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Optimization of Injection Molding Process condition in Nepalese shoe manufacturing industry using Taguchi Design of Experiment

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Abstract
Injection Molding is Rapid method for production of Plastic Part. Molding condition and process parameters play decisive role in productivity and quality of injection molded plastic parts. Design of experiment (DoE) is employed and Taguchi orthogonal array is used to find out the most significant process variables affecting the injection molding. Poly vinyl chloride (PVC) have been used as sole material. "Lower the better" characteristics have been chosen as critical to quality characteristic to reduce weight and weight variation of the manufactured sole through injection molding process. Simulation of the plastic injection molding process and design of experiment is done in Autodesk Moldflow insight. The result thus obtained through simulation process is verified through real-time experiment.

Keywords
Plastic Injection Molding, Design of Experiment, Taguchi, Poly vinyl chloride, Weight

1. Introduction

Plastic injection molding is a versatile process and plays a major role in today's plastic manufacturing industries. Sole materials which are commonly used for injection molding are thermoplastics such as poly vinyl chloride (PVC), Polyurethane (PU) and Thermoplastic Rubber (TR) [1]. Quality of injection molded plastics products is greatly influenced by the process variables. Improper settings of these process variables will produce various defects in the final product [2]. Injection molding process begins with feeding the pallets into the hopper. These pallets are subsequently passed into the barrel where they are heated, melted and made to flow. Thus obtained molten material is injected at high pressure into the mold, where it is held under pressure until it is removed in solid state duplicating the cavity of the mold [3]. Applying and using DOE in injection molding is relatively simple compared to its use in other manufacturing or production processes, because here most responses to process changes are linear. In injection molding, all plastic material variables are related to speed, pressure, time, and temperature.[4] The control of part weight, in injection molding, is of great commercial interest. Especially in the molding of large quantities of small parts, small variations in part weight could have a significant financial impact.

Moreover, weight variability could reflect poor process and quality control, which could be also associated with the variation of some other important part properties [5]. Lightweight materials can be utilized by developing effectively advanced materials, pioneered molding processes, and construction technologies. Injection molded plastic materials are widely used today to replace ferrous and non-ferrous metals [6].

Back-Propagation Neural Network (BPNN), and combination of swarm optimization, and Genetic Algorithm (GA) have been used by [7] to find optimal parameter settings for quality characteristic and stability of the process and have verified it effectively with considerable reduction in the variability. In their research, [8] have used digital image processing for quantitative measurement of product surface defects and model free optimization for quality. optimization and found out proposed method can effectively eliminate the defects through experimental verification. Injection molding problems can be predicted and rectified before start of real time manufacturing during mold design with the aid of different injection molding simulation software such as Autodesk Moldflow®, Moldex3D® and

C-MOLD^{TM}. These software not only predict the defects but also recommend the appropriate mold design [9]. In this research Autodesk Moldflow insight 2019 have been used for simulation of design of Experiment. Autodesk Moldflow insight had been employed by [10] to design the plastic part and estimate the cost of injection molded part. He have emphasized on the economic consequences of technical choices we make. [11] have used Moldflow advisor to find out the optimum process parameters in plastic toy manufacturing industry and reduce potential part defects, cycle time and improve overall quality of the part. [12] Found out that injection velocity and the injection temperature play controlling role in part quality during filling phase, packing pressure and the packing time play controlling role during packing phase and mold temperature and cooling time play controlling role during cooling phase.

Besides process parameters, even gate location also play important role maintaining quality of the injection molded part. Impact of gate location in injection process had been studied by [13] and found out, optimized gate location could reduce waste and energy cost. The effect of varying gate size on air trap had been done by [14] using Autodesk Moldflow and concluded number of air traps depend upon gate size at the filling point.

In this paper, design of Double sole PVC is done in Catia V5R20 and simulation of injection molding process for light weight sole with minimal weight variation is done In Autodesk Moldflow insight 2019 and the optimum process conditions from the simulation are validated through experiment.

