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Parameter Optimization of Metal Injection Moulding: A Review

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ABSTRACT

Metal injection moulding (MIM) is a newly developed technology to form metals and alloys into desired shape. MIM is a combination of conventional plastic injection moulding and powder metallurgy. Detailed analysis of powders, binders, injection moulding, binder removal process and parameter optimization process is discussed. Taguchi method can also be applied for optimal design configurations when significant interactions exist between and among the controlled variables. This paper provides an overview of MIM process, optimization of parameters using Taguchi method.

Keywords: *Metal Injection Moulding, Parameter Optimization, Taguchi Method*

Introduction

Metal Injection Moulding (MIM) is a newly developed technology to form metals and alloys into desired shape. MIM is a combination of convention plastic injection molding and powder metallurgy. The advantages of MIM have emerged as being able to produce cost-effective, complex shaped parts in both large and small volumes using almost all types of metals and intermetallic

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compound. MIM is a process that was developed from the combination of plastic injection moulding and traditional powder metallurgy and is rightly regarded as a branch of both technologies. MIM is similar to plastic injection moulding as the material is fed into a heated barrel, mixed and pushed into a mould cavity where it cools and then hardens to the mould cavity shape. Moreover, MIM is similar to traditional powder metallurgy in that procedure is able to compact a lubricated powder mix in a rigid die by uniaxial pressure, eject the compact from the die and sinter it. MIM is also a branch of powder injection moulding (PIM), which is a subject that covers both metallic and non-metallic powder used in the manufacturing of small-to-medium-complex-shaped parts in large numbers [1]-[7].

The MIM process consists of four main steps which is mixing, injection moulding, debinding and sintering as shown in Figure 1. During the mixing process, the metal powders is mixed with a binder at a selected volume ratio to form a homogenous feedstock. The molten feedstock is then allowed to cool down and solidify. The attained feedstock after cool down and solidified is molded to produce a "green" compact and the binders hold particles together. The binder components are then removed to produce "brown" compact. Finally, sintering process is performed to give required mechanical properties for the sintered product also known as sintered body. Thus, the development and improvement of binders results in faster debinding procedures, cost reduction and less environmental defect. The flow diagram for the MIM process is shown in Figure 1.

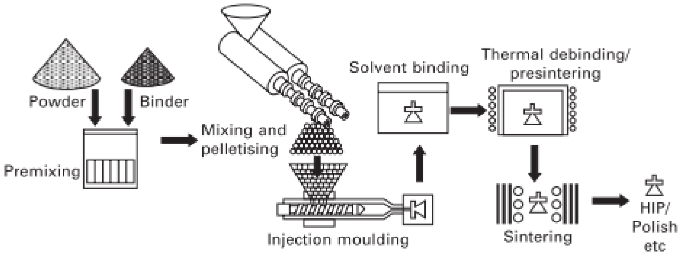

Figure 1: Flow Diagram for MIM process [4]

The rheological properties of the feedstock, which consists of the powder and binder mix, are of major importance. The requirement is that the mix flows smoothly into the die cavity without segregation at the moulding temperature and therefore the viscosity should be as constant as possible over a range of temperature. The as-moulded part, which is also called a green part, contains a high volume percentage of binder and the result is that during sintering a large shrinkage occurs. Therefore, a major requirement of the sintering process to ensure that this shrinkage is controlled because this affects the density as well as mechanical properties. It is in this regards that MIM has an advantage over traditional powder metallurgy because if the sintering is optimized the shrinkage should also be uniform [8]-[11].

Powders for Metal Injection Moulding

The primary raw materials for MIM are metal powders and a thermoplastic binder. The properties of the powder determine the final properties of the MIM product and therefore the characteristics of the powder used in metal injection moulding are important in the control of the process [13]. The properties that are considered in the powders used in MIM are:

- Particle shape: slightly non-spherical with an aspect ratio of 1:2 to 1:5
- Particle size: 0.1-20µm sizes are recommended
- Mean particle size: 2-8µm sizes are recommended
- Tap density: the recommended is at least 50% of the theoretical
- Dense, discrete particle free of voids
- Clean particle surface

All of these above characteristics and properties, the particle size distribution is the most important because it determines the sinterability and surface quality of the final product. The finer powders sinter more readily than coarser powders and it is for this reason that the finer powders are preferred in MIM to coarser powders. The other powder property that is considered to be important is the particle shape of the powder because it is desirable to incorporate as high a proportion of metal as possible [14]. The choice of powder is in reality often determined by availability, but the growth in demand has encouraged powder manufacturers to produce powders that meet the requirements of MIM as desired.

