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The Influence of Temperature Dependant Parameters in Plastic 0.0nd Metal Injection Molding using Taguchi Method

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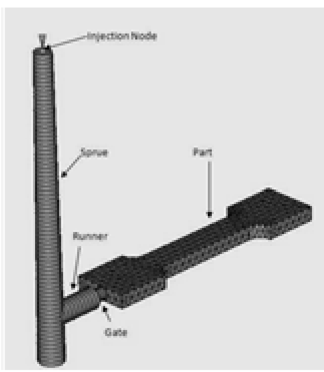
Graphical abstract



Abstract

Injection molding is a promising manufacturing process because of several advantages. Conventional injection molding was dominated by plastic as the raw material, but for better engineering properties feasibility, metal injection molding (MIM) has been given special attention. However, because of different properties and rheology, processing parameters for both processes must be treated accordingly. In this paper, the most influencing process parameter is identified for both processes using the state of the art Taguchi method. Simulation using Moldflow software is conducted with various process settings. From the study, it is proven that due to rheological behaviour, all the input parameters influence the MIM process while only one parameter is dominating during the injection molding of polypropylene.

Keywords: Metal injection molding; simulation; Taguchi

Abstrak

Pengacuan suntikan adalah satu proses pembuatan yang menjanjikan beberapa kelebihan. Pengacuan suntikan konvensional dikuasai oleh plastik sebagai bahan mentah, tetapi untuk sifat-sifat kejuruteraan yang lebih baik kemungkinan, pengacuan suntikan logam (MIM) telah diberikan perhatian khusus. Walau bagaimanapun, kerana sifat-sifat yang berbeza dan reologi, parameter pemprosesan untuk kedua-dua proses perlu dirawat dengan sewajarnya. Dalam kertas kerja ini, parameter proses yang paling mempengaruhi dikenal pasti untuk kedua-dua proses menggunakan keadaan seni kaedah Taguchi. Simulasi menggunakan perisian Moldflow dijalankan dengan beberapa tetapan proses. Dari kajian ini, ianya terbukti bahawa disebabkan tingkah laku reologi, semua parameter input mempengaruhi proses MIM manakala hanya satu parameter mendominasi semasa pengacuan suntikan daripada polipropilena.

Kata kunci: Pengacuan suntikan logam; simulasi; Taguchi

1.0 INTRODUCTION

Plastic Injection Molding (PIM) has been accepted increasing interest because of the advantages of preciseness, wide range of plastic material selection and ability to produce complex geometry. With the purpose of taking the benefit of the process, Metal Injection Molding (MIM) was inspired as the material properties are over polymers for some applications where better mechanical, electrical and magnetic properties might be required. In conventional injection molding, the raw material is thermoplastic pellet, but in MIM, feedstock which comprised mixture of selected metal powder and set of thermoplastic material as temporary binder are used. The basic steps of MIM process are mixing of powder-binder for feedstock preparation, injection molding to produce the green part in desired shape, debinding by removing binder components and finally sintering to near final density.

PIM and MIM are using different material, therefore process setting in PIM cannot be applied directly to MIM [1]. Therefore, process settings play very important roles in order to get high quality of a final product. In optimizing the parameters, researchers all over the world used various approaches such as Taguchi method [1, 2] and simulation [3].

To save cost and time, modeling and simulation would be desirable in process optimization as there is no necessity to conduct real process in order to predict the behavior of the process. Validation for modelling is nevertheless essential for the result to be claimed reliable. Simulation tools for PIM are maturely established and easily available but simulation software that is able to handle peculiar rheology of feedstock in

MIM is hardly found. Thus, because of similarity in process wise, MIM process always been simulated by using software tools that were purposely developed for casting and PIM process [4].

