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Minimization of sink mark defects in injection molding process – Taguchi approach

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Abstract

Optimal setting up of injection molding process variables plays a very important role in controlling the quality of the injection molded products. It is all the most important to control attribute defects like sink marks. Sink marks are basically a “designed in” problem and hence it is to be attended during designs stages. Owing to certain conditions and constraints, sometimes, it is rather ignored during design stages and it is expected to be handled by molders with only instruction to ‘do the best’. Handling of numerous processing variables to control defects is a mammoth task that costs time, effort and money. This paper presents a simple and efficient way to study the influence of injection molding variables on sink marks using Taguchi approach. Using the Taguchi approach, optimal parameter settings and the respective sink depth were arrived. The sink depth based on the validation trials was compared with the predicted sink depth and they are found to be in good agreement. The results demonstrate the ability of this approach to predict sink depth for various combination of processing variables with in the design space.

Keywords: Sink mark, plastic injection molding, Taguchi optimization, process optimization, attribute defects in injection molding

1. Introduction

Injection molding is one of the major net shape forming processes for thermoplastic polymers. Over 30% of all the plastic parts manufactured are by injection molding. Injection molding is ideally suited for manufacturing large quantities of mass produced plastic parts of complex shapes and sizes. In the injection molding process, hot melt of plastic is forced into a cold empty cavity of desired shape called mold. Then, the hot melt is allowed to solidify. Solidified net shape product is ejected out of the mold upon opening. Although the process is simple, prediction of final part quality is a complex phenomenon due to the numerous processing variables. Common defects in injection molding process can be classified in to two ways. They are:

1. Dimensional related
2. Attribute related

Dimensional related defects can be controlled by correcting the mold dimensions. But, attribute related defects are generally dependent on the processing parameters. Some of the common attribute related defects are splay marks, sink marks, voids, weld/meld lines, poor surface finish, air traps, burn marks etc. Of all attribute defects, sink marks are considered to be perennial.

Sink marks can be defined as ‘an unwanted depression or dimple on the surface of molding due to localized shrinkage’. The sink marks can be minimized by optimizing the process parameter settings. The process parameter settings were traditionally based on operator’s experiences.

A great deal of research is being carried out to understand, identify critical factors and possibly to optimize the molding process. Most of the work carried out in the last decade was based on: theoretical, computer aided engineering based simulation models and practical experimental trials (Kazmer, 1997). Shi and Gupta (1998) tried to predict sink mark depths using localized shrinkage analysis through finite element methods. They also tried to establish approximate empirical equations based on the rib geometry, packing time and packing pressure (Shi and Gupta, 1999). But, other parameters like melt temperature, mold temperature, etc were not considered. Predicted Sink mark depths were observed to be smaller than the actual. Dan Tursi and Bistany (2000) attempted to study the effect of tooling factors like kind of mold material, gate type in addition to some processing parameters. In their study, barrel temperature was considered instead of melt temperature. It was observed that, gate design did not significantly contribute to sink marks but choice of mold material did significantly influence sink marks. Iyer and Ramani (2002) in an attempt to study the use of an alternate high thermal conductivity mold material, sink mark defect was taken up as quality control parameter. Using finite element method, an attempt was made to a study sink marks. It was observed that thermal conductivity of the mold material does influence sink marks.

DOE has been widely used by various researchers for optimization of injection molding process to control defects and improve quality. Patel and Mallick (1998) applied DOE for defect reduction in injection molding. Sink index was included as one of the quality indicators for investigation as part of their study. Processing variables like melt temperature, injection time, ejection temperature, fill/pack switch over, pack time, injection rate and coolant temperature were considered. Effect of mold temperature, rib-to-wall ratio and rib distance from feed point were ignored. Erzurumlu and Ozcelik (2006) used Taguchi technique to minimize warpage and the sink index. In their study, certain processing variables like mold temperature, melt temperature, packing pressure, rib cross section and rib layout (orientation) were considered. Shen *et.al*. (2007) made an investigation on effect of molding variables on sink mark index using Taguchi's fractional factorial design methodology. Shen *et.al*. considered melt temperature, mold temperature, injection time, pack time, distance between gate and rib and global increase of thickness. Mathivanan and Parthasarathy (2009a, 2009b) reported comprehensive modeling of sink marks using DOE based regressions.