Even though almost any metal that can be produced in suitable powder form can be processed by MIM, there are some metals such as aluminium that are difficult to process via MIM. This is because they have an adherent oxide film that is always present on the surface and this inhibits sintering. For example, researchers found that mixing the aluminium with small quantities of magnesium overcomes the oxide barrier [15]. In general, the list of metals that are widely used in MIM includes many common and several less common metals and their alloys – plain and low alloy steels, high speed steels, stainless steels, super alloys, intermetallic, magnetic alloys and hard metals (cemented carbide) [14]. The more expensive materials like titanium offer better prospects for economic gain because, unlike alternative processes such as machining, there is practically no waste due to scrap which helps to offset the high cost of producing the powder in the required form.

Binders for Metal Injection Moulding

The development of binder composition has been instrumental in the progress that MIM has made as a technology for manufacturing parts. The binder material is present in the green part to assist in processing by providing plasticity and it is removed from the products after injection moulding in a process widely known as debinding [20,21]. One of the early challenges that presented itself during the early development of MIM was to find suitable compositions which fulfil several tasks as listed below:

- To be able to incorporate a high volume of fine metal powders, typically 60% by volume.
- To form a coherent mass that can be plastified and injection moulded at elevated temperature.
- To allow removal of the main binder constituent in a reasonably short, environmentally friendly process.
- To provide enough strength after debinding by means of the 'backbone binder'.
- To be supplied in a regular granular form that can easily be fed into an injection moulding machine.
- To be able to produce runners and green scrap which are easily recyclable.
- To be cost effective

In general, there are five types of binder used in the MIM process and these are classified according to the following categories:

- Thermoplastic compounds
- Thermosetting compounds
- Water-based systems
- Gelation systems
- Inorganics

Binder Removal (Debinding)

The binder material in MIM green components is only an intermediate processing aid and it is always removed from the products after injection moulding. Removal of the binder from the green part is also considered a key stage of the process and that one requires most careful control. The stage at which the binder is removed is known as debinding. The manner in which the binder is extracted consists of the heating of the green compact in order to melt, decompose, and/or evaporate the binder. This binder extraction has to be optimized so that there is no disruption of the as-moulded part. The process normally takes several hours, depending on the thickness of the component.

It has been the challenge for MIM developers to reduce and optimize the times for debinding. There are different methods which serve to obtain parts with the required interconnected pore network without destroying the shape of the components in the shortest possible time. Different commonly used debinding methods applied in MIM industry are further explained.

Thermal Debinding

Binders that usually lend themselves to this process are polymers such as polyethylene or polypropylene, a synthetic or natural wax and stearic acid [20, 21]. The MIM feedstocks based on these type of binders are easy to mould, but the removal of the binder requires very careful and slow heating in a thermal pyrolysis process. The debinding time lasts 24 or more hours and is therefore considered costly. In order to overcome the long and costly debinding times associated with thermal debinding, other methods have been adopted for use in conjunction with the process such that MIM components are debound in multi stages. Thermal debinding is now widely used as a second stage of debinding to remove organic binder material prior to sintering.

Solvent Debinding

Thermal debinding is now often used as a second stage of debinding in systems where the first stage is solvent debinding. Solvent debinding involves immersing the MIM compact in liquid that dissolves the binder material. The binder composition includes a constituent that can be dissolved in the liquid at low temperature. Acetone or heptane is sometimes used as the solvent although water-soluble binder compositions are preferred since it is easier to handle aqueous solvents than organic solvents. The times for debinding during solvent extraction are considered to be intermediate, which is shorter than thermal debinding times but take longer than catalytic binder removal. The investment and operating costs are lower so that total processing costs are competitive [20].

Catalytic Debinding

Catalytic debinding of the binder is a process where most of the binder is attacked by a catalytic acid vapour [24] such as highly concentrated nitric or oxalic acid. Binder removal is done using a vapour catalyst at relatively low temperatures of approximately 120°C, which is below the softening temperature of the binder and has the advantage of reducing thermal defects. The acid acts as a catalyst in the decomposition of the polymer binder. Reaction products are burnt in a natural gas flame at temperatures above 600°C. The binder material is that is mainly used with this process is known as polyoxymethylene (POM) and it belongs to a grade of polymers known as polyacetals. These MIM feedstocks based on this binder are also easy to mould and possess excellent shape retention but there are hazards associated with acid catalysts and additional material costs.