Taguchi techniques were widely used in engineering analysis in the system, parameter and tolerance design [5]. The most important stage in Taguchi Method is the selection of control factors so that it would be possible to identify non-significant variables at the earliest opportunity [6]. Based on the Taguchi design method, four factors at each level were adopted. The fractional factorial designs used in this study was a standard L9 orthogonal array [7].

Dealing with the process setting to determine the quality of a final product, causal relationship between input and output parameters is often not straight forward [3]. Ahn *et al*. [8] used a classification of output parameter into three main categories which are pressure, temperature and velocity (flow) dependent parameter for systematic analysis of the process design. These parameters are important and need to be dealt accordingly as it may avoid defects and will determine the characteristic of final product. Temperature has been identified as major contributing factors in both MIM and PIM process. This paper will focus only on the temperature dependent output parameter which consist of Melt Front Temperature Difference (MFTD), Cooling Time (t_{cool}) and Packing Time (t_{pack}) [2,5]. Lack of control of these parameters may possibly cause types of defects such as short shot, warpage and flashing.

The main objective of this paper is to determine the optimized process condition for both processes differently. Another objective of this study is to prove that both process are influenced differently by the process setting and to investigate the sensitivity of process output towards certain controlled parameter. To achieve this objective, Taguchi method is employed by means of determining the percent of influence of every identified factor.

■2.0 METHODOLOGY

2.1 Material Properties

For plastic material, polypropylene (PP) was chosen to represent thermoplastic material. PP is the similar type of material employed by [1] in their comparison study. The details of the plastic properties are as stated in Table 1.

Table 1 Properties of plastic material

Family name	Polypropylenes (PP)
Identification	Lupol TE-5007B
Manufacturer	LG Chemical
Density	928 kg.m^{-3}
Specific heat capacity	2931 J/kg.C
Thermal conductivity	0.118 W/m.C

For MIM, material testing has been done to the feedstocks prepared, and the properties are used in this study to represent MIM material. The feedstocks is a mixture of Stainless Steel SS316L powder, and a binder which consist of 73% PEG, 25% PMMA and 2% Stearic Acid as the binder system. The stainless steel powder is water atomized and manufactured by Atmix Corporation Japan, with average particle size of 5µm. In the binder system, PEG acts as the main component, PMMA as the backbone polymer while Stearic Acid works as surfactant. The best powder loading of 61.5% as claimed by [9] is used. Details properties of the stainless steel powder material are simplified in Table 2.

Table 2 Material properties of SS316L stainless steel powder

Identification	SUS316L powder
Manufacturer	Epson Atmix Corp., Japan.
Particle shape	Irregular
Grade	PF-10F
Density - Tap	4.06 g/cm^3
- Pycnometer	8.0471 g/cm^3
Average particle size	D_{10} = 2.87µm D_{50} = 5.96µm D_{90} = 10.65µm

Source: Material Safety Data Sheet

2.2 Process Parameters and Design of Experiments

All the process setting used in this study are according to the investigation reported by [1]. The simulation runs were executed based on L9 orthogonal array designs for each material (Park, 1996). Similar series of study had been done recently, but the array being used in [1] and [8] are not orthogonal, hence the result might be erroneous. Table 3 showed the new proposed combination array for this study and the orthogonally has been confirmed.

Table 3 The orthogonal array

Run	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

By using a new combination array as stated in Table 3, it is expected that the result will be different because the contributing factor for every run has been adjusted.

Four factors at three levels each are conducted as shown in Table 4 and 5 for PIM and MIM respectively. The effect of these factors on the temperature dependent output parameters will be observed.

