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Green density optimization of stainless steel powder via metal injection molding by Taguchi method

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Abstract. Metal injection moulding (MIM) has gains much attention due to its ability in producing large amount of small part with complex geometry and intricate shape. In order to obtain better shape retention, optimum density of green part is required. This paper deals with the application of Taguchi method in optimising the green density of moulded components base on parameters setting in plastic injection moulding machine. For this purposes only 7 process parameters were considered here are injection pressure, injection temperature, cooling time, injection speed, injection time, packing time and mould temperature. An orthogonal array of L27 experimental base design was conducted. Base on the experimental results, cooling time plays significant contribution to density followed by injection pressure, time, speed, mould temperature, packing time and injection temperature. Confirmation test was done base on optimization level for each factors and shows good results in green density of the injected moulded samples.

1 Introduction

Metal injection moulding is a manufacturing process with a capability of producing complex geometry and intricate parts from mixing of metals, ceramic or cermet powder with combination of polymers, wax and surfactant [1] with a few shot as compare to other fabrication process [2]–[4]. Due to its versatility, near net shape and less materials waste, it's becomes attraction to most researchers in exploiting it into new dimensions whether in terms of its binder, powder characteristic, injection moulding conditions, debinding and sintering [5].

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The traditional approach to experimental work is to vary one factor at a time, holding all other factors fixed. This method does not produce satisfactory results in a wide range of experimental settings. In order to obtain high efficiency in the planning and analysis of experimental data, various robust designs of DOE had been implemented in manufacturing area. Design of experimental (DOE) has long been applied by many researchers in terms of mixing the metal or ceramics powder with binder [6] to the sintering stage [7], [8]. Effect of powders and binders on injection moulding parameters has been analysed by Ahn et al. [3] where they indicate that the binder plays critical role in minimizing the injection pressure, clamping, temperature, cooling time and velocity. Their finding states very minimized influential by the types of powder. Application of DOE in MIM is continued by Yakimov and Coyle [9] where they use full factorial design in determining the factors that affecting the thermal debinding processes. Jorge et al. [10] using full factorial design in optimizing solvent and thermal debinding. Factorial design was also used by [11], [12] in optimizing the thermal and sintering parameters of the injected parts.

Dr. Geneichi Taguchi is founded Taguchi's robust design which functioning to reduce economically the variations of product function and optimizing the parameters involved in laboratory or manufacturing environment to meet the requirement of target quality. Taguchi parameter design applied to investigate and optimize the process involved in MIM has been implemented by Ji et al.[7] using Taguchi's method in optimizing the sintering parameters with L9 orthogonal arrays with four factors and 3-level design in their experimental data [13] of sintering.

Lee et al. [14] implementing the Taguchi's method by using L9 orthogonal arrays with 4 factors and 3 level design for studying the effect of gas the effect of processing variables on gas penetration during MIM. Ibrahim [15], [16] use Taguchi with Grey relation in optimizing the microMIM process. Chua et al.[17] optimizing the injection density and solvent process of parameters using L25 orthogonal array and found that mould temperature and powder loading are the most influential parameters for green part surface quality and injected part strength and density, respectively.

In this paper, 316 L stainless steel feedstock which contains of restaurant waste lipids (RWL) and polypropylene (PP) as binder with ratio of 40/60 respectively was moulded via injection moulding process and the parameters setting was optimized using Taguchi method for obtaining the optimum density of the green compacts. Orthogonal array of L27 with 7 factors and 3 levels factor were used in determining the optimized parameter for injected optimum green density of the moulded parts.

2 Experimental work

The 316L water atomized stainless steel powder used in this study has mean particle size of 6μm. Particles size was measured via particle analyser Fritsch analysette 22 compact. The stainless steel powder has the tap density of 8.0471 g/cm^3 and was supplied by Epson Atmix Japan. Figure 1 shows the powder particles size distribution and powder morphology of the 316L water atomized stainless steel. Physical properties and the chemical composition of the powder is shown in Table 1.