Taguchi Method

Taguchi method is a capable of establishing an optimal design configuration, even when significant interactions exist between and among the controlled variables. The Taguchi method can also be applied to designing factorial experiments is an experiment whose design consist of two or more factors, each with discrete possible values or levels, and whose experimental units take on all possible combinations of these levels across all such factors [27]. Factorial experiments can be used when there are more than two levels of each factor. Taguchi parameter are used for optimizing the parameters and to obtain the minimum warpage. Huang and Tai [28] determined the most effective factors regarding warpage in injection molding of a thin shell part such as packing pressure, mold temperature, melt temperature and packing time injection parameters. Taguchi method is also strong tool for the design of high quality systems. To optimize designs for quality, performance and cost, Taguchi method presents a systematic approach that is easy to use and effective. Taguchi extensively uses experimental design primarily as a tool to design products more robust (which mean less sensitive) to noise factors.

Robust design is an engineering methodology for optimizing the product and process conditions which are minimally sensitive to the various causes of variation, and which produce high-quality products with low development and manufacturing costs [29]. Hence, Taguchi developed manufacturing system that were robust or insensitive to daily or seasonal variations of environment, machine wear, and other external factors. Taguchi's parameter design is an important tool for robust design. His tolerance design can also be classified as a robust design. Robust optimization methods account for the effects of process variation by simultaneously optimizing the objective function and minimizing its sensitivity to parameter variation. Figure 5 demonstrate the step of taguchi parameter design.

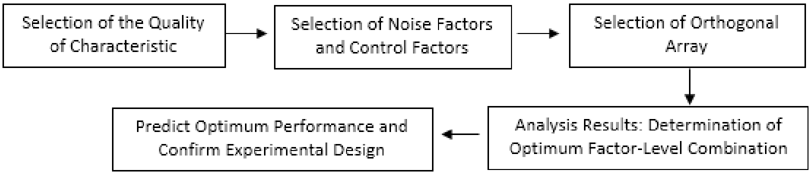

Figure 5: Steps of Taguchi parameter design [33]

Taguchi Approach

Two important tools are also used in parameter design are signal-to-noise (S/N) ratios and orthogonal arrays. Orthogonal arrays allow researcher or designer to study many type of design parameters and can be used to estimate the effects of each factor independent of the other factors. Orthogonal Arrays (OA) are a special set of Latin squares, constructed by Taguchi to lay out the product design experiments. By using this table, an orthogonal array of standard procedure can be used for a number of experimental situations. Consider a common 2-level factors OA as shown in Table 1 below:

This array is designated by the symbol L_8, involving seven 2-level factors, zeroes and ones. The array has a size of 8 rows and 7 columns. The number (zeroes/ones) in the row indicate the factor levels (be it fluid viscosity, chemical compositions, voltage levels, etc.) and each row represents a trial condition. The vertical columns represents the experimental factors to be studied. Each of assigned columns contain four levels of zeroes (0), and four levels of ones (1), these conditions can combine in four possible ways, such as (0,0), (0,1), (1,0), (1,1), with 27 possible combinations of level. The columns are said to be orthogonal or balanced, since the combination of the levels occurred the same number of times, when two or more columns, of an array are formed. Thus, all seven columns of an L array, are orthogonal to each other [27].

Orthogonal Array L_8 (2^7)

Table 1: An orthogonal array of L_8 [33]

Trial No.	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	0	0	0	0	0	0	0
2	0	0	0	1	1	1	1
3	0	1	1	0	0	1	1
4	0	1	1	1	1	0	0
5	1	0	1	0	1	0	1
6	1	0	1	1	0	1	0
7	1	1	0	0	1	1	0
8	1	1	0	1	0	0	1

The signal-to-noise ratio is a quality indicator by which the experimenters and designers can evaluate the effect of changing a particular design parameter on the performance of product. There are 3 Signal-to-Noise ratios of common interest for optimization of Static Problems:

Smaller-the-Better

$n = -10\ \mathrm{Log}_{10}$ [mean of sum of squares of measured data]

This is usually the chosen S/N ratio for all undesirable characteristics like “defects” etc. for which the ideal value is zero. Also, when an ideal value is finite and its maximum or minimum value is defined then the difference

between measured data and ideal value is expected to be as small as possible. The generic form of S/N ration then becomes,
$n = -10 \, \text{Log}_{10}$ [mean of sum squares of {measured – ideal}]

Larger-the-Better
$n = -10 \, \text{Log}_{10}$ [mean of sum squares of reciprocal of measured data]
This case has been converted to Smaller-the-Better by taking the reciprocals of measured data and then taking the S/N ratio as in the smaller-the-better case.