Table 4 Factors and levels for PIM study

Factors		Levels		
Filling time (t_f)		1.0 (s)	1.25 (s)	1.5 (s)
Switch Over (*SO*)		99%	98%	97%
Melt temperature (T_m)	PIM	210°C	230°C	250°C
Wall temperature (T_w)	PIM	45°C	60°C	75°C

Table 5 Factors and levels for MIM study

Factors		Levels		
Filling time (t_f)		1.0 (s)	1.25 (s)	1.5 (s)
Switch Over (*SO*)		99%	98%	97%
Melt temperature (T_m)	MIM	150°C	160°C	170°C
Wall temperature (T_w)	MIM	30°C	40°C	50°C

In laboratory experiment, these parameters are usually fed into the machine control setting. However in this paper, data were gathered from multiple series of simulation procedures by employing the conditions as depicted in Tables 4 and 5. These conditions range were decided as the best and common from literatures and experienced.

Optimised characterisation was done by taking four input processing parameters as control factor and three output parameters. In this paper, the smaller the better characteristic of Signal to Noise (S/N) ratio was chosen for all three output parameters; MFTD, t_{pack} and t_{cool}. The equation for S/N Ratio is as stated in (1).

$$S/N = -10 \text{ Log} \sum y^2/n \quad (1)$$

The data gathered are then analysed using analysis of variance (ANOVA) to evaluate the most influencing and significant parameters for each material.

2.3 Molding Simulation Process

Simulation was conducted using Autodesk MoldFlow Plastic Insight 2010. Tensile bar shaped sample as shown in Figure 1 was used in the simulation. The meshed geometry of the sprue, runner, gate and the tensile bar sample with 3976 elements and 1995 nodes. The feeding system consisted of one cold tapered sprue, one cold runner with circular section and one gate with semi-circular section. The gate was positioned about the middle of the part to reduce the polymer flow length during mould filling step [10].

For both materials, Moldflow described the feedstock viscosity by using Cross-WLF viscosity model. This model described viscosity as a function of temperature, shear rate and pressure.

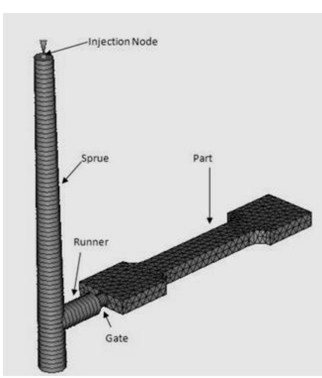


Figure 1 The design of the tensile bar and feeding system

3.0 RESULTS

From nine runs of MoldFlow simulation, the data of three output parameters for both materials was summarised in Table 6.

Table 6 The output values from simulation results

Run	PIM			MIM		
	MFTD (°C)	t_{cool} (s)	t_{pack} (s)	MFTD (°C)	t_{cool} (s)	t_{pack} (s)
1	0.10	35.25	29.99	11.40	11.75	9.99
2	0.10	45.50	37.81	12.30	18.05	9.96
3	0.10	61.25	50.79	13.00	31.25	12.19
4	0.10	58.25	49.58	16.80	31.00	11.99
5	0.20	40.00	33.46	20.90	14.00	9.95
6	0.10	42.50	36.08	16.00	18.25	9.92
7	0.30	47.75	39.73	25.90	18.50	9.98
8	0.20	55.00	47.79	19.70	30.50	11.44
9	0.30	37.75	31.66	25.00	12.75	9.91

Figure 2, 3 and 4 show S/N ratio plots for both PP and MIM materials for different responses; MFTD, Cooling Time and Packing Time respectively. From Figure 2, the optimized condition for the smallest melt front temperature different are the combination of [A1(1s), B3(99%), C1(150°C), D3(50°C)] for MIM and for PP material, smallest MFTD is achievable with the condition of [A1(1s), B3(99%), C1(120°C), D3(75°C)].