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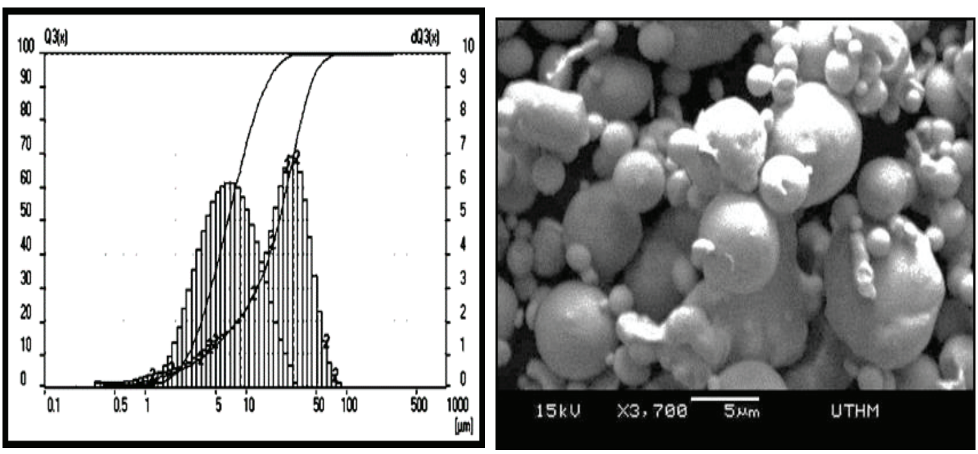
Table 1: Physical properties and chemical composition of 316L stainless steel metal powder

Powder size and density

Powder	SS316L	Size	D10	D50	D90	Density
Epson Atmix Corp						
		6.0µm	2.87µm	5.96µm	10.65µm	8.0471 g/cm^3

Powder chemical composition (% wt)

Ci	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.027	0.84	0.19	0.016	0.012	12.20	16.40	2.10	0.03



(a) (b)

Fig. 1: (a) Particle size distribution and (b) SEM image of water atomised 316L stainless steel powder (PF-10F)

Table 2: Binder composition and thermal properties of binder components

Binder	Fraction in binder	Density (gcm^{-3})	Melting Temperature (°C)	Degradation Range (°C)
Polypropylene (PP)	0.6 (8.3g)	0.90	165	350~470
RWL derivatives	0.4 (5.6g)	0.90	50	270~360

For making the feedstock, 316L stainless steel powder of 60% powder volume which is equivalent to 186.1g of powder weight along with binder fraction shown in Table. 2 were used. 60% powder loading was chosen because it is approximately 5% below the critical powder volume concentration [18] which in this case Critical Powder Volume Concentration (CPVC) of the selected stainless steel powder was found to be 64.8% [15]. The compound was blended using Brabender Plastograph EC mixer at temperature of 175°C with 30rpm for 90min. The compound was left cool at the ambient atmosphere and temperature before being crushed into smaller pallets for ease of feeding inside the injection moulding machine.

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After crushing was done, the feedstock was fed into horizontal injection moulding machine modelled Nissei NP7 Real Mini to obtain the green sample as shown in Figure 2. The density optimization was conducted by implementation of Taguchi orthogonal array (Statistical Method). The injection process was run in 3 level design of experiment with 7 parameters and 3 trial of experiment. The parameters and its level is shown in Table 3. The results were analyzed by using Signal to Noise Ratio (S/N ratio) terms

In detailed explanation, S/N ratios is help in prediction the optimum result besides improve the quality via variability reduction and improved the measurement based on repetition [19]. Thus, paper are discussed the optimization of optimum green density with 60% Powder loading. The analysis is based on Signal to noise ratio or well known as S/N ratio. This analysis are based on Nominal is better characteristic base on Equation 1.

According to Table 3, injection pressure, 64.4 MPa has been used as the minimum pressure, which could force the feedstock to flow smoothly inside the cavities and avoiding from short mould. Mould temperature being implemented to aid the flow of the feedstock and avoiding the thermal shock of the green parts and also improve the ejection condition of the part. When the part was allowed to cool rapidly the part becomes so brittle, which slight bending from the ejector, could break the green part. Mould temperature was made slightly above the room temperature (40°C) for allowing the backbone becomes slightly flexible and could be ejected without any defects.

Here cool time was set for allowable shrinkage, which in turn reduce the friction between the green part and the wall cavity. Injection speed was selected to promote shear rate for the feedstock to flow inside barrel. Too high in shear rate could promotes voids and binder separation. Injection time also being considered as the factor here since it could avoid jetting, cracks, flashes, and short mould associate with improper injection speed and filling time.

Packing time plays significant effect of sink mark on the surface of the green part. As mentioned before, feedstock, which has filled up the mould cavities, could experience shrinkage due to cooling conditions. With the help of proper packing time shrinkage, flashes and voids can be prevented.