Nominal-the-Best
$n = 10 \, \text{Log}_{10}$ (square of mean / variance)
This case arises when a specified value is most desired, meaning neither a smaller nor a larger value is desirable. [30]-[34].

The Taguchi Approach is popular not only in the design stage, but also applicable during manufacturing stage for improving processes which reduce the variation. Having a certain degree of refinement without being too mathematical, the methodology should be readily understandable to engineers.

Process Parameters in Metal Injection Moulding

In the MIM process the most critical step is the moulding phase and more often many problems arise during this stage and lead to various kinds of defects such as voids, sinks, distortion and cracks. These defects can be avoided by proper selection of process parameters such as held pressure, temperature of the mould and melt. High injection pressure is needed to force the melted powder mixture of high viscosity into the mould within a short period of time. On the other hand, higher pressure would lead to residual stresses which result distortion or cracking. Even though the increase of melt temperature can reduce viscosity and make mould filling easier, too low viscosity may result in problems with mould filling such as jetting, splashing or air entrapment. Increasing the mould temperature reduces heat losses and the maximum temperature difference at the end of the mould filling stage. This improves the quality of the part, but increases cooling time consequently the production time. Hence it can realized that the relationship between process parameter for MIM process is very complex and most of these parameters are inter-connected. Few examples of parameter optimization of few researchers are explained.

Parameter optimization of Natural Hydroxyapatite/SS316L via injection moulding process is an important process in order to produce the higher strength and great quality green part. The injection parameters are nominated based on the most significant parameter via screening trial by using classical analysis of variance (ANOVA). From ANOVA results the whole control factors are orthogonal, hence interactions effects are neglected [5] and preferred injection parameters are injection temperature, mold temperature, pressure and speed [35]. The optimization process are conducted by using L_9

(3^4) Orthogonal Array (OA) which is proposed of three level designs of experiment with 4 selected parameter in 9 trial. Table 3 demonstrates the three level of injection parameter design.

Table 2: Three level of injection parameter design [35]

Indicator	**Parameter**	**0**	**1**	**2**
A	Injection Temperature (°C)	165	170	175
B	Mold Temperature (°C)	40	45	50
C	Injection Pressure (%)	55	60	65
D	Speed (%)	55	60	65

Table 3: Taguchi's L_9 (3^4) orthogonal arrays demonstrate the value of experimental trials (strength) and quality characteristic [35]

		Factors			**S/N Ratio Larger is better**	
Trial	A	B	C	D	Average	S/N ratios
1	0	0	0	0	4.996	13.973
2	0	1	1	1	4.893	13.792
3	0	2	2	2	5.045	14.058
4	1	0	1	2	5.465	14.752
5	1	1	2	0	5.374	14.605
6	1	2	0	1	5.983	15.538
7	2	0	2	1	5.372	14.603
8	2	1	0	2	5.155	14.245
9	2	2	1	0	5.146	14.229
					Σ	**129.75**
					$\underline{T}$	**14.422**

As mentioned before, Taguchi method optimizes the performance characteristics over the setting of design parameters. A model based on L_9 orthogonal array of Taguchi method was created by employing the S/N ratio optimization process [17]. Table 3 exhibit L_9 (3^4) orthogonal arrays and demonstrates the value of experimental trials (strength) and quality characteristic. In simple explanation based from table 4, $A_{1,}$ Injection Temperature 170°C, B_2, Mold Temperature 150°C, C_0, Pressure 55%, and $D_{1,}$ Speed 60% is the optimum configuration.

Besides that this researcher [5] chose, L_{18} orthogonal array (OA) as the experimental design for this study. The OA is sufficient enough since the system has 1 control factor with 2 level, and another 3 control factors with 3 levels (Table 4), and because all the control factors are orthogonal, so interactions effects are not studied. The output response is the green density, because not only it reflects the green strength of the part, but also the best green density could lead to the best sintered density of the final part. The P-diagram and the ideal function are shown in Figure 6.

