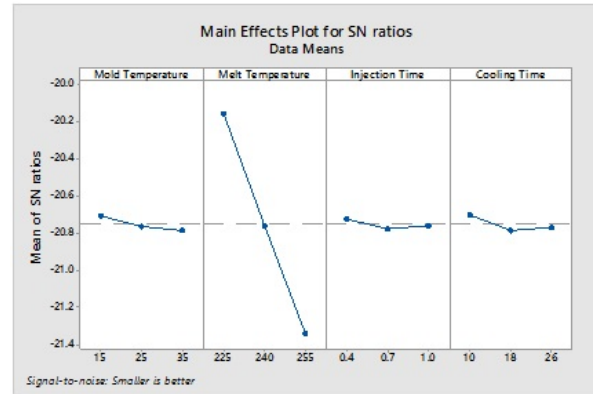
Figure-6. Signal to noise (S/N) graph for volumetric shrinkage at ejection.

Analysis of Variance (ANOVA) for Volumetric Shrinkage at Ejection

By using ANOVA, the significance parameter level that affects the volumetric shrinkage at ejection can be determined. Table-12 represents the summary of ANOVA result. By considering the p-values of the parameter, if the p- value is very small which less than 0.05, then the parameter has a significant effect on the response. P-value for the melt temperature is 0.000 which is less than 0.05 and it indicates that melt temperature is the most significant parameter.

Table-12. One-way ANOVA for volumetric shrinkage at ejection.

Input parameters	MoT (°C)	MeT (°C)	IT (s)	CT (s)
R-Sq (%)	0.44	98.86	0.18	0.52
R-Sq (adj) (%)	0.00	98.48	0.00	0.00
P	0.987	0.000	0.995	0.984
Rank	3	1	4	2

Validation of Parameter for Volumetri Shrinkage at Ejection

The optimum parameter combination of the injection molding process were mold temperature 15° C (Level 1), melt temperature 225° C (Level 1), injection time 0.4 s (Level 1), and cooling time 10 s (Level 1). This setting of parameters should lower than percentage volumetric shrinkage at ejection of 10.03 %. In Minitab software, Taguchi can predict the result of response for these optimal parameters setting. It means that by using predict Taguchi result, the software can determine the signal to noise ratios as well as response characteristics for selected new factor settings. The result of prediction by using optimum parameter setting is the same value with

www.arpnjournals.com

run 1 which is 10.03%. From the calculation, the difference between lowest volumetric shrinkage value of simulation and optimize volumetric shrinkage value is 0.0%. The result is very acceptable and proves that the verification result correlates with the verification test. Therefore, in order to achieve the lowest percentage value of volumetric shrinkage at ejection, the optimum parameters is considered valid.

Analysis Results of In-Cavity Residual Stress In First Principal Direction
The smaller the better characteristic is also used in order to obtain the optimum process parameters for lowest value of in-cavity residual stress Table-13 the corresponding S/N ratio for in-cavity residual stress and the lowest value is 27.91 MPa from run 3 and the simulation result is shown in Figure-7.

Table-13. Corresponding S/N ratio for in-cavity residual stress.

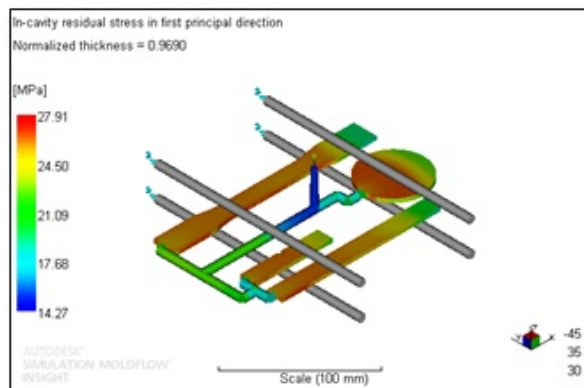| Run	MoT (ᵒC)	MeT (ᵒC)	IT (s)	CT (s)	In-Cavity Residual Stress (MPa)	S/N
1	15	225	0.4	10	30.88	-29.7935
2	15	240	0.7	18	29.02	-29.2539
3	15	255	1	26	27.91	-28.9152
4	25	225	0.7	26	30.47	-29.6774
5	25	240	1	10	28.80	-29.1878
6	25	255	0.4	18	28.53	-29.1060
7	35	225	1	18	30.22	-29.6059
8	35	240	0.4	26	29.55	-29.4111
9	35	255	0.7	10	28.13	-28.9834

Figure-7. Simulation result of in-cavity residual stress from run 3 in autodesk simulation moldflow software.