The detailed literature survey indicates the following:

1. Though comprehensive studies on the effects of molding variables on sink marks do exist, a simple to use method for the molders is still required on the same lines. An approach like Taguchi method by applying a comprehensive approach as proposed (Mathivanan and Parthasarathy, 2009a, 2009b) will be of quick use to the molders.
2. Most of the Taguchi based studies used sink mark index or sink index as the parameter. It is an indirect measure for the sink marks. The sink index is an indication of the potential shrinkage due to a hot core. However, whether or not the shrinkage would result in sink mark depends on geometry characteristics (MPI user guide, MoldFlow). Hence, need for a study on sink using sink mark depth as direct response does arise.

Hence the present work was aimed at:

1. Conducting a comprehensive study on effects of variables on sinks using sink mark depth as direct response.
2. Bringing out an easy to use methodology like Taguchi, suitable for molders as well as designers, for control of sink marks.

Conducting comprehensive study on injection molding process using conventional practical approach is very expensive and also time consuming. With the advent of CAE technology, numerical simulation of injection molding process, comparatively less expensive and quicker trial runs can be experimented virtually (Mathivanan and Parthasarathy, 2008). Hence, in this research, it is proposed to employ Taguchi's design of experiments in combination with computer aided engineering (CAE) based simulated experimental data for investigation.

2. Materials and methods

Different steps involved in the methodology are as follows:

1. Design of simple and scalable generic model
2. Selection of processing variables and their levels
3. Initial screening Taguchi's experiments, data collection and analysis
4. Arriving at critical variables based on initial screening
5. Additional expanded Taguchi's experiments for minimization of sink marks

2.1. Design of simple, scalable and generic model and machine selection: A simple and scalable disc part (Figure 1) was prepared using Pro/Engineer. The model base wall was fixed at 3mm. The model was constructed in such a way that, it had 3 different rib thicknesses (1.5mm,1.95mm and 2.4mm) having rib-to-wall ratios of 50%, 65% and 80%. The ribs were located at three levels from the feed point (15mm, 40mm and 65mm). Distance between ribs (25mm) was calculated to maintain a minimum distance of 10 times the maximum thickness of rib (2.4mm). This is required to isolate effects of neighborhood ribs on sink mark.

2.1.1 Molding material and machine: Commercially available, amorphous, Cycolac AR ABS Co-Polymer from GE Plastics and a generic injection molding machine with 7000T clamping tonnage capable of applying 180 MPa injection pressure were selected for the study. Properties of the Cycolac resin are given in Table -1.

2.1.2 Taguchi methodology: Taguchi techniques were developed by Dr. Genichi Taguchi. Taguchi developed the foundations of robust design and validated its basic philosophies by applying them in the development of many products (Phadke, 1989). Taguchi method can be used for optimization methodology that improves the quality of existing products and processes and simultaneously reduces their costs very rapidly, with minimum engineering resources and development man-hours. It achieves this objective by making the product or process performance "insensitive" to variations in factors such as materials, manufacturing equipment, workmanship and operating conditions. It also makes the product or process robust and therefore it is called as robust design.

