International Journal of Mechanical and Materials Engineering (IJMME), Vol.6 (2011), No.1, 126-132

OPTIMIZATION OF INJECTION MOLDING PARAMETER OF Ti-6Al-4V POWDER MIX WITH PALM STEARIN AND POLYETHYLENE FOR THE HIGHEST GREEN STRENGTH BY USING TAGUCHI METHOD

N. H. M. Nor[a,b], N. Muhamad[a], M.H.I. Ibrahim[a], M. Ruzi[a] and K.R. Jamaludin[c]

[a]Precision Process Research Group, Dept. of Mechanical and Material Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

[b]Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

[c]Department of Mechanical Engineering, College of Science and Technology, Universiti Teknologi Malaysia, City Campus, 54100 Kuala Lumpur, Malaysia

Email: norhafiez@yahoo.com, hamidi@eng.ukm.my

Received 28 January 2010, Accepted 11 March 2011

ABSTRACT

This paper present the Taguchi method of L^{27} (3^{13}) orthogonal array as a tool in optimization of Metal injection molding (MIM) parameters for the highest green strength. Injection pressure, injection temperature, powder loading, mold temperature, holding pressure and injection speed are Parameters to be optimized. Besides those, interaction of the injection pressure, injection temperature and powder loading were studied. The metal powder of Ti-6Al-4V is mixed with binder 60wt% of palm stearin and 40wt% of polyethylene successfully injected at optimum parameter condition: 350 bar of injection pressure, 140^{o}c of injection temperature, 65vol% of powder loading, 50^{o}c of mold temperature, 600 bar of holding pressure, and 10ccm/s of the injection rate. 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 has highest significant percentage (27.59%) followed by powder loading (15.44%) and injection pressure (12.30%) Nevertheless, the analysis of variance does not show any contribution from interaction.

Keywords: Taguchi method, Metal Injection Molding (MIM), green strength, Ti-6Al-4V, Palm stearin

1. INTRODUCTION

Metal injection molding (MIM) is a cost-effective technique for producing small, complex and precision part in high volumes. MIM consist of four main processing steps: mixing, injection molding, debinding and sintering (German and Bose, 1997; Mohamad Nor et al. 2009). Earlier investigations on titanium MIM (Ti-MIM) employed the thermoplastic and/or thermoset binder system typically used in other MIM processes, with these materials constituting ~ 40-50vol% of the feedstock and downstream binder removal taking place via thermal pyrolysis (Gerling et al. 2006; Rack et al., 2006; Scott Weil et al., 2006). Solvent extraction routes are now finding more favour among Ti-MIM practitioners. The debinding can be carried out entirely with a liquid solvent or one or more of soluble components of the binder may be leached, followed by thermal evaporation of the non-soluble component(s) (Anwar and Davies, 2007; Jamaludin et al., 2008a). For example, palm stearin binder which developed by Iriany et al. (2001) is believed that can be replace the conventional binder system which mainly comprise of three to four components. Research on palm stearin in MIM is still new and most of researchers mixing with stainless steel powder (Iriany et al., 2001; Subuki et al., 2007; Setasuwon et al., 2008). In this study, palm stearin of 60 wt% component binders is employed with titanium alloy of Ti-6Al-4V. To establish MIM process for more complicated materials such as Ti-6Al-4V, process control is necessary.

The objective of this paper is to optimize the molding parameters that simultaneously satisfy a green part quality required for the MIM compact before it undergoes a debinding or sintering process to attain its mechanical properties. High green strength has been identified as the green part quality or as an output for this study. To optimize parameter injection process, Taguchi method recently has become a powerful tool for improving productivity during research and development (Kamaruddin et al., 2006; Jamaludin et al., 2009). Berginc et al. (2006) and Jamaluddin et al. (2008b) studied the influence of injection molding parameters on the properties of green parts using DOE technique. Taguchi method has been chosen to study the influence of injection parameter to the weight and strength of the green part. Variables studied consist of injection pressure, injection temperature, mold temperature, powder loading, holding pressure, and flow rate. Two factor levels were used for each variable. The analysis of variance (ANOVA) presented by Jamaluddin et al. (2008b) discovered that the powder loading has a big influence to the strength of the green part. Taguchi method uses a special orthogonal array (OA) to study the entire parameter space with a small number of experiments only and thus, it results in a lot of cost as well as time saving. Design Of Experiment (DOE) using Taguchi method was used in this study to optimized the injection parameters and the experimental results are then transformed into a signal-to-noise (S/N) ratio. Analysis of variance (ANOVA) also can be used to determine the contribution factors which influence the quality characteristics (Roy, 2001). With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted (Jamaludin et al., 2009; Ahmad et al., 2009). Finally, a confirmation experiment is conducted to verify the optimal process parameters obtain from the parameter design.

