INJECTION MOLDING PARAMETER OPTIMIZATION USING THE TAGUCHI METHOD FOR HIGHEST GREEN STRENGTH FOR BIMODAL POWDER MIXTURE WITH SS316L IN PEG AND PMMA

K. R. Jamaludin[a], N. Muhamad[b], M. N. Ab. Rahman[b], S. Y. M. Amin[b], Murtadhahadi[b], M. H. Ismail[c]

Department of Mechanical Engineering
College of Science and Technology
University of Technology Malaysia
City Campus Kuala Lumpur
54100 Kuala Lumpur. Malaysia

Precision Process Research Group
Dept. of Mechanical and Materials Engineering
Faculty of Engineering
National University of Malaysia
43600 Bangi.
Selangor Darul Ehsan. Malaysia

Centre for Advanced Materials Research (CAMAR),
Faculty of Mechanical Engineering
Mara University of Technology
40450 Shah Alam.
Selangor Darul Ehsan. Malaysia

ABSTRACT

Injection molding parameters for the highest green strength of the metal powder mixture has been optimized using L_{27} (3^{13}) Taguchi orthogonal array. Parameters optimized are the injection pressure, injection temperature, powder loading, mold temperature, holding pressure and injection rate. The metal powder mixture used is SS316L powder in bimodal particle-sized distribution, and a composite binder consisting of PEG and PMMA. Stearic acid is used as a surfactant to improve its flowablity. Interactions of the injection pressure, injection temperature and powder loading were studied. Analysis of variance (ANOVA) for the best signal to noise ratio (S/N) presents the contribution of the parameters to the quality characteristic (green strength). Results show that the mold temperature contributes about 48.28 % (highest) followed by the powder loading (8.33 %) and, injection rate (6.00 %) while, other parameters were pooled because the confident level was lower than 90 %. Nevertheless, the analysis of variance does not show any contribution from the interactions.

INTRODUCTION

Metal injection molding is increasingly being accepted as a suitable and cost effective method for the high volume production of small, complex-shaped and high-performance parts. The technique involves the mixing of metal powder with a binder, the injection of resulting mixture into the mold, the removal of the binder and then sintering to consolidate the part to its final density [1]. Optimization of each of these process procedures and appropriate selection of the starting materials, the powder and binder, are critically important to the overall success of the process.

The determination and optimization of the process parameters have motivated numerous research works, as it needs deep knowledge on different processes and accurate modeling techniques for each stage. The traditional approach to experimental work is to vary one factor at a time, holding all other factors as fixed. This method does not produce satisfactory results in a wide range of experimental settings. Researchers [2-5] have been using classical Design of Experiment (DOE) Technique to study the effects of injection parameters on the green part quality characteristics such as green density, green strength and green defects. In order to obtain high efficiency in the planning and analysis of experimental data, the Taguchi parameter design is applied to investigate and optimize injection parameters to produce stronger green parts. This is because, from another experiments, in another area of study such as plastic molding, metal removal processes, the Taguchi method is recognized as a systematic application of design and analysis of experiments for the purpose of designing and improving product quality. [6] In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development [7] so that high quality products can be produced in a short period of time and at low cost.

The objective of the paper is to show how DOE using a Taguchi method is used to optimize the injection parameter and analysis of variance can be used to rank the contributing factors which influence the quality characteristics, in this case, green strength. The interactions of the major parameters such as injection temperature and injection pressure are discussed in this paper and also the powder loading which have its influence to the green strength.

METHODOLOGY

Sample preparation

A 316L stainless steel gas atomized powder with pynometer density of 7.93 g/cm^3 is mixed with 73 % PEG weight of polyethylene glycol (PEG) and 25 % weight of polymethyl methacrylate. (PMMA) About 2 % weight of stearic acid (SA) is used as a surfactant.

A powder metal particle-sized distributions are used in the bimodal distribution consisting of 70 % of coarse powder in weight fraction. The distribution of the particle size is as shown in Table 1 and is measured by using Mastersizer, Malvern Instrument.

TABLE 1 Particle sized distributions in μm

	D_{10}	D_{50}	D_{90}	S_W
Coarse	9.563	19.606	40.058	4.159
Fine	5.780	11.225	19.840	4.873

Prior to the injection, compositions are mixed in a sigma blade mixer for 95 minutes at a temperature of 70°C. Here the MPIF 50 standard tensile bars are injection molded using Battenfeld BA 250 CDC injection molding machine.

Design of experiment (DOE)

Taguchi's orthogonal arrays are used in the production and they consist of the ranges of MIM process parameters based on three-level design of experiments as shown in Table 2.

