Screening design of process parameters for Isotactic polypropylene by Injection moulding process

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Abstract - In this research work, the significant process parameters for an injection molding (IM) environment are identified to control the performance of the molded plastic products. An experimental plan is developed through Design of Experiments (DoE) using Taguchi (L12, orthogonal array) wherein the parameters are varied at two levels. As per ASTM-638D (type-I), the tensile samples are prepared on tabletop Injection molding machine (make- BabyPlast/Italy) and tested over the Universal Testing Machine (make- Lloyds/USA) for generating the data for various responses to be analyzed for screening results. The eight parameters considered for screening are: injection pressures, injection rate, melt and mould temperature, hold on pressure, cooling time, hold on time and injection time. Analysis of mean (ANOM) is applied to analyze the results in order to determine the degree of significance of different process parameters. The important mechanical properties (responses) considered are: Stress at break (ASSB), Young's modulus (AYM), Strain at break (ASTB) and Work at break (AWB) and for the material of Isotactic polypropylene (iPP). It may concluded that the injection pressure, melt and mould temperature are the three significant factors with different order for the responses Average stress at break (ASSB), Average strain at break (ASTB) and Average work at break (AWB) whereas injection rate, hold on pressure, injection pressure seems to be the significant factor for Average Young's modulus (AYM).

Keywords: Injection moulding, isotactic polypropylene iPP, Screening experiment, Taguchi method, responses, process parameters

I. INTRODUCTION

Among all plastic processing technologies, injection moulding (IM) has the best efficiency, yield, and dimensional accuracy. Over 30% of all thermoplastic materials and more than 50% of all plastic processing products are produced via the process of injection moulding. [1]. Nowadays, injection-moulded plastic parts are utilised in the mass manufacture of plastic components to fulfil the fast expanding market demand for a wide range of consumer items, including medical, electronics, and automobiles [2]. As, IM is a cyclic discrete part manufacturing process, it is only possible to modify a process setting related to a particular moulded part ex situ (between runs), as opposed to in situ (within runs), in order to correct operational instabilities and maintain output quality characteristics at predetermined target values. As a result, from a process control standpoint, the IM process may be seen as a 'run to run' (RTR) process [3]. The popularity of IM process may be attributed to the fact that the finished goods have good dimensional precision and a smooth surface finish that too at high efficiency and at economic rate resulting in good profitability to the company.

IM is a cyclic process having four major phases: filling, packing (holding), cooling, and ejection. As a result of intricacy of the injection moulding process, significant effort is required to maintain quality attributes under control. Product quality is a priority for both producers and consumers, and excellent product quality consistency with a high production rate is the key to the industry's success. Many variables influence the quality of injection-moulded components during manufacturing. The quality issues may arise from a number of sources viz. the material selection, part geometry, mould designs, the process parameters and their interactions, while determining the performance of plastic product [4]. An injection moulding machine may have 15–20 process variables that need to be optimized before start of the production. The settings of these processing parameters influence, for example, cycle time and the quality of the product, thereby greatly affecting the efficiency and economy of the production [5]. Numerous manufacturing issues may be brought on by the improper mix of material choice, product and mould design, and processing factors. These include a lengthy lead time, a lot of scrap, high manufacturing expenses, and product flaws like warpage, shrinkage, blow holes, etc., which lessen the company's

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ability to command a premium price and lower its profitability. The removal of the underlying causes of the flaws will not only enhance the quality of the moulded product and assist to eliminate the part faults.

The quality issues are the serious challenge to the plastic manufacturer because of common defects like warpage, shrinkage etc. Mold design, process parameters, and the material itself are the three most common causes of defects. Cavities and flow lines on the product might be the result of poor mould design. It's possible that picking the wrong stuff is to blame for the short shot. The process parameters are crucial for making a high-quality end-result. Improper selection and adjustment of process parameters is a typical source of defects such sink marks, weld lines, burn marks, and warping. Shrinkage taking place in the finished product is the main cause of the defects e.g., sink mark, short shot or warpage defect [6]. In order to save the scarce resources and to reduce the quality issue up to some extent and to improve the economy of production, it is imperative to perform the screening experiment before the start of production in bulk.