Table 3: 7 factors and 3 level for each factors involved in otimising process of injecting the green parts

Factors	Level 1	Level 2	Level 3
Injection Temperature, A (°C)	180	190	200
Injection Pressure, B (MPa)	64.4	80.5	96.6
Mould Temperature, C (°C)	40	60	80
Cool time, D (s)	5	10	15
Injection speed, E (RPM)	70	105	140
Injection time, F (s)	1	3	5
Packing time, G (s)	1	2	3

(a)

(b)

Fig. 2. (a) Injection machine used (b) injection moulded compacts

$$\frac{S}{N} = 10\log_{10}\sum\frac{\bar{y}^2}{\sigma_{N-1}^2} \tag{1}$$

Orthogonal array of L27 structure is shown in Table 4 where replication of three parts of the same tested parameters being employed. Density of the three replication injected moulded parts were taken by means of Archimedes principle and recorded for calculating Mean and S/N ratio as shown in Table 5. S/N ratio was calculated base on Nominal is better by using Equation 1. From Table 5, S/N ratio and Mean were calculated from the average density of the replication for each level structure of the L27 and the variability of the S/N ratio and Mean are shown in Table 6 and 7.

Table 4: Orthogonal array of L27 structure

A	B	C	D	E	F	G
1	1	1	1	1	1	1
1	1	1	1	2	2	2
1	1	1	1	3	3	3
1	2	2	2	1	1	1
1	2	2	2	2	2	2
1	2	2	2	3	3	3
1	3	3	3	1	1	1
1	3	3	3	2	2	2
1	3	3	3	3	3	3
2	1	2	3	1	2	3
2	1	2	3	2	3	1
2	1	2	3	3	1	2
2	2	3	1	1	2	3
2	2	3	1	2	3	1
2	2	3	1	3	1	2
2	3	1	2	1	2	3
2	3	1	2	2	3	1
2	3	1	2	3	1	2
3	1	3	2	1	3	2
3	1	3	2	2	1	3
3	1	3	2	3	2	1
3	2	1	3	1	3	2
3	2	1	3	2	1	3
3	2	1	3	3	2	1
3	3	2	1	1	3	2
3	3	2	1	2	1	3
3	3	2	1	3	2	1

Table 5: Mean and S/N ratio calculated from density replication of L27 structure experiment

Density Replication (g/cm^3)			Mean ($\bar{y}$)	$(\bar{y})^2$	$\frac{1}{(\bar{y}^2)}$	S/N Ratio
R1	R2	R3				
4.9331	5.0095	5.0366	4.993	24.93	0.0401	13.967
5.0367	4.9458	5.0373	5.007	25.07	0.0399	13.991
5.0782	5.0631	5.0719	5.071	25.72	0.0389	14.102
5.104	5.0834	5.1095	5.099	26.00	0.0385	14.150
5.0716	5.0833	5.0847	5.080	25.81	0.0388	14.117
5.1078	5.0793	5.0935	5.094	25.94	0.0385	14.140
5.0731	5.0999	5.0768	5.083	25.84	0.0387	14.123
5.1069	5.0772	5.1167	5.100	26.01	0.0384	14.152
5.0842	5.0976	5.079	5.087	25.88	0.0386	14.129
5.04	5.1017	5.1016	5.081	25.82	0.0387	14.119
5.0693	5.0458	5.0842	5.066	25.67	0.0390	14.094
5.0848	5.1002	5.06	5.082	25.82	0.0387	14.120
5.082	5.0984	5.0954	5.092	25.93	0.0386	14.138
5.0949	5.1085	5.1106	5.105	26.06	0.0384	14.159
5.0964	5.0787	5.0877	5.088	25.88	0.0386	14.130
5.0831	5.0658	5.0422	5.064	25.64	0.0390	14.089
5.0976	5.0835	5.0866	5.089	25.90	0.0386	14.133
5.1067	5.0906	5.1106	5.103	26.04	0.0384	14.156
5.0997	5.106	5.077	5.094	25.95	0.0385	14.142
5.083	5.0776	5.0562	5.072	25.73	0.0389	14.104
5.073	5.1014	5.1049	5.093	25.94	0.0386	14.140
5.1086	5.0885	5.1261	5.108	26.09	0.0383	14.165
5.0938	5.1098	5.1196	5.108	26.09	0.0383	14.165
5.0814	5.0942	5.1035	5.093	25.94	0.0386	14.140
5.0786	5.1126	5.1181	5.103	26.04	0.0384	14.157
5.0775	5.0723	5.0879	5.079	25.80	0.0388	14.116
5.0024	5.074	5.0106	5.029	25.29	0.0395	14.030

3 Results and discussion

In this section, analysis of optimised parameters of the injection moulding parameters with its level are analysed. Variability analysis table of S/N ratio was calculated as shown in Table 6. From Table 6 average S/N ratio was calculated for each level factor and the difference between the levels of highest S/N ratio for the same factor being substituted with the lowest one. The difference was shown by the Delta value. The Delta values were then being plotted as shown in Figure 3 for clear viewing of significant factors that contributes to the green density of the moulded parts.