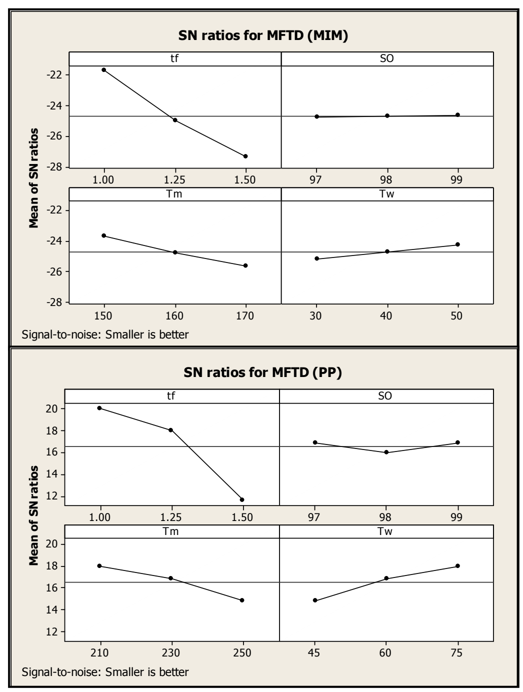


Figure 2 S/N plots for MFTD response

In order to get the highest cooling rate, MIM optimized process condition are [A1(1s), B3(99%), C1(150°C), D1(30°C)]. For PP, shortest cooling time the machine setting required are [A1(1s), B1/B3(97%/99%), C1(210°C), D1(45°C)].

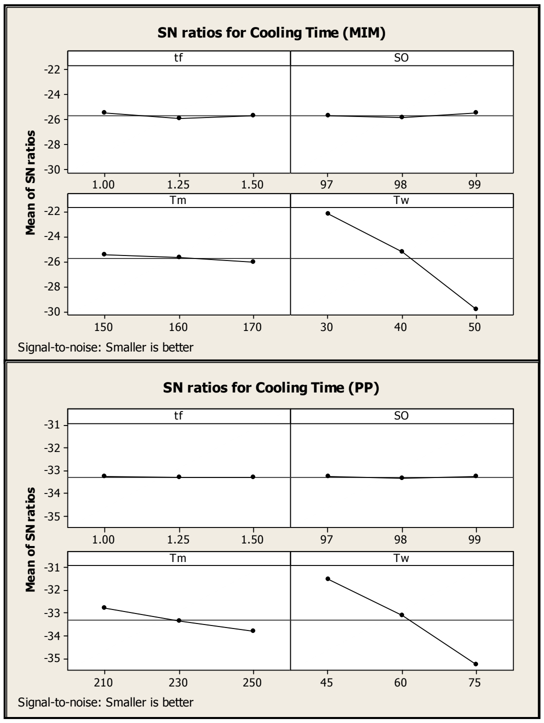


Figure 3 S/N plots for cooling time response

In this study, S/N ratio for packing time is set to smaller is better. The fastest packing time for MIM can be achieved by the condition of [A1(1s), B2(98%), C1(150°C), D1/D2(30°C/40°C)]. For PP, the best packing time is achieved by applying machine setting at [A1(1s), B1(97%), C1(210°C), D1(45°C)].

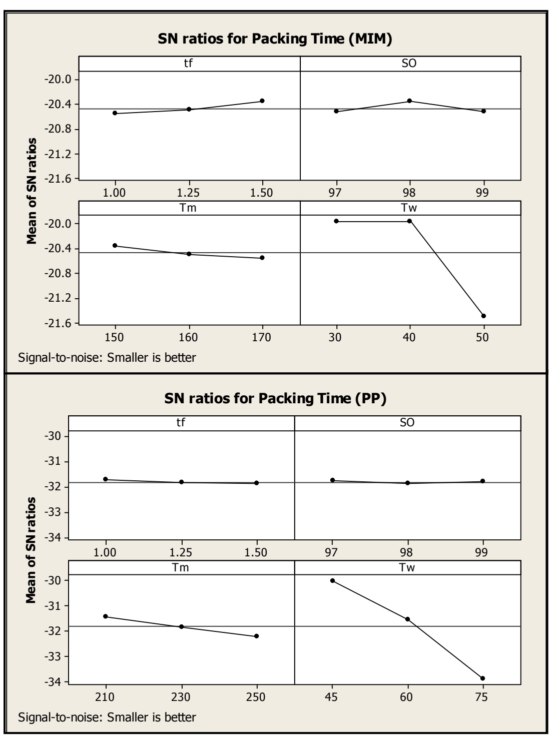


Figure 4 S/N plots for packing time response

From the statistical results by ANOVA, the S/N ratios at three levels were summarized in Table 7 for PIM and Table 8 for MIM materials.