2. Materials and Methods

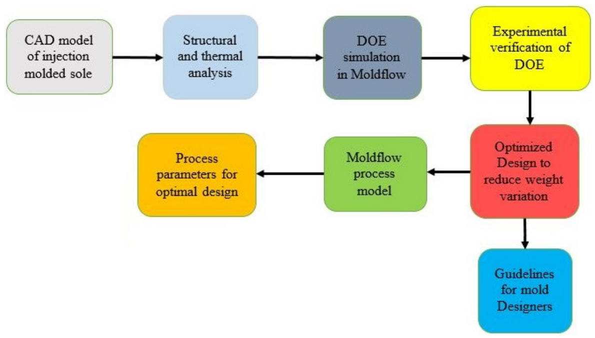

Figure 1: Process flowchart

From the literature review it was evident that there exist complex relationship between injection molding process conditions, part quality and design of the part. Thus, in order to improve the part quality and reduce weight variation, it has become necessary to find out the optimum combination of the process parameters and best injection location.

2.1 Material

Commercial injection molding grade PVC is used in this study is shown in the following table.

Table 1: Specification of PVC

SN	Characteristics	Unit	Specification
1	Specific Gravity	-	1.21
2	Hardness Shore A	Shore	63
3	Thermal Stability $@200 \pm 0.5^0C$	minutes	30
4	Tensile Strength	Kg/cm^2	59
5	Elongation at Break	%	218

2.2 Injection Molding

Specimen (Figure 2) was injection molded using injection molding machine (from Ottogalli inc. Italy). Injection process was adjusted in reference to experimental parameters via use of control program.

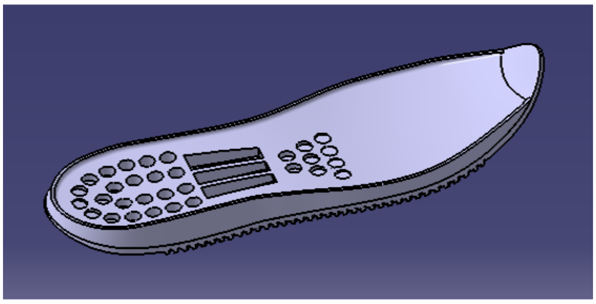

Figure 2: Sole design

2.3 Weight Measurement

Weight was measured in electronic weighing machine with the least count of 0.001 grams.

2.4 Experimental Design

Firstly, optimum injection locations were determined using Autodesk Moldflow. Considering those injection location, fill and pack analysis was performed. In order to determine the optimal process conditions and the effect of the processing parameters on the weight Quality, Taguchi method, Design of Experiment (DoE) was performed. Considering 3.5% of the volumetric shrinkage as permissible, design of experiment was conducted. 'Variable influences then response' technique was used for design of experiment purpose. It uses Taguchi method to determine which variable have most influence on specific quality criteria, and then run extensive factorial experiment on most significant input variables to determine how they impact the part quality.

Table 2: Design of Experiment variables and Ranges (For Upper sole)

Variables	Min value	Middle value	Max value
Mold Surface Temperature (^{0}C)	24	29	34
Melt Temperature (^{0}C)	160	165	170
Injection Time (Secs)	1.6	2	2.4
Cooling Time (Secs)	16	20	24

Table 3: Design of Experiment variables and Ranges (For Lower sole)

Variables	Min value	Middle value	Max value
Mold Surface Temperature (^{0}C)	24	29	34
Melt Temperature (^{0}C)	160	165	170
Injection Time (Secs)	1.6	2	2.4
Cooling Time (Secs)	40	50	60

Table 4: Design of Experiment (DoE) Quality Criteria

SN	Quality Criteria	Goal	Weight
1	Injection Pressure	Minimum	7
2	Maximum Sink Mark Depth	Minimum	4
3	Maximum Temperature at flow front	Minimum	6
4	Volumetric shrinkage	Minimum	7
5	Total Mass	Minimum	9