It was found that factor D or cooling time plays significant effect as compare to other factors (6.274) since mould temperature would assist the melt feedstock flow inside the mould cavity. The second most influencing factor was come from injection pressure (B), which has the Delta value of 5.95. Injection time (F), injection speed (E), mould temperature (C), packing time (G) and injection temperature (A) become the third, fourth, fifth, sixth and seventh important factor respectively according to delta value.

Table 6: Response table of S/N ratio variability analysis

Level	A	B	C	D	E	F	G
1	49.791	47.299	49.716	45.779	48.287	50.834	49.662
2	51.523	53.251	49.409	52.053	51.570	48.373	49.772
3	50.049	50.813	52.238	49.607	51.506	52.155	51.929
Delta Δ	1.732	5.951	2.522	6.274	3.283	3.781	2.267

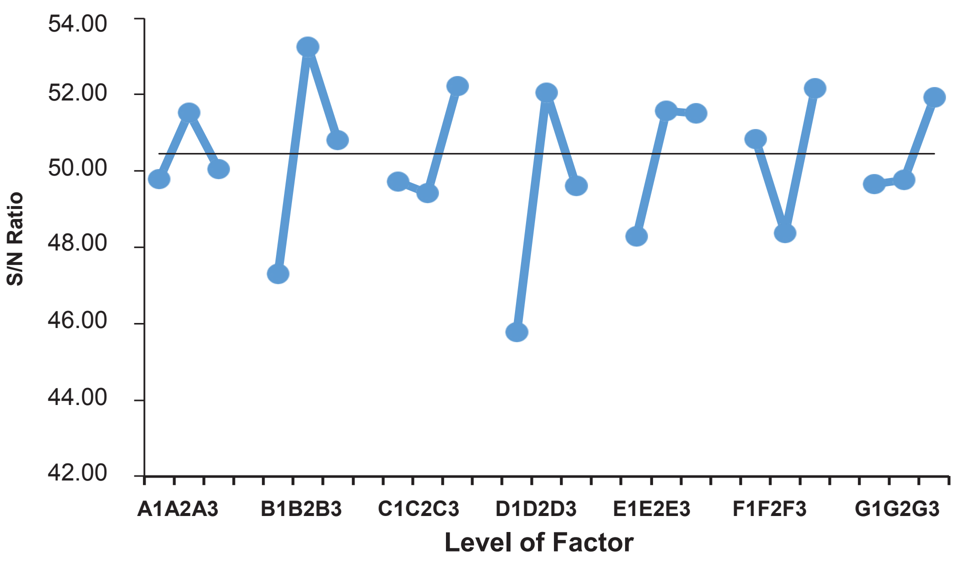

Fig. 3. S/N ratios variations of green part density at various levels of injection parameters

Response table for Mean variability analysis (Table 7) also being tabulated since this table can gives the results of any variability of green part density in response to the factors level. The delta analysis was then being plotted as shown in Figure 4.

From Figure 3 and 4, agreement of level factors of injection pressure, mould temperature and injection time were found for analysis of Mean and S/N ratio which indicates this level of parameters would give optimum and low fluctuation density of the green compact. For injection temperature, S/N ratio indicates that level 2 has the significant effect in obtaining optimum density and this result was contradicts to the Mean analysis, which indicates level 3 has significant factors in reducing the fluctuations of density obtained. Disagreement also was found for factor level for D, E and G which representing the factor of cooling time, injection speed and packing time respectively.

Although the optimum level between the four levels was not the same, if we compare the gradients of A factors for Mean between level 2 and 3 only slight change affect the optimum density variability as compare to S/N ratio gradients. Shifted the level from 1 to 2 and from 2 to 3 would results in greatest change in optimum green density. Therefore since shifted the level from 2 to 3 for factor A would results in greatest change S/N ratio as compare to Mean, therefore level 2 of factor A was selected since he Mean variability of the green density would only slightly change the density. The same goes to the factor D, E and G where level 2, 3 and 3 are chosen respectively.