Table 7 Sum of S/N ratios and influence percent Polypropylene materials

PP			Fill time	SO	Melt Temp	Mold Temp
MFTD	S/N	Level 1	20.00	16.82	17.99	14.81
		Level 2	17.99	15.99	16.82	16.82
		Level 3	11.63	16.82	14.81	17.99
		R	8.37	0.83	3.18	3.18
		P_i (%)	**53.79**	**5.33**	**20.44**	**20.44**
Cooling Time	S/N	Level 1	-33.28	-33.28	-32.77	-31.51
		Level 2	-33.30	-33.34	-33.33	-33.10
		Level 3	-33.31	-33.28	-33.79	-35.29
		R	0.03	0.06	1.01	3.78
		P_i (%)	**0.61**	**1.23**	**20.70**	**77.46**
Packing Time	S/N	Level 1	-31.74	-31.76	-31.45	-30.01
		Level 2	-31.85	-31.88	-31.82	-31.56
		Level 3	-31.86	-31.81	-32.20	-33.87
		R	0.12	0.12	0.77	3.86
		P_i (%)	**2.46**	**2.46**	**15.81**	**79.26**

Table 8 Sum of S/N ratios and influence percent for MIM materials

MIM			Fill time	SO	Melt Temp	Mold Temp
MFTD	S/N	Level 1	-21.74	-24.77	-23.70	-25.17
		Level 2	-25.00	-24.70	-24.75	-24.72
		Level 3	-27.37	-24.64	-25.65	-24.22
		R	5.63	0.14	1.95	0.94
		P_i (%)	**65.01**	**1.62**	**22.52**	**10.85**
Cooling Time	S/N	Level 1	-25.48	-25.74	-25.44	-22.14
		Level 2	-25.99	-25.91	-25.69	-25.23
		Level 3	-25.71	-25.52	-26.05	-29.80
		R	0.52	0.39	0.62	7.66
		P_i (%)	**5.66**	**4.24**	**6.75**	**83.35**
Packing Time	S/N	Level 1	-20.56	-20.52	-20.36	-19.96
		Level 2	-20.49	-20.36	-20.49	-19.96
		Level 3	-20.36	-20.52	-20.55	-21.49
		R	0.20	0.16	0.19	1.53
		P_i (%)	**9.62**	**7.69**	**9.13**	**73.56**

From all the data collected, the contibution of each factor on MFTD, cooling time and packing time are shown in Figures 5, 6 and 7 respectively.

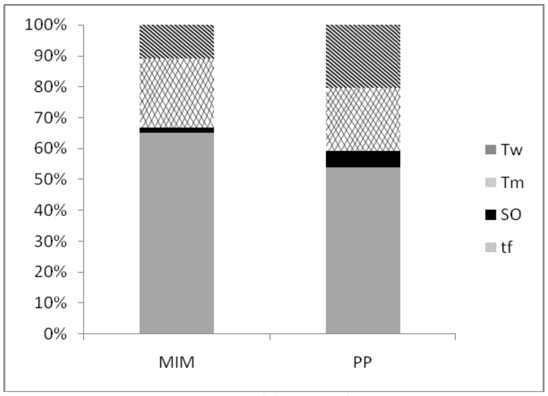


Figure 5 Comparison of factor influence on MFTD

4.0 DISCUSSION

4.1 Effect of MFTD Output

Figure 5 clearly depicted that both material were affected by all the controlled parameter, but with different percentage. The most striking observation emerged from the comparison was both of the material were highly influenced by the same parameter; the filling time. Surprisingly, the ANOVA showed that parameters that directly related to temperature (melt temperature and wall mold temperature) gave only minor consequences on the MFTD output. Therefore, to minimize the MFTD, the filling time parameter must be given special attention, and based on Figure 2, smallest MFTD can be achieved by filling the mold as quick as possible.