3. Simulation Results

3.1 Fill Analysis

The main benefit of doing fill analysis are predicting the fill pattern this will help us understand some of the flaws, if any, in the product. It helps to reduce scrap, balance filling pressure distribution, material selection, determining clamp force, identifying weld line and gas trap locations, short shots and also identify shear stress levels. [15][16]

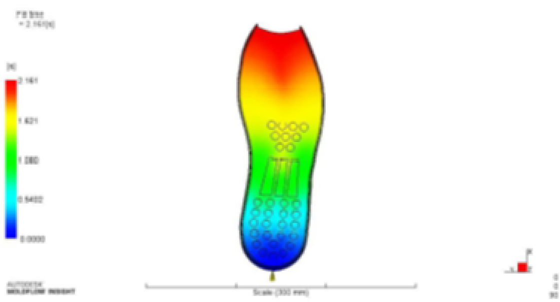

Figure 3: Fill analysis (sole upper)

Table 5: Filling results summary for upper sole

Current time from start of cycle	2.1608 s
Total mass	140.4326 g
Injection pressure	59.2782 MPa
Frozen volume	5.9136 %
Injection pressure	59.2782 MPa

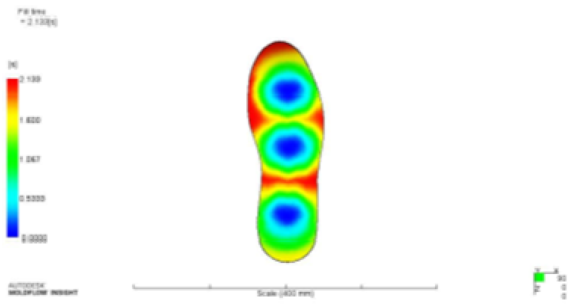

Figure 4: Fill analysis (sole lower)

Table 6: Filling results summary for lower sole

Current time from start of cycle	2.1608 s
Total mass	88.1112 g
Injection pressure	36.0993 MPa
Frozen volume	11.4830 %
Maximum Clamp force - during filling	26.5707 tonne

3.2 Design of Experiment Simulation Results for Upper sole

The relative influence of process variables on quality criteria weight are tabulated in the table 5 below;

Table 7: Relative influence on weight

Mold surface temperature	5.65%
Cooling time (Specified)	3.87%
Melt temperature	28.92%
Filling control (Injection time)	4.15%
Duration	1.72%
Filling pressure	55.69%

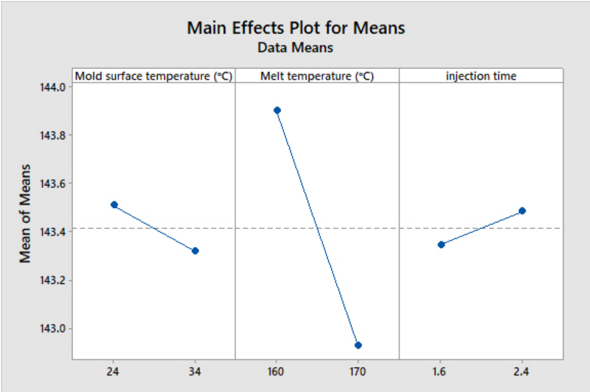

Figure 5: Main effect plot for means

With increase in the mold surface temperature and melt temperature, weight is decreasing whereas with increase in injection time weight shows increasing trend.

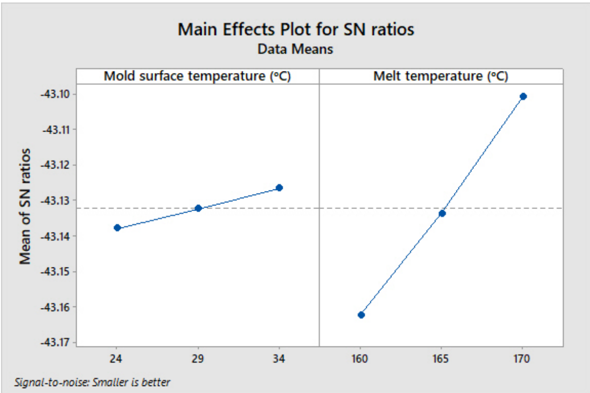

Figure 6: Main effect plot for SN ratios

Melt temperature has greater effect on S/N ratio than mold surface temperature.