2. METHODOLOGY

2.1 Feedstock Preparation

The particle of titanium alloy (Ti-6Al-4V) in spherical shape with pycnometer density 4.38 g/cm^3 was mixed with 60wt% of PS and 40wt% of polyethylene (PE). The mixing process was done in a sigma blade at 150^{o}C for 1 hour. The feedstock was then injected using Battenfeld, BA 250 CDC injection molding machine. Figure 1 shows the schematic diagram of the tensile bar cavity.

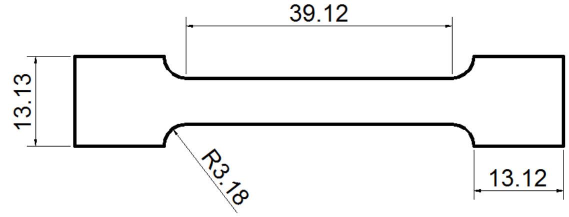

Figure 1 Dimension (mm) of Tensile Bar Cavity with Thickness of 3.17mm

2.2 Design of Experiment

In order to select an appropriate (OA) for the experiments, the total degree of freedom needs to be computed. Information of the process parameters for injection is shown in Table 1. Based on three-level design of experiments and interactions between three important parameters such as injection pressure, injection temperature, and powder loading, the overall degree of freedom will be 24. Basically, the degree of freedom for the OA should be greater than or at least equal o those for the process parameters (Jamaludin et al. 2008b). So Taguchi's OA of L_{27} is the most suitable for the DOE followed by ANOVA to determine the significant level and contribute of each variable to the green strength.

2.3 3-Point Bending Test

A green strength was measured using 3-point bending test apparatus as standard test recommended in MPIF 15. The green strength, as used in this standard, is the stress calculated from the flexure formula, required to break the green compact as a simple beam. The specimen is supported near the ends, and broken by applying the force midway between the fixed centre of the support. The procedure was repeated five times for each specimen to obtain five different values of maximum bending deflection. The schematic view of the 3-point bending test is shown in Figure 2.

Table 1 Injection Parameters and Levels

Process Parameter	Symbol	Level		
		0	1	2
Injection Pressure (bar)	A	350	450	550
Injection Temperature (°C)	B	130	140	150
Powder Loading (vol.%)	C	63	65	67
Mold Temperature (°C)	D	40	45	50
Holding Pressure (bar)	E	500	600	700
Injection Speed (ccm/s)	F	10	15	20

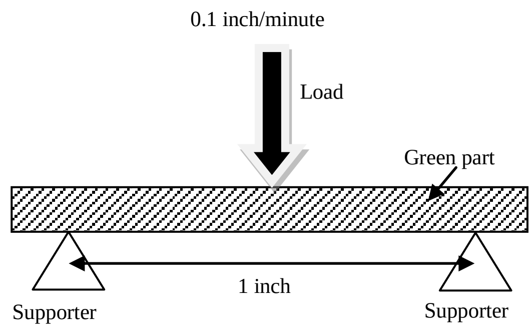

Figure 2 Schematic diagram of the 3-Point Bending Test

3. RESULTS AND DISCUSSION

3.1 3.1 Analysis of S/N Ratio

In the Taguchi method, the term "signal" represents the desirable value (mean) for the output characteristic and the term "noise" represents the undesirable value (S.D) for the output characteristic. Therefore, the S/N ratio of the mean to the S.D. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio of the highest-the-better quality characteristic for green strength should be taken for obtaining optimal performance of the green parts which is defined as:

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

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

Table 2 shows the experimental results for the green strength characteristic and corresponding S/N ratio using equation (1). From these data, the S/N response plot was constructed as shown in Figure 3. The optimum set of factors can be formulated from that plot by selecting the level with the highest S/N value of each value. Thus, without considering any interaction the result is a combination of A0, B1, C1, D2, E1 and F0 as the best set of factors. This means that the injection pressure at 350 bar; injection temperature, 140^{o}C; powder loading, 65 vol.%; mold temperature, 50^{o}C; holding pressure, 600 bar and the injection rate at 10ccm/s are the optimum level. However since the paper evaluates the effects of the interactions among A, B and C, so Figure 4 shows the interaction plot for the mean ratios. The interaction plot indicates that A0B2, A1C1 and B1C1 have the highest mean S/N ratio at 8.85769dB, 8.89426dB and 8.8531dB respectively. It shows that any changes of 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 D (mold temperature) was found at the optimal factor level 2 (50^{o}C) while factor A and F are optimal at the lowest factor (level 0) at 350 bar and 10ccm/s respectively. The investigation also found that high injection temperature and high powder loading do not compulsorily produce 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.