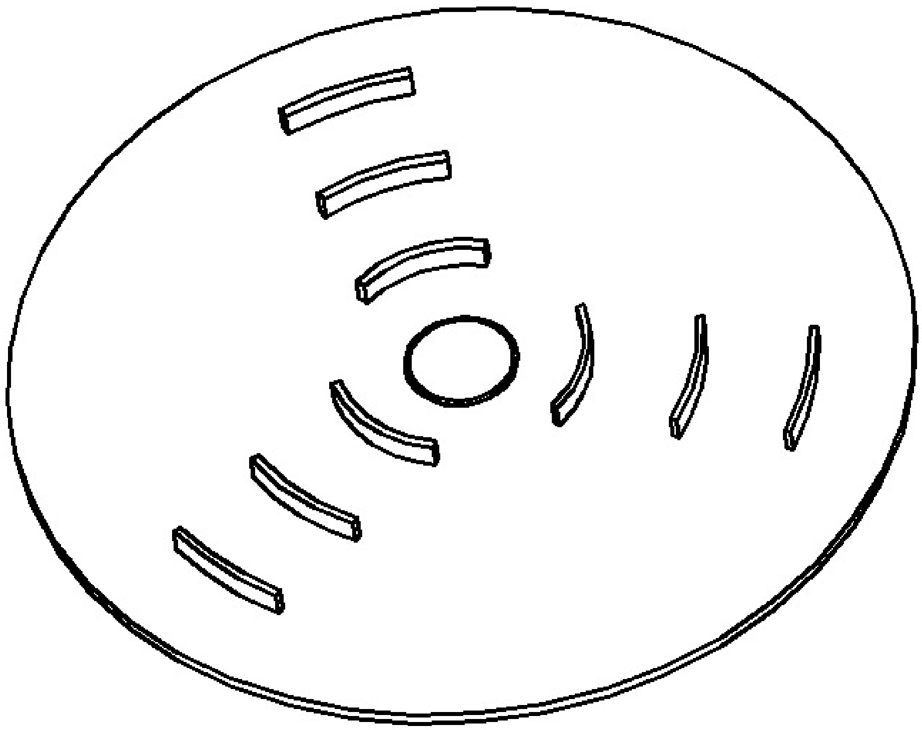

Figure 1. Disc part

Table-1 Properties of cycolac AR ABS Material

Properties of the Material	
Commercial product name	Cycolac AR
Solid Density (g/cm^3)	1.0541
Melt Density (g/cm^3)	0.94383
MoldFlow Viscosity index	VI(240)0234
Recommended Mold Temperature °C	60
Recommended Melt Temperature °C	240
Material Characteristics	Amorphous
Ejection Temperature °C	108
Modulus of Elasticity Mpa	2240
Poisson ratio	0.392
Shear Modulus	804.6
Thermal Conductivity W/m-C°	0.27 @ 2408C

All man-made machines or set-up are classified as engineering systems according to Taguchi. Engineering systems can be classified in to two categories: 1. Static and 2. Dynamic. Dynamic system has signal factors (input from the end user) in addition to control and noise factors, whereas in static system signal factors are not present. Optimization of injection molding process is a static system (Refer Figure 2). Figure 2 is called the P-diagram. The 'P' means process or product according to Taguchi.