A "screening experiment" is a kind of experimental design that may be used when a large number of possible variables must be investigated to determine which are most important and may have an impact on one or more of the discussed responses. As a result, fewer process parameters will need to be examined in subsequent experiments. Moreover, it will result in better operational condition thereby reducing the quality issue to a larger extent. This will eliminate unimportant factors thereby saving investigation time and money in the more elaborate experiments. The screening experiment has a number of valuable outcomes. Determining the process variable's upper and lower control limits is very beneficial for enhancing process quality control. The manufacturing process may be improved more affordably by determining the important/influential variables. The ultimate aim of such experimentation is to maximise information while minimising the number of tests without sacrificing the product's qualities. Additionally, the organised method, which maintains the concepts and material in an intelligible and legible style, has the potential to increase the product's quality. Because a screening experiment's findings are expressed mathematically, they may be verified effectively and reliably [7].

In order to decrease surface roughness and shrinkage utilising S/N ratio and composite desirability function, Jan et al.[8] performed screening experimental to fix the relevant parameter for multi-response optimization of the injection moulding process for polystyrene and polypropylene. They provide four important parameters with various PS and PP values. Injection temperature, injection pressure, injection speed, and mould temperature are the key variables.

Using polypropylene material packed with calcium carbonate, which is widely used in the automotive sectors, Kusic and Hancic [9] employed the Taguchi approach to experimentally explore the effect of moulding circumstances on shrinkage and warpage behaviour of standardised test specimens. In order to create the test specimen for shrinkage and warpage analysis, six process factors, including melt temperature, packing and injection pressures, injection speed, packing duration, and cooling time, were taken into consideration. They discovered that the factor with the greatest impact on the shrinkage and, as a result, warpage of the standardised test specimens was the packing pressure.

Through the design of tests based on six criteria that affect surface quality, flow length, and aspect ratio, Packianather et al. [10] attempted to improve the micro injection moulding process. Barrell temperature, mould temperature, injection speed, holding pressure, the presence of air evacuation, and the breadth of micro-legs were all under scrutiny. In this investigation, three experimental materials were used: acrylonitrilebutadiene-styrene, two semi-crystalline polymers like polypropylene and polyoxymethylene, and one amorphous polymer. The important variables were discovered to be barrel temperature and injection speed for PP, barrel temperature, mould temperature, injection speed, and width for POM, and barrel temperature, injection speed, and width for ABS with the mould temperature maintained at a given value.

In a screening research done by Rajendra et al. [11], six parameters—injection pressure, suck back pressure, injection duration, cooling time, zone 1 temperature, and zone 2 temperature (barrel temperatures)—were taken into account to see how they affected black spots and short-shots (defects). It was determined that the faults were mostly influenced by the injection pressure, injection time, and zone 1 temperature.

Before moving on to the optimization of optical lenses' features using RSM, Tsai and Wang [12] carried out a screening experiment utilising the Taguchi experimental technique (L18, OA) to determine the relevant parameters. Melt temperature, injection speed, injection pressure, filling to packing switchover position, packing duration, packing pressure, mould temperature, and cooling time are the eight elements that are taken into account for screening. The results demonstrate that mould temperature, melt temperature, and cooling time are the three important variables.

To ascertain the impact of injection moulding parameters on the characteristics of green components in powder injection moulding, Berginc et al. [13] employed design of experiments (DOE) method employing Taguchi approach with analysis of variance (ANOVA). The weight and size of the green components have been discovered to be significantly influenced by the injection moulding settings.

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The factors that have the greatest of an impact on the dimensions are the mould temperature, melt temperature, and holding pressure.