TABLE 2 Injection parameters for three levels of Taguchi Design

Level	Injection Pressure, A (bar)	Injection Temperature, B (°C)	Powder Loading, C (%volume)	Mold Temperature, D (°C)	Holding Pressure, E (bar)	Injection rate, F (ccm/s)
0	350	130	64	45	700	10
1	450	140	64.5	48	900	15
2	550	150	65	51	1100	20

Beside these parameters, interactions between three important parameters such as injection pressure, injection temperature and powder loading are involved in the investigation. As the overall degree of freedom (DOF) for the single parameters and interactions being 24, Taguchi orthogonal array L_{27} is the most suitable for the DOE. Refer to the linear graph for L_{27} orthogonal array which allocates the parameters in the array. (Table 3)

<u>RESULTS AND DISCUSSION</u>

Taguchi technique utilizes the signal noise ratio (S/N) approach to measure the quality characteristic deviating from the desired value. It is also uses the S/N ratio approach instead of the average value to convert the experimental results into a value for the evaluation characteristic in the optimum parameter analysis [8]. The S/N ratio is quoted in decibel as shown in equation (1).

$$S/N = -10\log\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{Y_{ij}^2}\right) \quad (1)$$

Where Y_{ij} is the amount of score for the green strength obtained from Table 3 and, N is the total number of shots for each trial.

TABLE 3 Taguchi’s L_{27} (3^{13}) orthogonal array demonstrates the quality characteristic and the experimental trials

Trial	Parameter													S/N RATIO: HIGHEST THE BETTER					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**						
	A	**B**	**A X B**	**e**	**C**	**A X C**	**e**	**B X C**	**D**	**E**	**e**	**E**	**F**	REP 1	REP 2	REP 3	REP 4	REP 5	S/N (dB)
1	0	0	0	0	0	0	0	0	0	0	0	0	0	11.43	10.52	10.64	10.02	10.34	20.4734
2	0	0	0	0	1	1	1	1	1	1	1	1	1	9.15	9.41	9.57	11.26	10.022	19.8297
3	0	0	0	0	2	2	2	2	2	2	2	2	2	8.92	7.02	8.05	8.49	7.54	17.9721
4	0	1	1	1	0	0	0	1	1	1	2	2	2	11.31	11.47	9.55	10.78	10.51	20.5511
5	0	1	1	1	1	1	1	2	2	2	0	0	0	9.03	8.93	11.34	9.07	10.14	19.6288
6	0	1	1	1	2	2	2	0	0	0	1	1	1	11.63	10.93	10.73	11.1	10.78	20.8438
7	0	2	2	2	0	0	0	2	2	2	1	1	1	8.49	10	9.53	9.34	9.25	19.3528
8	0	2	2	2	1	1	1	0	0	0	2	2	2	10.49	10.41	9.22	10.87	8.22	19.7190
9	0	2	2	2	2	2	2	1	1	1	0	0	0	9.8	9.66	7.71	9.06	8.39	18.9049
10	1	0	1	2	0	1	2	0	1	2	0	1	2	9.61	7.39	11.63	8.71	9.51	19.1527
11	1	0	1	2	1	2	0	1	2	0	1	2	0	9.71	9.6	10.25	11.21	10.41	20.1628
12	1	0	1	2	2	0	1	2	0	1	2	0	1	10.6	11.06	10.51	10.72	10.89	20.6286
13	1	1	2	0	0	1	2	1	2	0	2	0	1	10.92	10.19	8.7	9.94	9.45	19.7842
14	1	1	2	0	1	2	0	2	0	1	0	1	2	11.02	11.32	9.63	11.78	10.94	20.7178
15	1	1	2	0	2	0	1	0	1	2	1	2	0	9.54	9.85	10.12	9.84	9.98	19.8778
16	1	2	0	1	0	1	2	2	0	1	1	2	0	12.23	9.97	10.47	11.35	11.35	20.8204
17	1	2	0	1	1	2	0	0	1	2	2	0	1	10.84	10.64	11.71	9.14	8.31	19.9066
18	1	2	0	1	2	0	1	1	2	0	0	1	2	6.6	8.02	8.16	6.5	7.33	17.1759
19	2	0	2	1	0	2	1	0	2	1	0	2	1	10.64	8.24	8.18	9.44	8.81	19.0231
20	2	0	2	1	1	0	2	1	0	2	1	0	2	11.2	10.78	12	11.77	11.52	21.1605
21	2	0	2	1	2	1	0	2	1	0	2	1	0	7.86	8.92	8.46	8.41	8.39	18.4727
22	2	1	0	2	0	2	1	1	0	2	2	1	0	7.82	10.55	11.75	11.48	9.96	19.9785
23	2	1	0	2	1	0	2	2	1	0	0	2	1	8.67	10.34	11.3	10.52	10.72	20.1569
24	2	1	0	2	2	1	0	0	2	1	1	0	2	7.78	7.81	7.75	6.69	7.51	17.4647
25	2	2	1	0	0	2	1	2	1	0	1	0	2	8.28	9.96	9.31	10.24	9.84	19.5025
26	2	2	1	0	1	0	2	0	2	1	2	1	0	8.56	9.33	7.15	8.89	6.45	17.8842
27	2	2	1	0	2	1	0	1	0	2	0	2	1	9.48	10.55	12.85	10.96	11.91	20.8048
																		$\sum$	529.9503
																		$\bar{T}$	19.6278