Table 2 Taguchi's $L_{27}(3^{13})$ orthogonal array (OA) demonstrates the quality characteristic and the experimental trials

RUN	Parameter													Measured Parameter					
	1	2	3	4	5	6	7	8	9	10	11	12	13	REP1	REP2	REP3	REP4	REP5	S/N (dB)
	A	B	A X B	A X B	C	A X C	A X C	B X C	D	e	B X C	E	F						
1	0	0	0	0	0	0	0	0	0	0	0	0	0	3.65	2.67	1.81	2.98	2.19	7.74
2	0	0	0	0	1	1	1	1	1	1	1	1	1	2.48	2.66	2.49	2.56	2.01	7.62
3	0	0	0	0	2	2	2	2	2	2	2	2	2	2.79	2.37	2.72	2.19	2.88	8.12
4	0	1	1	1	0	0	0	1	1	1	2	2	2	2.41	2.79	2.88	1.71	2.75	7.47
5	0	1	1	1	1	1	1	2	2	2	0	0	0	2.95	3.05	3.21	2.98	3.08	9.69
6	0	1	1	1	2	2	2	0	0	0	1	1	1	2.48	2.56	2.93	2.88	2.74	8.63
7	0	2	2	2	0	0	0	2	2	2	1	1	1	2.57	3.60	3.64	2.75	2.52	9.25
8	0	2	2	2	1	1	1	0	0	0	2	2	2	3.04	2.84	2.93	2.65	2.77	9.06
9	0	2	2	2	2	2	2	1	1	1	0	0	0	2.88	2.45	2.75	2.36	2.61	8.27
10	1	0	1	2	0	1	2	0	1	2	0	1	2	1.99	2.87	2.53	2.42	1.85	7.02
11	1	0	1	2	1	2	0	1	2	0	1	2	0	3.10	2.77	3.25	2.97	2.77	9.41
12	1	0	1	2	2	0	1	2	0	1	2	0	1	2.64	2.29	2.84	2.87	2.46	8.27
13	1	1	2	0	0	1	2	1	2	0	2	0	1	2.72	2.17	2.64	2.54	2.95	8.18
14	1	1	2	0	1	2	0	2	0	1	0	1	2	2.63	3.38	2.50	3.47	2.96	9.29
15	1	1	2	0	2	0	1	0	1	2	1	2	0	2.37	2.76	2.89	2.10	2.34	7.76
16	1	2	0	1	0	1	2	2	0	1	1	2	0	2.38	3.17	2.27	3.31	3.36	8.86
17	1	2	0	1	1	2	0	0	1	2	2	0	1	2.71	3.01	2.89	2.37	1.92	7.86
18	1	2	0	1	2	0	1	1	2	0	0	1	2	2.55	2.42	2.97	2.22	2.52	7.97
19	2	0	2	1	0	2	1	0	2	1	0	2	1	2.17	2.14	2.67	2.58	2.39	7.46
20	2	0	2	1	1	0	2	1	0	2	1	0	2	2.66	2.79	2.85	2.65	2.25	8.34
21	2	0	2	1	2	1	0	2	1	0	2	1	0	2.35	2.44	2.19	2.81	2.67	7.83
22	2	1	0	2	0	2	1	1	0	2	2	1	0	3.04	2.21	2.03	3.32	2.89	8.14
23	2	1	0	2	1	0	2	2	1	0	0	2	1	2.70	2.75	2.82	2.81	1.75	7.71
24	2	1	0	2	2	1	0	0	2	1	1	0	2	2.82	2.71	2.51	2.56	2.24	8.11
25	2	2	1	0	0	2	1	2	1	0	1	0	2	2.11	2.37	1.42	1.56	2.26	5.21
26	2	2	1	0	1	0	2	0	2	1	2	1	0	2.46	2.70	3.54	2.34	3.11	8.74
27	2	2	1	0	2	1	0	1	0	2	0	2	1	2.88	2.80	1.56	2.99	2.09	7.00