In order to reduce sink mark faults, Mathivanan et al. [14] employed Taguchi L8 OA for the first screening of seven processing variables. Only five of the seven processing factors were deemed important and assigned to an L27 OA for more research.

Mathivanan and Parthasarathy [15] used fractional factorial design (FFD) for the first screening of processing parameters to anticipate sink mark depths with a sufficient level of accuracy. Only four of the eight screening parameters—melt temperature, mould temperature, packing pressure, and rib-to-wall ratio—were chosen because they were the most significant and controllable. In order to create a central composite design (CCD) of trials for further research, these four key factors are taken into account.

In a micro injection moulding, Attia and Alcock [16] conducted screening experiments using five processing parameters to determine their potential impact on the filling of the moulded parts, using the part mass as an output parameter. The five factors taken into account are the following: cooling time, injection speed, metering size, hold pressure time, and melt temperature. They discovered that for all the various forms, the holding pressure is the most important processing parameter. Additionally, it's been noted that the geometry of the parts influences which processing parameters are statistically significant; for example, when a component has complicated geometry, both the injection speed and the mould temperature are statistically significant.

Liao et al., [17] proposed the optimum processing variable for thin-wall components took the impacts of parameter interactions into consideration. A Taguchi technique was utilised to create a DOE plan, and ANOVA was used to identify the most important parameter. The holding pressure was shown to be the most important input factor affecting shrinkage and warpage.

Three plastic materials—high-density polyethylene, general-purpose polystyrene, and acrylonitrile-butadiene-styrene—were examined for shrinkage behaviour and injection moulded component optimization using the Taguchi technique by Chang and Faison [4]. To explore the impact of processing variables on the shrinkage of the aforementioned plastic, they methodically utilised the Taguchi technique. According to the findings, semicrystalline plastic HDPE shrinks more than amorphous ABS and GPS. They looked at the amount of shrinkage in both the flow-along and flow-across directions. It was discovered that HDPE shrank differently than ABS and GPS. In HDPE, more shrinkage was seen in the direction across the flow than the direction along the flow. For GPS and ABS, the opposite is true. The most important factors affecting the shrinkage behaviours of three materials were mould and melt temperatures, holding pressure, and holding duration, albeit their value varied for each plastic.

The impact of processing variables on the shrinkage of polymeric components was examined by Jansen et al. [18]. For seven widely used plastics, including high density polyethylene (HDPE), polystyrene (PS), acrylbutiene styrene (ABS), polybutylene terephthalate (PBT), high impact polystyrene (HIPS), polycarbonate (PC), and 30% glass fibre reinforced PBT, they systematically varied mould temperature, melt temperature, holding pressure, and injection velocity (PBT-GF30). For all of the plastic materials under examination, it was discovered that the packing pressure had the greatest impact, followed by the melt temperature. In contrast, no overarching pattern was established for the injection velocity or mould temperature.

The goal of this effort is to reduce operating condition uncertainty by prioritising and optimising the processing conditions, which will enhance the quality and cost-effectiveness of the injection moulded goods. i.e., the process parameters. The injection moulding process produces a range of plastic items with diverse forms and geometries that are utilised in the automotive, medical, packaging, and other related sectors. So, care must be taken regarding the process setting before the start of the production. In this study, a 12-run Taguchi design (L12, Orthogonal array) is applied for experimentation with eight factors and five responses to determine the degree of significance of the factors to obtain better experimental results in terms of responses during the production of a certain plastic product. The eight process parameters (factors) are varied at two levels as per the expert opinion, literature survey and after initial processing window estimation at the injection moulding machine. For each of the 12-run, the five replicates are prepared and the average of the five values for each response is reported as the value of response (mechanical properties). The average value of the test results for each response is analysed using Analysis of mean (ANOM) technique wherein the degree of significance for different process parameters is determined on the basis of their rank obtained in the ANOM result. The higher the rank obtained in the ANOM result for a certain parameter the higher will be its priority (significance).