The aim of the analysis of variance (ANOVA) is to evaluate the significance of the process parameters to the green strength (Table 4). Interaction of A × B, A × C and B × C are less significant because the F test indicates that the confident interval is less than 90 %. The same results show for factors A, B and E and thus, those factors are pooled and do not show any contributions to the green strength. Furthermore, the ANOVA shown in Table 4 demonstrate factors C, D and F as the confident interval is above 90 %. The contributions to the green strength are 8.33 %, 48.28 % and 6 % respectively. The error shown in Table 4 is from the empty column in the orthogonal array in Table 3.

Figure 1 shows the main effects plot for the S/N ratio. The main effect plot shown in Figure 1 indicates that the highest point is the optimum parameter for each factor. Initially, without considering any interactions Figure 1 indicates A1 B1 C1 D0 E2 and F1 as the optimum. This means that the injection pressure at 450 bar; injection temperature, 140^{o}C; powder loading, 64.5% volume; mold temperature, 45^{o}C; holding pressure, 1100 bar and; the injection rate of 15ccm/s are at the optimal level. The plot shown in Figure 1 is developed from the S/N ratio shown in Table 3. As an example, the mean for factor A at level 0 (A0) is calculated by taking the sum of the S/N ratio of factor A at level 0 which equals to 177.27 dB and the mean is 177.27/9= 19.70 dB.

TABLE 4 ANOVA Table after Pooling

	COLUMNS FACTOR	**FACTORS**	**DF**	**SUM OF SQUARES**	**VARIANCE**	**F**	**% CONTRIBUTION**
1	**A**	Injection Pressure	(2)	(0.8585)	Polled		
2	**B**	Injection Temperature	(2)	(1.3601)	Polled		
3	**A × B**	Interaction 1 × 2	(4)	(1.8732)	Polled		
5	**C**	Powder Loading	2	3.3975	1.6988	3.9	8.33
6	**A × C**	Interaction 1 × 5	(4)	(0.5206)	Polled		
8	**B × C**	Interaction 2 × 5	(4)	(1.957)	Polled		
9	**D**	Mold Temperature	2	15.5046	7.7523	17.79	48.28
12	**E**	Holding Pressure	(2)	(1.9)	Polled		
13	**F**	Injection rate	2	2.6891	1.3445	3.09	6.00
	error		20	8.7154	0.43577		37.38
	Total:		26	30.3066			100

However, since the paper attempts to evaluate the effects of the interactions between factor A, B and C, so Figure 2 shows the interaction plot for the mean ratios. The interaction plot indicates that A0B1 and B0C1 have the highest mean S/N ratio. Consequently, the optimum injection pressure after considering the interactions of factor A, B and C becomes A0 B1 C1 D0 E2 and F1. Note that the optimum parameter for factor A has changed from level 1 (450 bar) to level 0 (350 bar). Figure 2 shows that factor A, B and C have an interaction and that indicates that any changes to these factors simultaneously will affect the green strength. The optimal result demonstrates that the injection parameter for producing a strong green part is not necessarily achieved at the highest factor level. Only factor E (holding pressure) was found at the optimal factor level 2 (1100 bar) while factor A and D are optimal at the lowest factor level (level 0) at 350 bar and 45^{o}C respectively. The investigation also found that high injection temperature and high powder loading do not compulsorily produce a strong green part. It also indicates that the injection temperature at 140^{o}C and powder loading at 64.5% volume are optimal for a strong green part. Perhaps, a too high injection temperature, as well as injection pressure and, low powder loading may cause the binder to separate from the powder binder matrix which would result in a brittle green part. A brittle green part may also be a result from high powder loading as the green part contains less binder to hold the powder particles in the matrix.