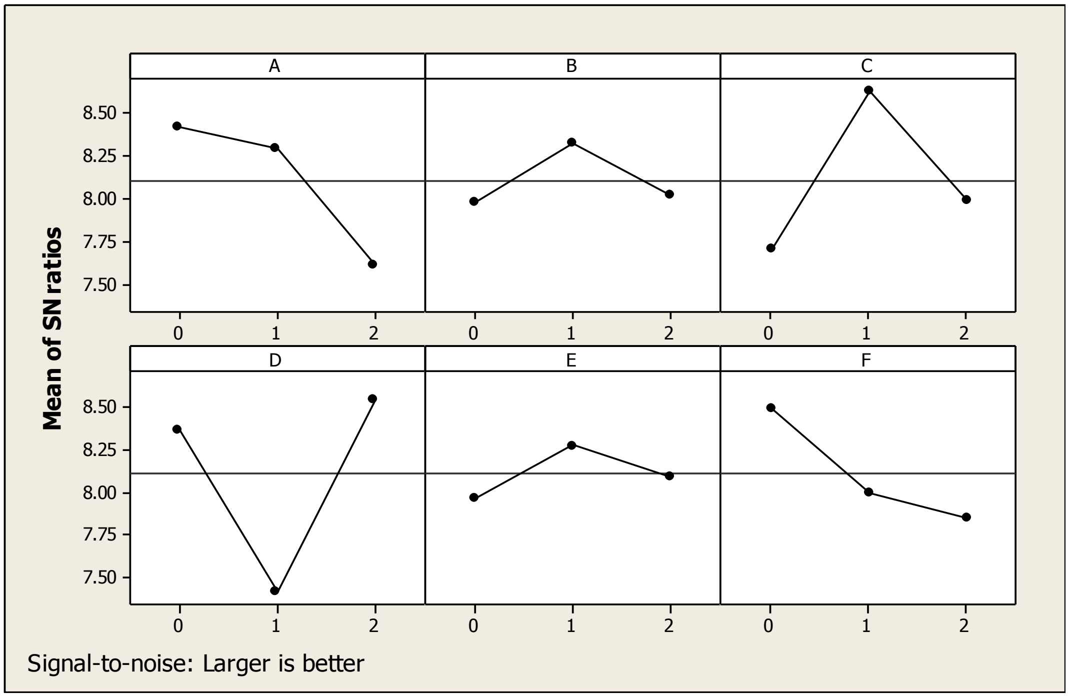

Figure 3 The Response Plot of S/N Ratio

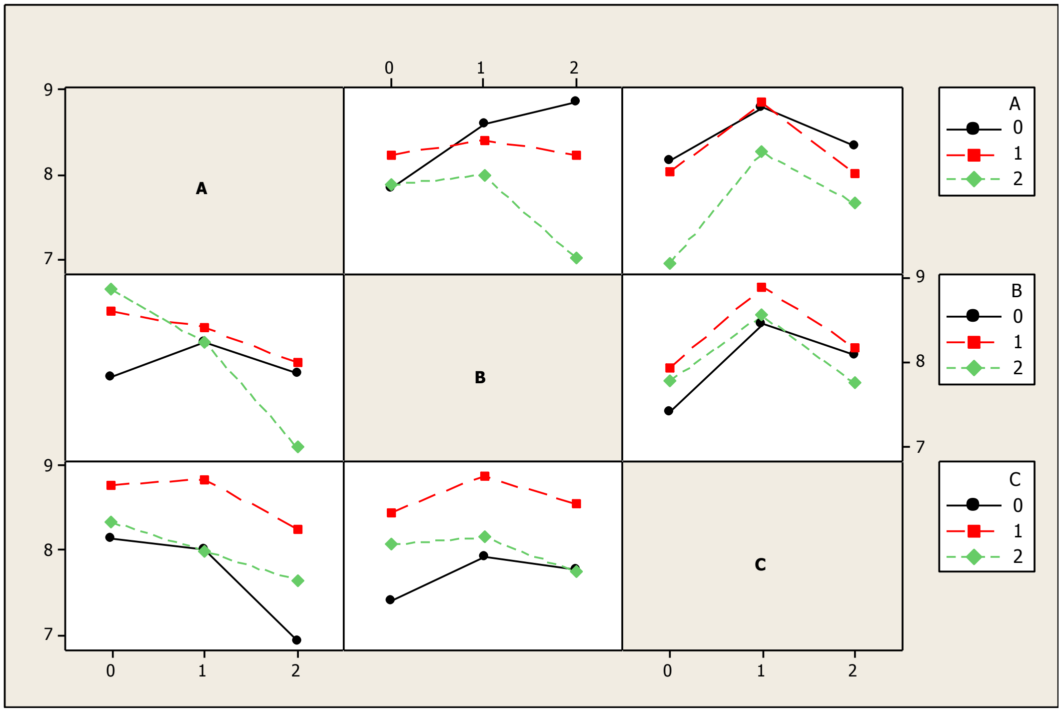

Figure 4 Interaction Plot of S/N Ratio

3.2 Analysis of Variance

ANOVA table has been generated to determine the statistical significance of the parameters as shown in Table 3. It is clear that the mold temperature (factor D) of the machine significantly affect the green strength, followed by powder loading (factor C) and injection pressure (factor A). Insignificant factors (contribution of factors are small) such as injection temperature (factor B), holding pressure (factor E), injection rate (factor F), interaction AXB, interaction BXC and interaction BXC will be pooled in order to increase the confident level of the significant factors. Table 4 shows the results of ANOVA after pooling with at least 95% of confidence interval. It is shown that factor A, factor C, and factor D has significantly affect the green strength at contribution of 12.30%, 15.44% and 27.59% respectively. F test indicates that the factor A, factor C and factor D have significant level at 95%, 97.5% at 99% respectively. Furthermore, since only factor A, C and D have a confident level greater than 95% thus only three factors were used to calculate the S/N ratio at the optimum performance. This is shown in Table 5 where the optimum performance is at 9.3895dB compared to the current grand average performance of 8.111dB (as in Table 3).

Table 3 ANOVA of Green Strength

COLUMNS	FACTORS	PARAMETERS	DF	SUM SQUARED	VARIANCE	F	% CONTRIBUTION
1	A	Injection Pressure	2	3.3980	1.69899	10.75	15.74
2	B	Injection Temperature	2	0.6560	0.32802	2.08	3.04
3	AXB	Interaction 1x2	4	2.9293	0.73232	4.63	13.57
5	C	Powder Loading	2	4.0751	2.03754	12.89	18.87