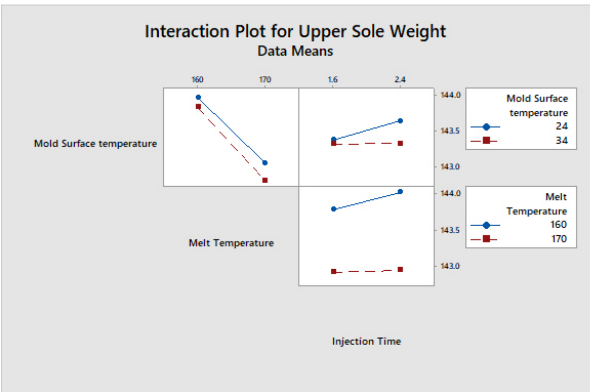

Figure 7: Interaction plot for total mass

In these results, the lines are close to parallel for mold surface temperature vs melt temperature. However, there is slight interaction between melt temperature and injection time and significant interaction between mold surface temperature and injection time.

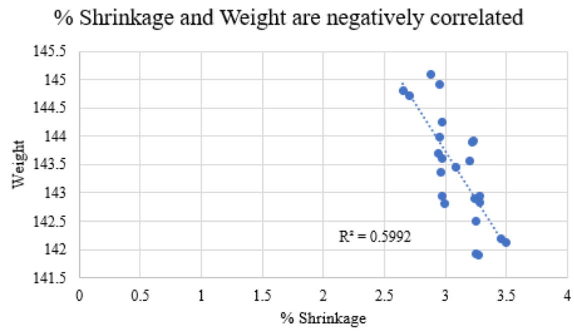

Figure 8: Correlation plot

Weight and shrinkage percentage are negatively correlated heavier upper sole have lower shrinkage percentage.

3.3 Design of Experiment Simulation Results for Lower sole

The relative influence of process variables on quality criteria weight are tabulated in the table 6 below;

Table 8: Relative influence on weight

Mold surface temperature	6.48%
Cooling time (Specified)	3.15%
Melt temperature	27.75%
Filling control (Injection time)	8.61%
Duration	1.21%
Filling pressure	52.79%

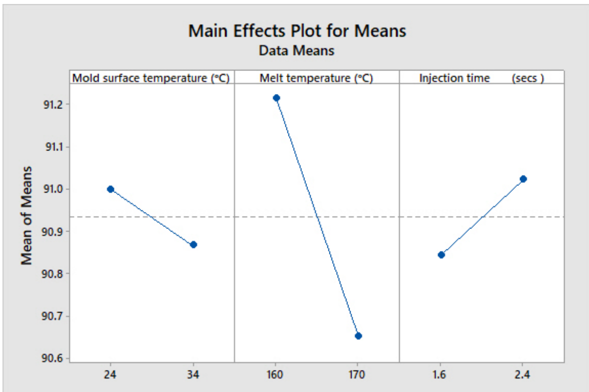

Figure 9: Main effect plot for means

All three parameters have significant effect on weight of the sole. mold surface temperature and melt temperature exhibit negative slope with respect to mass. injection time shows positive slope, thereby exhibiting increase in mass of sole with the increase in injection time.