Table 7: Response table of Mean variability analysis

Level	A	B	C	D	E	F	G
1	5.068	5.062	5.071	5.063	5.080	5.078	5.072
2	5.085	5.096	5.079	5.088	5.078	5.071	5.085
3	5.087	5.082	5.090	5.090	5.082	5.091	5.083
Delta Δ	0.018	0.034	0.020	0.027	0.004	0.020	0.013

Base on the analysis of factors and levels the predicted optimisation S/N ratio value is calculated using equation 2 below.

$$\frac{\boldsymbol{S}}{\boldsymbol{N}}\,\boldsymbol{ratio} = \overline{\boldsymbol{T}} + (\overline{\boldsymbol{A}}_{\boldsymbol{2}} - \overline{\boldsymbol{T}}) + (\overline{\boldsymbol{B}}_{\boldsymbol{2}} - \overline{\boldsymbol{T}}) + (\overline{\boldsymbol{C}}_{\boldsymbol{3}} - \overline{\boldsymbol{T}}) + (\overline{\boldsymbol{D}}_{\boldsymbol{2}} - \overline{\boldsymbol{T}}) + (\overline{\boldsymbol{E}}_{\boldsymbol{2}} - \overline{\boldsymbol{T}}) + (\overline{\boldsymbol{F}}_{\boldsymbol{3}} - \overline{\boldsymbol{T}}) + (\overline{\boldsymbol{G}}_{\boldsymbol{3}} - \overline{\boldsymbol{T}}) \quad (1)$$

Where T is the average S/N ratio, $\bar{A}_2$ is the injection temperature level 2, $\overline{\boldsymbol{B}}_2$ is the injection pressure level 2, $\overline{\boldsymbol{C}}_{\boldsymbol{3}}$ is the mould temperature level 3, $\overline{\boldsymbol{D}}_2$ is cool time level 2, $\overline{\boldsymbol{E}}_2$ is injection speed level 2, $\overline{\boldsymbol{F}}_{\boldsymbol{3}}$ is injection time level 3 and $\overline{\boldsymbol{G}}_{\boldsymbol{3}}$ is packing time level 3.

Therefore, predicted S/N ratio is;

$$\frac{S}{N}ratio = 50.45 + (51.52 - 50.45) + (53.25 - 50.45) + (52.24 - 50.45) + (52.05 - 50.45) + (51.57 - 50.45) + (52.16 - 50.45) + (51.93 - 50.45)$$

$$\frac{S}{N}ratio = 60.92$$

Confirmation analysis was done base on the selected levels of factors with 10 replications of injected moulded sample. The results of S/N ratio density obtained for 10 replications are 60.65, which is 0.4% difference and below 10% as compare to the predicted S/N ratio.

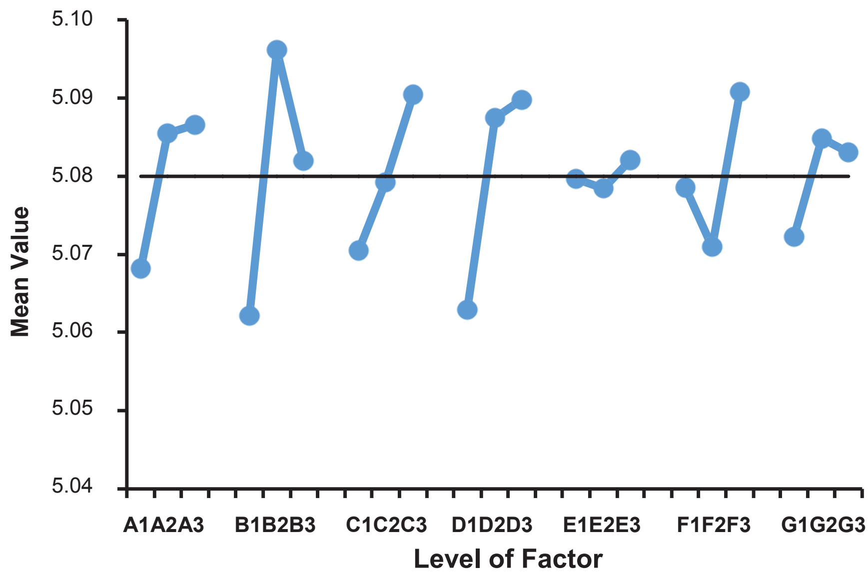

Fig. 4. Mean variations of green part density at various levels of injection parameters

Table 8: Mean and S/N ratio of confirmation test base on the optimized parameters with 10 replications sample

$\bar{y}$	$\bar{y}^2$	(δ_{N-1})	$(\delta_{N-1})^2$	S/N ratio
5.025	25.25	0.005	0.000022	60.650

4 Conclusion

From the results and discussion, Taguchi L27 was successfully being implemented in determining the optimum green density of moulded stainless steel powder. Base on the experimental results, cooling time plays significant contribution to density followed by injection pressure, time, speed, mould temperature, packing time and injection temperature. Results of confirmation test also indicate of 0.4% difference as compare to the predicted value of the S/N ratio base on the selected parameters.

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