Table 4: Control Parameters for injection moulding-step [5]

Factors (unit)		**Level 1**	**Level 2**	**Level 3**
Injection rate (cm/s)	A	10	20	-
Powder Loading (% vol)	B	59	61	63
Injection Temperature (°C)	C	140	150	160
Holding Pressure (bar)	D	1700	1800	1900

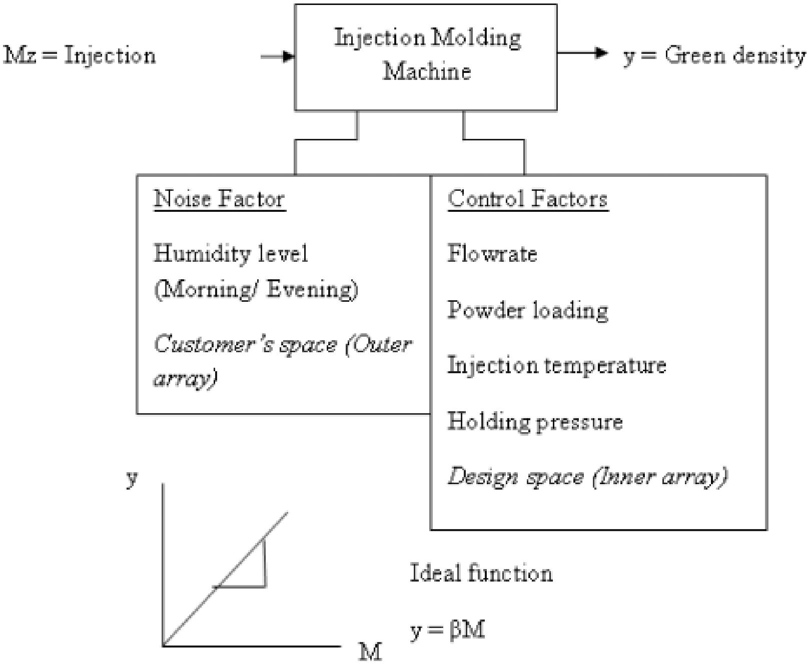

Figure 6: P-Diagram and Ideal Function [5]

Based from the results obtained, factor D (holding pressure) contributed the most from each factor. This is by the fact that the holding pressure compresses the melt and fills the cavity, and has an effect until the gate solidifies. If the holding pressure is not enough sufficiently, slumps can occur on the surface [36]. Thus, the highest holding pressure could lead to the highest density of the green part. The second largest contribution is factor B (powder loading). The higher the powder loading, the bonding between powder particles increased within feedstock and make the green part to pack more densely due to the less void age created [37]. Thus, the density of the green parts increases. This finding is quite similar with work [38], which also got powder loading as the second most influencing factor after optimization process done on stainless steel based feedstock. Injection temperature (factor C) is still important since the temperature of materials has an effect on the viscosity of the melt, and consequently on the ability of the melt to fill up the cavity [36]. The parts will be unfilled if the viscosity of the melt is too high. Meanwhile for factor A (injection rate), the significance is too low and the effect can be neglected. This is because the injection rate only controls the time and amount of melt to fill up uniformly into the die cavity.

Table 5: The optimal condition for injection-moulding step (5)

Factor		**Parameter**
Injection rate	A2	20ccm/s
Powder loading	B3	63% vol.
Injection Temperature	C1	140°C
Holding Pressure	D1	1700 bar

Table 6: Injection Parameters for 3 Level Taguchi Design [39]

Level	**Injection Pressure (bar) A**	**Injection Temperature (°C) B**	**Mold Temperature (°C) C**	**Injection Time (s) D**	**Holding Time (s) E**
0	10	150	55	5	5
1	11	155	60	6	6
2	12	160	65	7	7

Optimization of injection parameter to achieve highest green strength will be investigated using design of experiment (DOE) at which injection moulding parameter are optimized using L_{27} (3^{13}) Taguchi orthogonal array [39]. The injection parameters that will be used are injection pressure, injection temperature, mold temperature, injection time and holding time, refer Table 7. Three–level designs of experiment with 5 parameters mentioned above are considered in the injection moulding. With total 24 DOF for both single and interactions parameter, L_{27}'s Taguchi orthogonal array is the most suitable for design of experiment. L_{27} means 27 runs will be conducted with 5 replications at each run in order to guarantee statistical accuracy.

In other words, based from 3 Level Taguchi Design optimization for L_{27} (3^{13}) results in injection pressure 11 bar, injection temperature 155°C, mold temperature 65°C, injection time 5s and holding time 5s.

Conclusions

Metal Injection Moulding (MIM) is a newly developed technology to form metals and alloys into desired shape. Optimization of process parameters of MIM has been thoroughly discussed in the paper. Few parameters that are considered during optimization process such as injection pressure, injection temperature, mold temperature, injection time, holding time, holding pressure, injection rate and powder loading has been discussed. Besides that, there are still few factors for example cooling time, screw feeding speed, and etc. need to be studied further. Taguchi method is proven to be suitable for optimization process parameters of MIM.

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