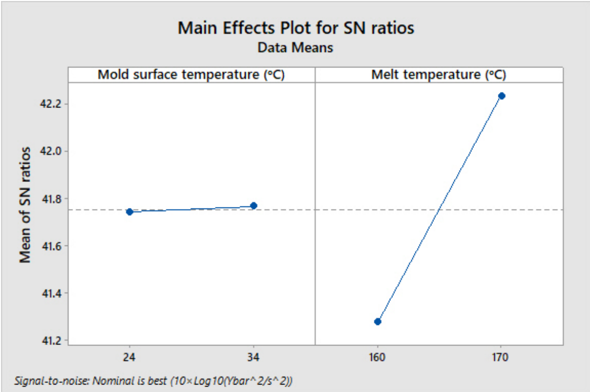

Figure 10: Main effect plot for SN ratios

Main effect plot for S/N ratio indicates that melt temperature has significant on the signal to noise ratio. Effect of mols surface temperature on S/N ratio is nominal.

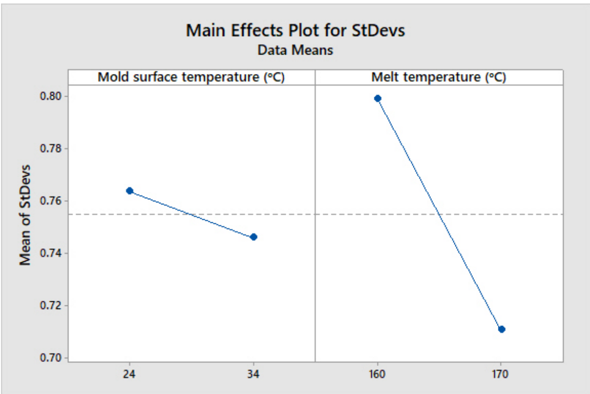

Figure 11: Main effect plot for standard deviation

There is notable change in standard deviation in case of both melt surface temperature and mold temperature. However, Standard deviation is more significant in case of melt surface temperature.

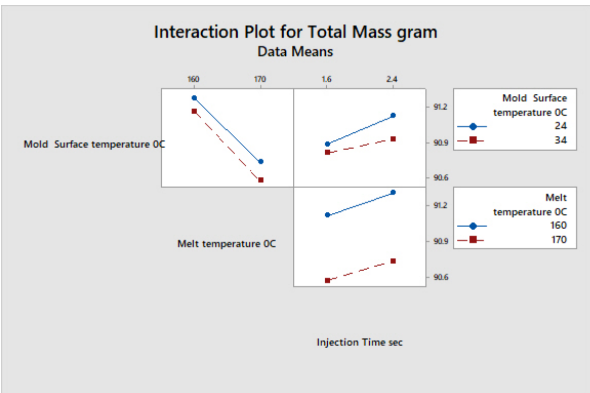

Figure 12: Interaction plot for total mass

In these results, the lines are close to parallel for injection time vs melt temperature and mold surface temperature vs melt temperature. However, there is significant interaction between mold surface temperature and injection time.

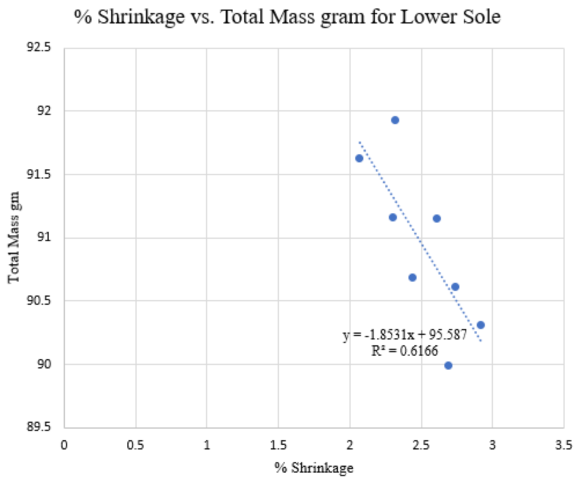

Figure 13: Correlation plot

Mass and % shrinkage are inversely correlated. Lower mass will lead to higher percentage shrinkage of sole.