The response table of S/N ratio for in-cavity residual stress in first principal direction for all parameters at different levels is shown in Table-14. From the table, in-cavity residual stress is significantly most influenced by the melt temperature (MeT). Then it is followed by injection time (IT), cooling time (CT) and mold temperature (MoT). The delta values for the parameters were 0.69, 0.20, 0.01 and 0.01 respectively.

Table-14. Response table for S/N ratio of in-cavity residual stress.

Level	MoT (oC)	MeT (oC)	IT (s)	CT (s)
1	-29.32	-29.69	-29.44	-29.32
2	-29.32	-29.28	-29.30	-29.32
3	-29.33	-29.00	-29.24	-29.33
Delta	0.01	0.69	0.20	0.01
Rank	4	1	2	3

Figure-8 shows the signal to noise ratio response graph for in-cavity residual stress. From the slope of graph, it is concluded that the optimum parametric combination were mold temperature 15ᵒ C (Level 1), melt temperature 255ᵒ C (Level 3), injection time 1 s (Level 3), and cooling time 10 s (Level 1). From the graph, it shows that melt temperature significantly affected the deflection values.
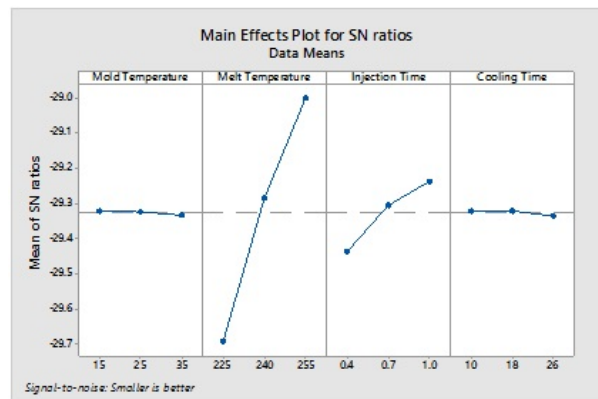

Figure-8. Signal to noise (S/N) graph for in-cavity residual stress

Analysis of Variance (ANOVA) for in-Cavity Residual Stress
By using ANOVA, the significance parameter level that affects the in-cavity residual stress can be determined. Table-15 represents the summary of ANOVA result. By considering the p-values of the parameter, if the p-value is very small which less than 0.05, then the parameter has a significant effect on the response. P-value for the melt temperature is 0.001 which is less than 0.05 and it indicates that melt temperature is the most significant parameter.

Table-15. One-way ANOVA for in-cavity residual stress.

Input parameters	MoT (ᵒC)	MeT (ᵒC)	IT (s)	CT (s)
R-Sq (%)	0.02	92.03	7.90	0.05
R-Sq (adj) (%)	0.00	89.37	0.00	0.00
P	0.999	0.001	0.781	0.998
Rank	4	1	2	3

www.arpnjournals.com

Validation of Parameter for In-Cavity Residual Stress

The optimum parameter combination of the injection molding process were mold temperature 15 º C (Level 1), melt temperature 255 º C (Level3), injection time 1 s (Level 3), and cooling time 10 s (Level 1). This setting of parameters should lower than in-cavity residual stress of 27.91 MPa. In Minitab software, Taguchi can predict the result of response for these optimal parameters setting. It means that by using predict Taguchi result, the software can determine the signal to noise ratios as well as response characteristics for selected new factor settings. The result of prediction by using optimum parameter setting is 27.87 MPa. From the calculation, the difference between lowest in-cavity residual stress value of simulation and optimize in-cavity residual stress value is 0.14%. The result is acceptable and proves that the verification result correlates with the verification test. Therefore, in order to achieve the lowest in-cavity residual stress, the optimum parameters were valid.

CONCLUSIONS

In this study, the optimization of injection molding parameters towards deflection, volumetric shrinkage at ejection, and in-cavity residual stress in a plastic injection mold is studied. Based on the simulations, to get the lowest value of deflection, the parameters should be set to mold temperature 15 º C, melt temperature 255 º C, injection time 0.4 s, and cooling time 10 s. In order to get the lowest percentage value of volumetric shrinkage at ejection the parameters should be set with the combination of mold temperature 15 ºC, melt temperature 225 ºC, injection time 0.4 s, and cooling time 10s. Meanwhile, to obtain the lowest in-cavity residual stress, the combination of parameters should be set to mold temperature 15 ºC, melt temperature 255 ºC, injection time 1 s, and cooling time 10 s. Through this finding, it can be concluded that the most influential parameters for polypropylene material is melt temperature. According to ANOVA result, all the three responses have significantly affected by melt temperature. It is proven that melt temperature is an important parameter to determine the deflection, shrinkage and residual stress that can lead to warpage of molded parts. High melt temperature value resulting in lowest value of deflection and in-cavity residual stress. Therefore, by using moldflow simulation software, it can helps manufacturers to predict and prevent any potential manufacturing defects as well as reducing cost and waste of material.