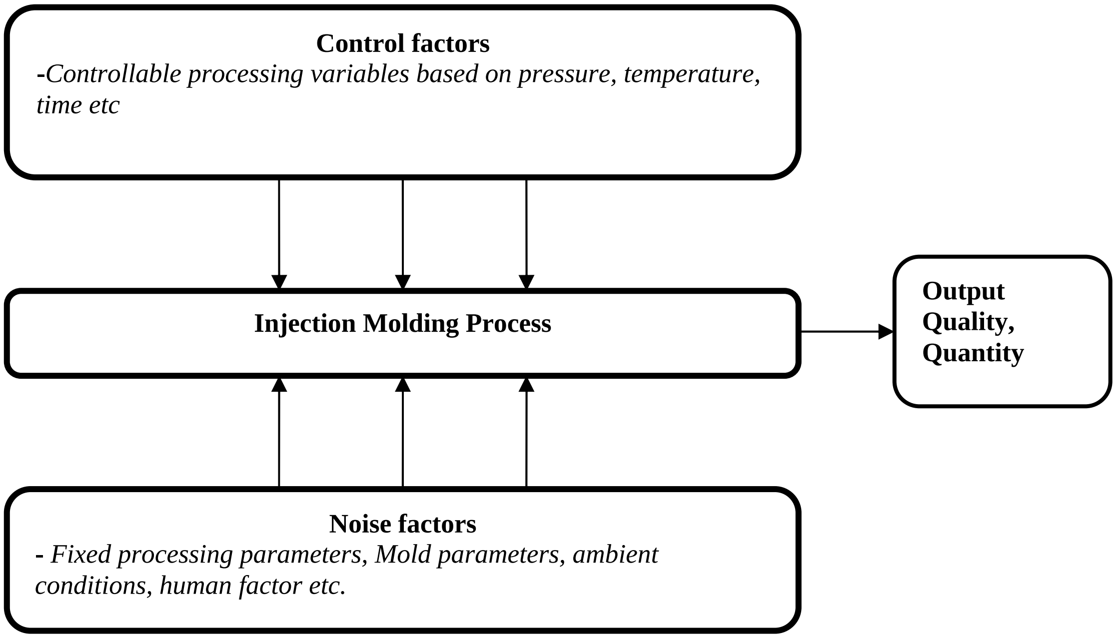

Figure 2. P-diagram of injection moulding process

Taguchi views design of any system as a three phase program: 1. System design, 2. Parameter design and 3. Tolerance design. Genesis of new idea, concepts, processes etc., due to technological advancements, comes under system design. Technological advantage gained by a new system design can be lost quickly when competitors produce the same idea in a more uniform manner. Hence, as a holistic approach, one needs to incorporate parameter design as well as tolerance design. Parameter design improves product/process uniformity and can be used to cost savings at no cost. This means that certain parameters are set to make the performance less sensitive to causes of variations. Tolerance design phase improves quality at a minimal cost (Ross, 1996). Few recent successful attempts using Taguchi's approach for modelling and analysis of abrasive wear performance of composites and parameter optimization of end milling can be seen from Mahapatra and Chaturvedi (2009) and Sanjit et.al. (2010).

In this present work, parameter design is utilized to arrive at the optimum levels of process parameters for minimization of sink depth/mark during manufacturing. According to Taguchi, two major tools are employed to achieve any quality goal or any robust design. They are: 1. Signal -to- Noise ratio (S/N ratio), which measures quality and 2. Orthogonal arrays, which are used to study many parameters simultaneously (Phadke, 1989)

Taguchi uses the S/N ratio to measure quality characteristic deviating from the desired value. The S/N ratio characteristics can be divided into three categories: the-nominal-the-best, the smaller-the-better, and the-larger-the-better when the quality characteristic is continuous (Ross, 1996). Since, the objective of this study was to minimize the sink mark depth; smaller-the-better quality characteristic was employed. Two orthogonal arrays (OA) were used for experiments. One OA is used for initial screening of processing variables and the other to arrive at optimal process conditions.

2.1.3 Experimental set-up: In order to mold a component on the injection molding machine, a proper mold based on good mold design is required. Mold design basically involves designing of feed system to feed the material from the machine nozzle into the mold cavity, cooling systems to solidify the product after injection and clamping system to keep the mold closed during pressurized injection. Feed system consists of sprue, runner and gate. Cooling system consists of cooling channels and it should be capable of maintaining the required mold temperature. For the present study, Tapered central sprue (4mm diameter) feed point, Disc type runner (4mm) and diaphragm gate (1mm) were designed to have uniform flow based on standard mould design guide lines. Twelve diameter cooling channels were designed for efficient maintenance of mold temperature.

The 3D Model, made using Pro/E, was exported to computer aided Simulation tool (in this study MoldFlow was used). Mid plane finite element model was created by meshing the 3D model with 1684 linear triangular elements. Average aspect ratio of the mesh was found to be 1.528. Mesh was thoroughly checked to eliminate mesh related errors. Feed system and cooling channels were created as designed earlier. This set-up was used for conducting trials. Meshed models are shown in Figure 3.