II. EXPERIMENTATION

2.1 Material

The material used in this study is isotactic polypropylene (iPP), grade Repol H110MA, manufactured by Reliance Industries Limited (RIL), India. This grade is suitable for injection moulding purposes. According to information

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provided by material manufacturer few of the material characteristics are, viz. the melt flow index is 11.0 g per 10 min as per ASTM D1238 (2.16 kg/230 ^{0}C), the tensile strength at yield is 36 MPa and the elongation at yield is 0.1 as per ASTM D638. The material is solid granular, off white and odourless as per data given in material safety data sheet (MSDS). The material was moulded into pellets without any prior treatment, however efforts were made to prevent moisture exposure both during storage and usage.

2.2 Screening experiments of the process parameters

2.2.1 Injection moulding of samples

The tensile test specimens as per ASTM D-638, type-I were moulded on a table top micro injection moulding machine make BabyPlast, Italy (model 6/10P) provided with mould temperature controller ranging from 10 to 90 ^{0}C. The dumbbell-shaped specimens have an overall length of 165 mm (with a gauge length of 50mm), width of 13.8 mm and thickness of 3.05mm as shown in **Fig. 1**. The "dogbone" or "dumbbell" shape ensures that the break occurs in the centre of the specimen rather than at the clamping areas. The specimens for screening experiments were moulded as per Taguchi (L_{12}, OA) design of experiment (DOE). The factors of screening experiment and their levels are summarized in **table-1**. The levels mentioned in table-1 is decided after the initial estimation of processing window to produce a completely filled sample (i.e., no short shot) and from the literature [19]. The injection moulding operation was conducted in automatic cycle mode and few of the initial shots were rejected so that the process attains the near steady state prior to sample collection for each run. For each run five replicates were produced and average of their response value is reported against each run.

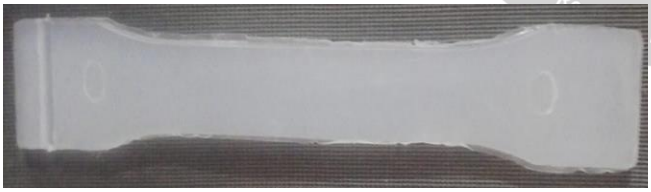

Fig. 1: Schematic diagram of the tensile test specimen (ASTM D638, Type-1)

2.2.2 Tensile testing of specimen for screening analysis

The test was conducted using a universal testing machine (UTM), also known as a tensile testing machine, manufactured by Lloyd in the USA. Model LS-5, with a 5 kN load cell and wedge action grippers, was used for the test. At room temperature, all of the experiments were run. The tests were carried out using type-I tensile specimens in accordance with ASTM D 638 standard. The crosshead speed used for all testing was 100 mm/min. Five samples were evaluated for each run, and the average tensile property values for each run were recorded and given as the value of response. The four key properties measured are: Stress at break (N/m^2), Young's modulus (MPa), Strain at break, and Work at break (N-mm).

Mechanical properties of the parts produced by the injection moulding process may be affected by the several input process parameters (factors). However, the degree of importance of the input process parameters may be different for different mechanical properties and materials therefore, it is necessary to determine their order of significance for a particular mechanical property. Screening experimentations were carried out with an aim to determine the degree of importance of the several input parameters for different mechanical properties. Eight input process parameters viz. injection pressure, injection rate, melt temperature, mould temperature, hold on pressure, cooling time, hold on time and the injection time; each at two levels, were considered in the screening experiments. The input process parameters and their levels are shown in Table 1.