Result from simulation:
Weight of lower sole: 89.99 grams
Weight of upper sole: 141.91 grams
Weight of upper stitching part: 55 grams
Total weight of shoe: 286.9 grams

3.4 Experimental verification of Simulation Results

In reference to the design of experiment performed in Moldflow software, the set of process variable with minimum weight was verified through the experiment.

Table 11: Operating condition parameters for upper sole

Variables	Values
Injection pressure(MPa)	95
Melt temperature (^0C)	170
Mold Temperature (^0C)	29
Injection time (secs)	2
Hold pressure (MPa)	25
Specific gravity	1.20

Table 12: Operating condition parameters for lower sole

Variables	Values
Injection pressure(MPa)	45
Melt temperature (^0C)	180
Mold Temperature (^0C)	29
Injection time (secs)	2
Hold pressure (MPa)	25
Specific gravity	1.22

After performing 264 experimental trials for optimum process variables as recommended by Moldflow

Table 9: Design of Experiment (lower sole)

Mold Surface temperature ^0C	Melt temperature (^0C)	Injection time (secs)	Cooling time (secs)	Volumetric Shrinkage at ejection (Standard deviation) (%)	Total Mass (gm)
34	170	1.6	60	2.69	89.99
24	170	2.4	60	2.92	90.31
24	160	1.6	40	2.74	90.61
34	160	2.4	40	2.44	90.69
24	170	1.6	40	2.61	91.15
34	170	2.4	40	2.3	91.16
34	160	1.6	60	2.07	91.63
24	160	2.4	60	2.32	91.93

Table 10: Design of Experiment (upper sole)

Mold Surface temperature ^0C	Melt temperature (^0C)	Injection time (secs)	Cooling time (secs)	Volumetric Shrinkage at ejection (Standard deviation) (%)	Total Mass (gm)
24	160	1.6	16	3.28	142.84
24	170	1.6	16	3.23	143.91
24	160	2.4	24	2.88	145.1
24	170	2.4	24	3.46	142.19
34	160	2.4	16	2.97	142.95
34	170	2.4	16	2.94	143.7
34	160	1.6	24	2.71	144.72
34	170	1.6	24	3.27	141.91
24	160			3.28	142.95
34	160			2.99	142.81
24	160			2.95	144.92
34	160			2.65	144.81
24	170			3.5	142.12
34	170			3.25	141.92
24	170			3.22	143.89
34	170			2.97	143.6
29	160			2.95	143.98
29	170			3.24	142.89
29	165			3.25	142.49
29	165			2.97	144.25
24	165			3.2	143.56
34	165			2.96	143.37
29	165			3.09	143.46

software the average weight came out to be 288.590 grams.

Validation through experimentation:

Table 13: Comparison between experimental and simulation result

Part weight (grams)	Simulation result	Experimental result
Sole (lower)	89.99	91.523
Sole (upper)	141.91	142.067
Upper stitching part	55	55
Total weight	286.9	288.590

4. Conclusion

This study successfully investigated the effect of injection molding process variables in PVC shoe sole on weight quality and volumetric shrinkage through simulation using Taguchi Design of Experiment.

From the simulation result it was evident that melt temperature and injection pressure played most influential role among other injection parameters, where injection time, mold surface temperature and cooling time had relatively lower impact for weight quality. Mold surface temperature had significant impact when it comes to volumetric shrinkage. Melt temperature and injection pressure exhibit inverse relation with weight. Volumetric shrinkage increased with the increase in the melt temperature and mold surface temperature. Thus, optimum process conditions for minimum sole weight keeping volumetric shrinkage below 3.5% was found out through simulation and validated through the experimentation.

Optimum weight for the shoe sole was found to be 286.9 grams which was obtained through series of DoE simulations. This result was verified through the real-time experiment, with similar process conditions and weight was found to be 288.590 grams with deviation of 1.69 grams from the simulation result. The weight was verified by running 264 experimental trial runs.

5. Recommendations

The relative influence of the process variables may slightly vary with respect to the geometry of the injection molded part. Further testing and trials could be done with the changes in mold design, injection locations and cooling channels.

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