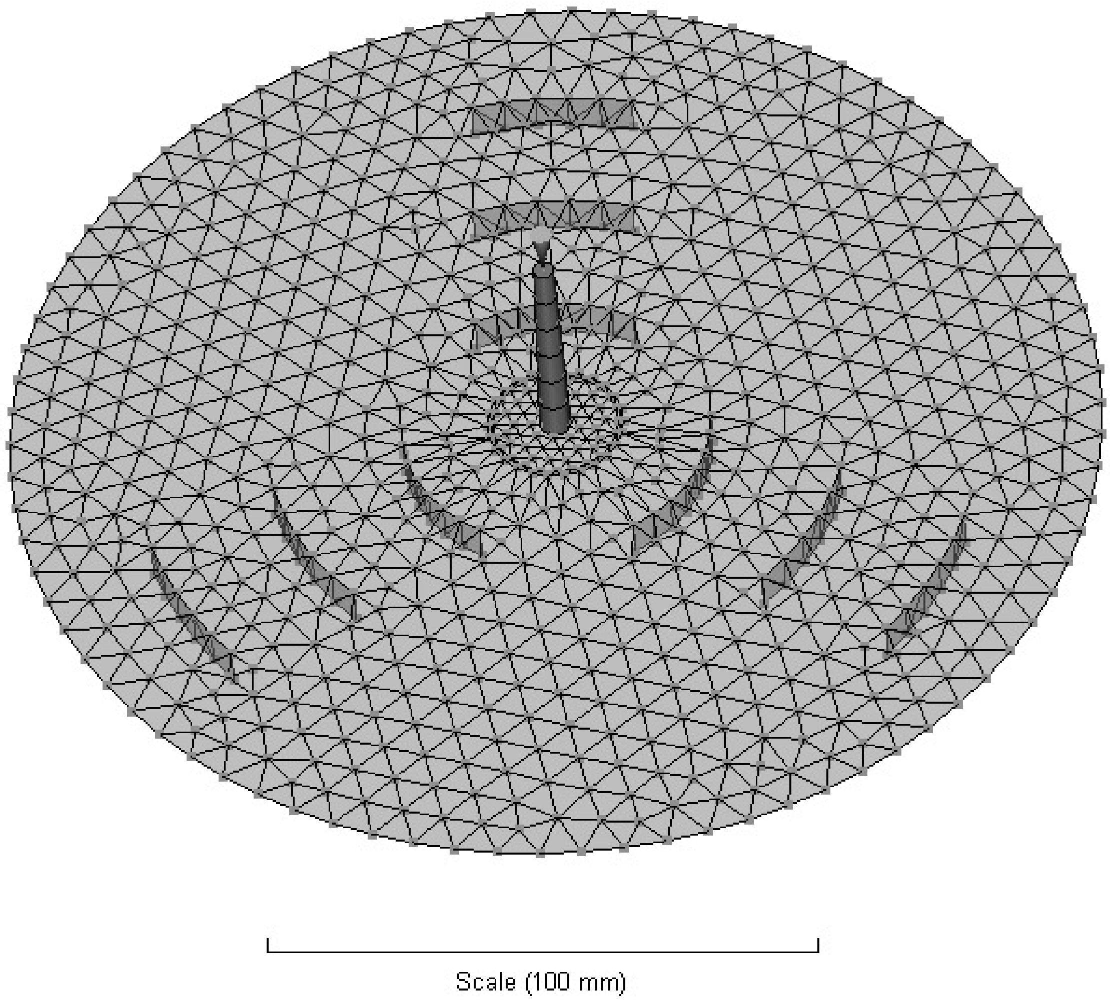

Figure 3. Meshed model of the disc part

2.2 Selection of processing variables and their levels: Based on the detailed literature survey, extensive discussion with molders and through one initial trial, the following processing parameters were considered for the initial screening experiments (Table -2).

Table: 2 Initial screening parameters and their levels

Number	Coded Parameters	Uncoded Parameters	Levels	
			Low (1)	High (2)
1	A	Melt Temperature (°C)	220	260
2	B	Mould Temperature (°C)	40	80
3	C	Injection Time (sec)	1.20	1.80
4	D	Packing Time (sec)	8	12
5	E	Packing Pressure (MPa)	23	29
6	F	Rib-to-wall Ratio (%)	50	80
7	G	Rib Distance from gate (mm)	15	65

3. Injection molding experiments

3.1 Initial screening Taguchi's experiments, data collection and analysis: Taguchi L8 screening experiments were conducted to identify the "most significant" input variables by ranking with respect to their relative impact on the sink mark. Table -3 shows the Taguchi's array for L8 experimental runs.

The S/N ratio η is given by:

$$\eta = -10\log(MSD) \tag{1}$$

Where MSD is the mean-square deviation for the output characteristic. MSD for the smaller-the-better quality characteristic is calculated by the following equation,

$$MSD = \frac{1}{N}\left[\sum_{i=1}^{n} Y_i^2\right] \tag{2}$$

Where Y_i is the sink mark depth for the i^{th} test, n denotes the number of tests and N is the total number of data points. The function '-log' is a monotonically decreasing one, it means that we should maximize the S/N value. The S/N values were calculated using equations (1) and (2). Table -4 shows the response table for S/N ratios using smaller-the-better approach.

Table-3 Taguchi L8 Array

Run	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Table -4 Response table for S/N ratios using smaller-the-better

Level	Melt temperature	Mold Temperature	Injection Time	Packing Time	Packing Pressure	Rib-to-Wall ratio	Rib Distance
1	25.72	27.55	26.58	26.42	26.66	28.13	29.96
2	27.73	25.90	26.87	27.03	26.80	25.33	23.49
Delta	2.01	1.64	0.30	0.61	0.14	2.80	6.47
Rank	3	4	6	5	7	2	1

3.2 Parameters selection for follow-up experiments: It was found that, rib distance made significant contribution in the formation of sinks followed by Rib-to-Wall ratio, melt temperature, mold temperature, packing pressure, packing time and injection time. After this initial screening and ranking, it was decided to treat injection time and pack pressure as fixed parameters. The Injection time was fixed at 1.2sec. The pack pressure was fixed at 26 MPa. These decisions were taken under the consideration of overall quality and economics in mind.