Furthermore, since only factor C, D and F have a confident level greater than 90 %, thus only three factors were used to calculate the S/N ratio at the optimum performance. This is shown in Table 8 where the optimum performance is at 21.2644 dB compared to the current grand average performance of 19.6278 dB. The current grand average performance is calculated from the average of S/N ratio as shown in Table 3.

The confident interval shown in Table 8 is calculated with equation (2) [9]:

$$\mathrm{CI} = \pm\sqrt{\frac{F_{\alpha}(f_1, f_2)\times V_e}{n_e}} \tag{2}$$

Where, F_{α} (f_1, f_2) is the variance ratio for DOF of f_1 and f_2 at level of significance α. The confidence level is (1-α), f_1 is the DOF of mean (usually equal to 1) and f_2 is the DOF for the error. Variance for error terms is V_e and number of equivalent replication is given as ratio of number of trials (1+ DOF of all factors used in the estimate). The confident interval will indicate the maximum and minimum levels of the optimum performance and it is shown as the expected result as optimum performance in Table 8.

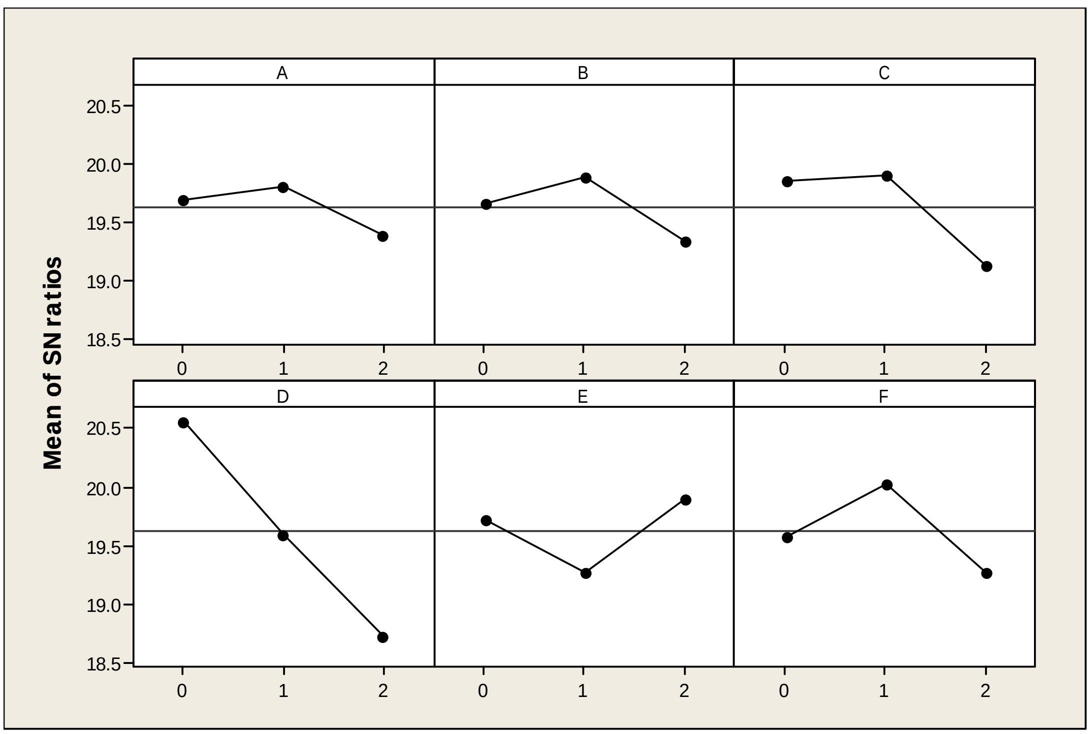

FIGURE 1 Main Effects Plot for S/N Ratio

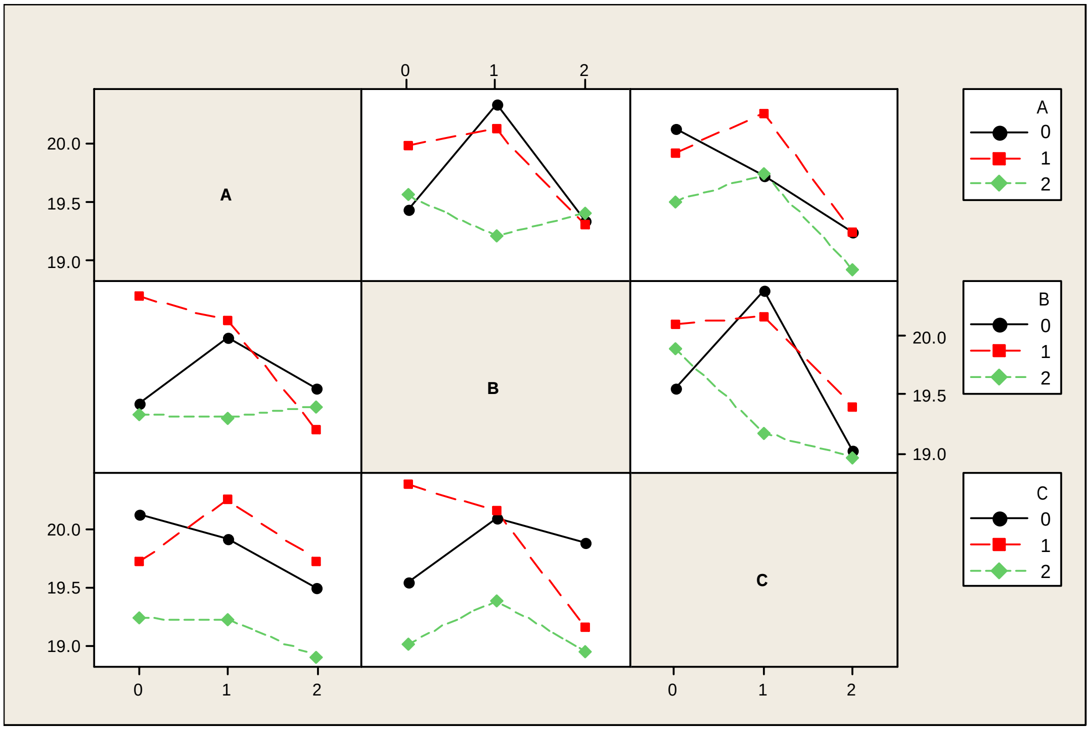

FIGURE 2 Interaction Plot for S/N Ratio

TABLE 8 Estimate of Performance as the Optimum Design after Pooling: Characteristics: Higher the Better

$C_1 D_0 F_1$	
Optimum performance calculation: $\overline{T} + (\overline{C_1} - \overline{T}) + (\overline{D_0} - \overline{T}) + (\overline{F_1} - \overline{T})$ 19.6278 + (19.91 - 19.6278) + (20.57 - 19.6278) + (20.04 - 19.6278) = 21.2644 dB	
Current grand average performance	19.6278 dB
Confident interval at the 90% confidence level	± 0.58
Expected result at optimum performance, μ	20.685 dB < μ < 21.844 dB