Table 1: Input parameters and their levels

Input parameter	Symbol	Unit	Level 1	Level 2
Injection pressure	*A*	bar	105	115
Injection rate (%)#	*B*	cc/s	80	90
Melt temperature	*C*	ºC	205	235
Mould temperature	*D*	ºC	30	50
Hold on pressure	*E*	bar	60	80
Cooling time	*F*	s	10	30
Hold on time	*G*	s	2	6
Injection time	*H*	s	4	6

Maximum injection rate = 10 cm^3/s

Twelve experiments as per the Taguchi's L_{12} orthogonal array (OA) were conducted. L_{12} OA in terms of coded values is shown in **Table 2**.

Table 2: L_{12} OA in terms of coded values

Expt. No.	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2
3	1	1	2	2	2	1	1	1
4	1	2	1	2	2	1	2	2
5	1	2	2	1	2	2	1	2
6	1	2	2	2	1	2	2	1
7	2	1	2	2	1	1	2	2
8	2	1	2	1	2	2	2	1
9	2	1	1	2	2	2	1	2
10	2	2	2	1	1	1	1	2
11	2	2	1	2	1	2	1	1
12	2	2	1	1	2	1	2	1

Each experiment was replicated five times and average value of four mechanical properties viz. Stress at break (ASSB), Young's modulus (AYM), Strain at break

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(ASTB) and Work at break (AWB) was obtained. L_{12} OA in terms of the actual values of the input process parameters and experimental results are shown in **Table 3**.

Table 3: L_{12} OA and experimental results

Expt. No.	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	ASSB (N/m²)	AYM (MPa)	ASTB	AWB (N-mm)
1	105	80	205	30	60	10	2	4	28071333	581.281	0.254	25314.26
2	105	80	205	30	60	30	6	6	18556113	552.078	0.614	53290.99
3	105	80	235	50	80	10	2	4	33410816	577.729	0.235	24994.22
4	105	90	205	50	80	10	6	6	32460441	639.69	0.245	26948.69
5	105	90	235	30	80	30	2	6	30691015	654.92	0.241	26324.67
6	105	90	235	50	60	30	6	4	33336280	634.136	0.22	23166.75
7	115	80	235	50	60	10	6	6	34852366	616.255	0.218	21694.6
8	115	80	235	30	80	30	6	4	33534272	597.228	0.213	22025.99
9	115	80	205	50	80	30	2	6	33465355	659.838	0.224	24456.17
10	115	90	235	30	60	10	2	6	34225180	616.253	0.231	23515.67
11	115	90	205	50	60	30	2	4	34946689	633.708	0.202	21122.15
12	115	90	205	30	80	10	6	4	32565729	638.802	0.246	25853.99

Four mechanical properties shown in Table 3 represent the four output responses and for each output response higher-the-better quality characteristic was considered as the objective was to achieve their maximum value. Signal-to-Noise (S/N) ratio for each output response was computed using Eqn. (1) and the values thus obtained are listed in **Table 4**.

$$S/N = -10log_{10}\left(\frac{1}{y_i^2}\right) \quad (1)$$

where, y_i represents the experimental value of the output response for *i*th experiment.

Table 4: Experimental results and the corresponding S/N ratio

Expt. No.	ASSB		AYM		ASTB		AWB	
	Value (N/m²)	S/N ratio (dB)	Value (MPa)	S/N ratio (dB)	Value	S/N ratio (dB)	Value (N-mm)	S/N ratio (dB)
1	28071333	148.97	581.281	55.29	0.254	-11.90	25314.26	88.07
2	18556113	145.37	552.078	54.84	0.614	-4.24	53290.99	94.53
3	33410816	150.48	577.729	55.23	0.235	-12.58	24994.22	87.96
4	32460441	150.23	639.69	56.12	0.245	-12.22	26948.69	88.61
5	30691015	149.74	654.92	56.32	0.241	-12.36	26324.67	88.41
6	33336280	150.46	634.136	56.04	0.22	-13.15	23166.75	87.3
7	34852366	150.84	616.255	55.80	0.218	-13.23	21694.6	86.73
8	33534272	150.51	597.228	55.52	0.213	-13.43	22025.99	86.86
9	33465355	150.49	659.838	56.39	0.224	-13.00	24456.17	87.77
10	34225180	150.69	616.253	55.80	0.231	-12.73	23515.67	87.43
11	34946689	150.87	633.708	56.04	0.202	-13.89	21122.15	86.49
12	32565729	150.26	638.802	56.11	0.246	-12.18	25853.99	88.25