Maintaining higher pack pressure requires additional power and cost. Packing a part with higher pressure normally leads to higher residual stress and it was not desirable. Though the ranking for pack time was the lowest, it was included in the follow-up experiments to study its impact.

3.3 Taguchi L27 follow-up experiments, data collection and analysis: During the follow-up experiments for minimization, processing variables were considered at three levels. Table – 5 shows the variables and its levels considered for the follow-up experiments.

Table – 5 Follow-up experiment variables and its levels

Number	Coded Parameters	Uncoded Parameters	Levels		
			Low (1)	Mid (2)	High (3)
1	A	Melt Temperature (°C)	220	240	260
2	B	Mold Temperature (°C)	40	60	1.80
3	D	Packing Time (sec)	8	10	12
4	F	Rib-to-wall Ratio (%)	50	65	80
5	G	Rib Distance from gate (mm)	15	40	65

Twenty seven experiments were conducted and all the sink mark data points were collected. Collected data points were analyzed using the "smaller-the-better approach". The S/N ratios were calculated using equations (1) and (2). Response table for signal to noise ratio was constructed (Table – 6). Main effects plot for S/N ratio is shown in Figure 4.

Table -6 S/N ratio table for follow-up experiments

Experimental Run	Melt Temperature (A)	Mold Temperature (B)	Pack Time (D)	Rib-to-wall Ratio (F)	Rib Distance (G)	Sink Depth In mm	S/N ratio
1	220	40	8	50	15	0.025460	31.883003
2	220	40	10	65	40	0.056458	24.965459
3	220	40	12	80	65	0.088900	21.021965
4	220	60	8	65	65	0.088617	21.049620
5	220	60	10	80	15	0.036564	28.739021
6	220	60	12	50	40	0.053858	25.374947
7	220	80	8	80	40	0.065347	23.695474
8	220	80	10	50	65	0.083950	21.519555
9	220	80	12	65	15	0.038355	28.323470
10	240	40	8	50	15	0.020054	33.955980
11	240	40	10	65	40	0.043997	27.131460
12	240	40	12	80	65	0.074100	22.603636
13	240	60	8	65	65	0.072478	22.795864
14	240	60	10	80	15	0.030481	30.319444
15	240	60	12	50	40	0.042833	27.364450
16	240	80	8	80	40	0.058235	24.696393
17	240	80	10	50	65	0.068565	23.277988
18	240	80	12	65	15	0.032409	29.786687
19	260	40	8	50	15	0.022367	33.007923
20	260	40	10	65	40	0.037175	28.595051
21	260	40	12	80	65	0.063400	23.958215
22	260	60	8	65	65	0.061962	24.157519
23	260	60	10	80	15	0.031746	29.966247
24	260	60	12	50	40	0.035834	28.914167
25	260	80	8	80	40	0.062701	24.054469
26	260	80	10	50	65	0.060334	24.388815
27	260	80	12	65	15	0.033013	29.626353

4. Results and discussion

From the Table – 6 and from main effects plot for S/N ratio (Figure 4), it is observed that, rib distance from the feed point is a most influential variable on sink. This factor needs to be considered while designing the part as well as during mold design. If the feed points cannot be provided near a rib, flow leaders can be designed in to the component. This could be an important input to product designers.