ACKNOWLEDGEMENTS

REFERENCES

[1] Harper, C. (2002). Handbook of Plastics, Elastomers, and Composites (4th ed.). McGraw-Hill Education LLC.

[2] Ghosh, P. (2011). Polymer science and technology plastics, rubbers, blends and composites (3rd ed.). New York: McGraw-Hill Education LLC.

[3] Harper, C. (2000). Modern Plastics Handbook. New York: McGraw-Hill Education LLC.

[4] Amran, M., Salmah, S., Zaki M., Izamshah, R., Hadzley, M., Shahir, M. and Amri, M. (2014). The effect of pressure on warpage of dumbbell plastic part in injection moulding machine. Advanced Materials Research, pp.61-66.

[5] Yin, F., Mao, H., and Hua, L. (2011). A hybrid of back propagation neural network and genetic algorithm for optimization of injection molding process parameters. Materials & Design, pp.3457-346.

[6] Dang, X. (2014). General frameworks for optimization of plastic injection molding process parameters. Simulation Modelling Practice and Theory, pp.15-27.

[7] Kwiatkowski, D., Gnatowski, A. and Nabiałek, J. (2011). Numerical analysis of residual stresses and deformation of injection moulded parts manufactured from polymeric composite with different processing conditions. Kompozyty, pp.294-298.

[8] Reddy, B., Kumar, J., Reddy, V. and Padmanabhan, G. (2009). Application of Soft Computing for the Prediction of Warpage of Plastic Injection Molded Parts.Journal of Engineering Science and Technology, pp.56-62.

[9] Kurtaran, H., Ozcelik, B. and Erzurumlu, T. (2005). Warpage optimization of a bus ceiling lamp base using neural network model and genetic algorithm. Journal of Materials Processing Technology, pp.314-319.

[10] Azaman, M., Sapuan, S., Sulaiman, S., Zainudin, E. and Khalina, A. (2014). Numerical simulation analysis of the in-cavity residual stress distribution of lignocellulosic (wood) polymer composites used in shallow thin-walled parts formed by the injection moulding process. Materials & Design, pp.381-386.

[11] Kazmer, D.O. (2007). Injection Mold Design, Hanser Gardner Publication, Ohio, USA.

www.arpnjournals.com

[12] Amran, M., Salmah, S., Izamshah, R., Shahir, M., Amri, M., Mohamad, E., Sanusi, M., Sivaraos, Marjom, Z., Al-Amani, U., Musa, M.K. and Abdullah, Z. (2015). Warpage analysis of different number cooling channels for dumbbell plastic part in injection moulding. Applied Mechanics and Materials, pp. 8-11.

[13] Sperling, L.H., (2006). Introduction to Physical Polymer Science, John Wiley and Sons, New Jersey.

[14] Mohd, A., Siti S., Raja, I., Mohd, S., Mohd, A., Effendi M., Mohd, S., Sivaraos, Zolkarnain, M., Umar, A., Mohd, K. and Zulkeflee, A. (2015). Warpage analysis of different number cooling channels for dumbbell plastic part in injection molding. Applied Mechanics and Materials, pp 8-11.

[15] Amran, M., Salmah, S., Faiz, A., Izamshah, R., Hadzley, M., Manshoor, B., Shahir, M., and Amri, M. (2014). Effect of Injection Moulding Machine Parameters on the Warpage by Applying Taguchi Method. Applied Mechanics and Materials, Vol 699, pp.20-25.

[16] Kim, J., Ahn, S., Atre, S.V., Park, S.J., Kang, T.G., and German, R.M. (2014). Imbalance filling of multi-cavity tooling during powder injection molding. Powder Technology, 257, pp.124-131.

[17] Amran, M., Hadzley, M., Amri, S., Izamshah, R., Hassan, A., Samsi, S., and Shahir, M. (2010). Optimization of gate, runner and sprue in two-plate family plastic injection mold. AIP Conference Proceedings, 1217, pp.309-313.