For a specific output response for which the mean value of the S/N ratio at each level of the input parameter was obtained, analysis of mean (ANOM) was used to establish the order of importance of the input parameters. For instance, the average of the S/N ratios for experiments 1 through 6 and experiments 7 through 12 was used to calculate the mean S/N ratio for injection pressure (designated as input parameter A) at level 1 and level 2, respectively. The same formula was used to get the mean S/N ratio for each level of the other input parameters. The mean S/N ratio at each level of the input parameter for the output response ASSB is shown in **Table 5** which is known as S/N response table.

Table 5: S/N response table for the output response ASSB

Level	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
1	149.2	149.4	149.4	149.3	149.5	150.3	150.2	150.4
2	150.6	150.4	150.5	150.6	150.4	149.6	149.6	149.6
Delta	1.4	1.0	1.1	1.3	0.9	0.7	0.6	0.8
Rank	1	4	3	2	5	7	8	6

Rank of the input parameters shown in Table 5 represents their degree of importance for affecting ASSB. It is evident from Table 5 that for ASSB the degree of significance of the input parameters in decreasing order is injection pressure (*A*) > mould temperature (*D*) > melt temperature (*C*) > injection rate (*B*) > hold on pressure (*E*) > injection time (*H*) > cooling time (*F*) > hold on time (*G*). Similar analysis was carried out for other output responses i.e. AYM, ASTB, and AWB and degree of significance of the input parameters was obtained which is summarized in **Table 6**.

Table 6: Degree of significance of the input parameters for the output responses

Output response	Degree of significance of the input process parameters in descending order
Average stress at break (ASSB)	injection pressure (*A*) > mould temperature (*D*) > melt temperature (*C*) > injection rate (*B*) > hold on pressure (*E*) > injection time (*H*) > cooling time (*F*) > hold on time (*G*)

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Average Young's Modulus (AYM)	injection rate (*B*) > hold on pressure (*E*) > injection pressure (*A*) > mould temperature (*D*) > injection time (*H*) > cooling time (*F*) > hold on time (*G*) > melt temperature (*C*)
Average strain at break (ASTB)	injection pressure (*A*) > mould temperature (*D*) > melt temperature (*C*) > injection time (*H*) > injection rate (*B*) > hold on time (*G*) > hold on pressure (*E*) > cooling time (*F*)
Average work at break (AWB)	injection pressure (*A*) > melt temperature (*C*) > mould temperature (*D*) > injection time (*H*) > hold on time (*G*) > injection rate (*B*) > cooling time (*F*) > hold on pressure (*E*)

It can be observed from Table-6 that the importance of each process parameter is different for each response and therefore, selection of a few critical input parameters for further detailed investigation can be made on the basis of screening, literature survey and moulding experience.

III. CONCLUSIONS

This work clearly demonstrated the level of complexity associated with the relationships between injection moulding conditions and resulting mechanical properties. The complexity and variability associated with the process shows that the underlying relationships are far from being fully understood. It may concluded that the injection pressure, melt temperature and mould temperature are the three significant factors with different order for the responses Average stress at break (ASSB), Average strain at break (ASTB) and Average work at break (AWB) whereas injection rate, hold on pressure, injection pressure seems to be the significant factor for Average Young's modulus (AYM). In general the order and the factors of significance are different for different response. The order of importance of the process parameters also vary from materials to material as reported in other studies [4]. Moreover, the finding of the previous researchers in regard to the significance of the process parameters is not consistent and the same has been deduced from the literature survey of other studies [20].

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