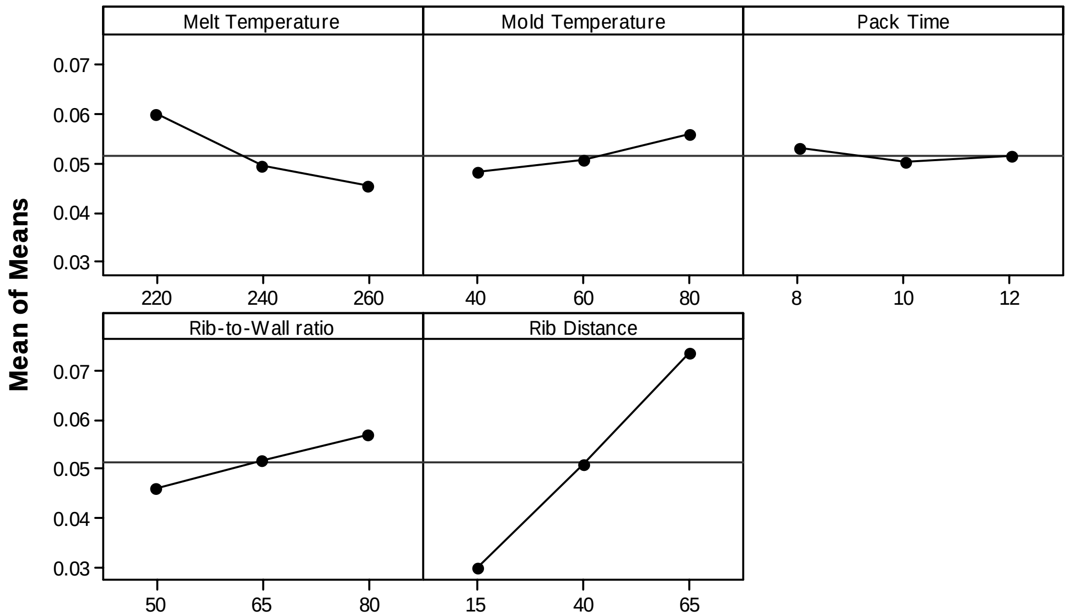

Figure 4. Main effects plot

The prime objective of this study was to find optimum level for each of the variables and to arrive at a combination of these factors that could result in minimum sink. From figure. 4, it can be observed that A3-B1-D2-F1-G1 is the optimum combination for minimum sink depth. Similarly, A1-B3-D1-F3-G3 is the combination for maximum sink depth. These combinations were not included in the experimental runs. Hence, additional two confirmation experiments were run at both combinations. The results are shown in Table 7.

Table -7 Verification experimental results

Validation Run	A	B	D	F	G	S/N ratio	Predicted Sink Depth	Measured Sink Depth	% Deviation
1	260	40	10	50	15	33.5847	0.0164416	0.0154293	6.2%
2	220	80	8	80	65	20.2139	0.0939485	0.0897736	4.4%

As is seen from the Table 7, the difference or the variation between the predicted and measured sink depth is well below 10%. It shows the adequacy of the approach in prediction of the sink depth.

Authors have also continued the research with regression analysis and further analyses on the prediction and minimization of the sink marks. Those analyses and findings are not included in this work, as they have been performed in a different study.

5. Conclusion

Manipulation of numerous processing variables of the injection moulding process to control defects is a mammoth task that costs time, effort and money. This paper presents a simple and efficient way to study the influence of injection molding variables on sink marks using Taguchi approach. Application of Taguchi approach also helps in arriving at optimal parameter settings. The sink depth through the validation trials based on the optimal parameters and the predicted sink depth using Taguchi's approach for the same settings are found to be in good agreement. The results show the ability of this approach to predict sink depth for various combination of processing variables with in the design space. It is observed that, increased distance of rib from the feed point seems to produce deeper sinks. This could be an important input to product designers for designing alternatives or to give effective and corrective solutions. This methodology can also be applied while designing parts. Though this study was meant for the sink marks, it can be extended to other defects and also for improving overall quality.

Nomenclature

%	-	Percent
°C	-	Degree centigrade
η	-	The S/N ratio
3D	-	Three Dimension
ABS	-	Acrylonitrile Butadiene Styrene
ANN	-	Artificial Neural Network
ANOVA	-	Analysis of Variance
A	-	Melt Temperature in °C
B	-	Mold Temperature in °C
C	-	Injection Time in sec
CAD	-	Computer Aided Design
CAE	-	Computer Aided Engineering
D	-	Packing time in sec
DOE	-	Design of Experiments
E	-	Packing Pressure in MPa
F	-	Rib-to-wall Ratio in %
FE	-	Finite Element
FEA	-	Finite Element Analysis
G	-	Rib Distance from gate in mm
mm	-	millimetres
MPa	-	Mega Pascal
MSD	-	Mean square deviation
N	-	Total number of data points
sec	-	Seconds

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