4.2 Effect on cooling time output

For cooling time effect, as we can see the trend is contradictory as compared to the previous concern, MFTD. Wall mold temperature played vital role in ensuring the shortest time for the part before it can be ejected. To determine the highest cooling rate, PIM did not seem to be affected by filling time parameter at all and only two parameter influencing the output. Contrary, MIM with its peculiar rheology behaviour influenced by all controlled parameters, but the most manipulating factor among them is the mold wall temperature.

The observed correlation between cooling time and mold wall temperature might be due to energy dissipation to the surrounding by the mold. The lower the temperature of the mold, the higher heat transfer activity taking place between the green part and the mold wall and this may explain the relatively good correlation between cooling time and wall temperature.

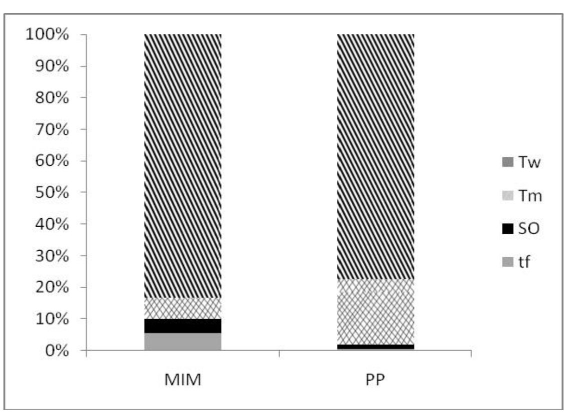


Figure 6 Comparison of factor influnce on cooling time

4.3 Effect on packing time output

Both materials shows comparable trend as on cooling time effect where they were only dominated by single parameter, which is the mold wall temperature. This finding has important implication for designing the mold and in setting the machine when dealing with either polymer or metal injection molding.

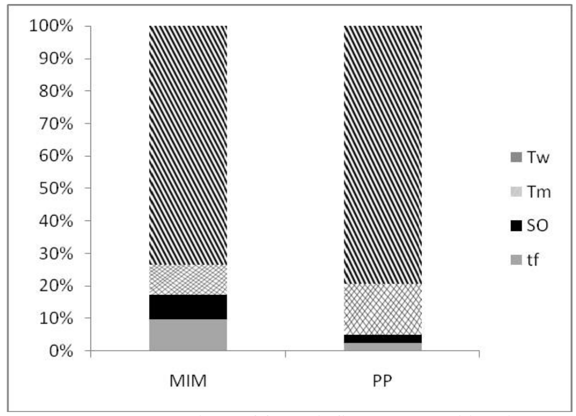


Figure 7 Comparison of factor influence on packing time

From all three observations, it is apparent that both process showed similar trend, dominated by same single parameter for every output observation. Metal powder is the main component in a feedstocks but the binder made from thermoplastic also play its role during the injection molding process. In MIM, binder effect was larger than the metal powder [5], which results in comparable trend between the MIM and PIM (purely thermoplastic) throughout the study.

5.0 CONCLUSION

In summary, this paper demonstrated that Taguchi method is capable to determine significant main parameter in injection molding for both metal and polymer materials. In general, switch over position did not have significant effect at this study, probably because this parameter is commonly associated with pressure related parameter.

In the future, it would be interesting to explore by narrowing down the range of every parameter value to optimize conditions better. At this stage, lower mold temperature is better for reducing the cooling time, so in the future the result can be iterated using new temperature range around the lowest temperature span.

Acknowledgement

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