The final step is to predict and verify the improvement of the quality characteristic by using the optimal level of the injection parameters. The predicted S/N ratio using the optimal level of the process parameters are as shown in Table 8 where the optimal level is between 20.685 dB and 21.844 dB. Table 9 shows the green strength of the green part molded by using the optimum injection parameter as shown in Table 8. The S/N ratio obtained in Table 9 demonstrates that the S/N ratio is beyond the confident interval as shown in Table 8.

TABLE 9 Confirmation experiment.

REP 1	REP 2	REP 3	REP 4	REP 5	REP 6	REP 7	REP 8	REP 9	REP 10	S/N (Highest the best)
10.74 MPa	12.17 MPa	13.24 MPa	11.01 MPa	9.61 MPa	10.56 MPa	10.45 MPa	10.67 MPa	12.23 MPa	9.63 MPa	20.73 dB **

** S/N value within 90 % confident level.
Note: The injection pressure and injection temperature are varied at random.

CONCLUSIONS

The Taguchi and ANOVA methods are very helpful in determining the importance of variables when optimizing a quality characteristic including, this case, the green strength of a MIM feedstock. Based on the SS316L feedstock formulations described, the following conclusions can be made regarding green strength.

- Mold temperature is the main influencing factor and is followed by powder loading and injection rate for achieving the highest green strength. Other parameters are found to be less significant because the confident level is less than 90 %.
- However, the less significant factors are still important and they are still required for the injection molding process. This is shown in Table 9 where the S/N ratio was found to be in the optimal range where even though the injection pressure and injection temperature are not kept constant.
- The ANOVA demonstrates that the powder loading also has its influence on the green strength. Nevertheless, the interactions of the powder loading with other major factors such as the injection temperature and injection pressure do not show any significant contributions as the F test indicates that the confident level is less than 90 %.
- The optimum parameter obtained has been verified by the confirmed experiment and this shows that the S/N ratio obtained is within the confident interval.

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