6	AXC	Interaction 1x5	4	0.6141	0.15352	0.97	2.84
8	BXC	Interaction 2x5	4	0.3870	0.09676	0.61	1.79
9	D	Mold Temperature	2	6.6985	3.34926	21.19	31.03
12	E	Holding Pressure	2	0.4453	0.22264	1.41	2.06
13	F	Injection Rate	2	2.0707	1.03537	6.55	9.59
	Error		2	0.3161	0.15803		1.46
	Total		26	21.5901			100

Table 4 ANOVA of Green Strength after Pooling

COLUMNS	FACTORS	PARAMETERS	DF	SUM SQUARED	VARIANCE	F	% CONTRIBUTION
1	A	Injection Pressure	2	2.6561	1.69899	4.58	12.30
2	B	Injection Temperature	2		Pooled		
3	AXB	Interaction 1x2	4		Pooled		
5	C	Powder Loading	2	3.3332	2.03754	5.49	15.44
6	AXC	Interaction 1x5	4		Pooled		
8	BXC	Interaction 2x5	4		Pooled		
9	D	Mold Temperature	2	5.9567	3.34926	9.03	27.59
12	E	Holding Pressure	2		Pooled		
13	F	Injection Rate	2		Pooled		
	Error		20	7.4185			44.67
	Total		26	70.7544			100

Table 5 Estimation of Performance as the Optimum Design after Pooling: Characteristic: Higher the Better

A0C1D2		
Optimum performance calculation: $\overline{T}+(\overline{A_0}-\overline{T})+(\overline{C_1}-\overline{T})+(\overline{D_2}-\overline{T})$ 8.111+(8.4272-8.111)+(8.6343-8.111)+(8.55-8.111) = 9.3895dB		
Current grand average performance	:	8.111
Confident interval at 95% confidence level	:	±0.5894
Expected result at optimum performance, μ	:	8.8001<μ<9.9789

Table 6 Confirmation Experiment

Replication	1	2	3	4	5	6	7	8	9	10	S/N Ratio
Parameter Measurement	3.17	2.99	3.00	3.00	3.01	2.79	2.87	2.95	3.01	2.75	9.3928

The confident interval is calculated with equation (2)(Roy, 1990):

$$CI = \pm\sqrt{\frac{F_{\alpha}(f_1, f_2)xV_e}{n_e}} \quad (2)$$

Where, $F_{\alpha}(f_1,f_2)$ is the variance ratio for DOF of f_1 and f_2 at level of significance α. The confidence level is $(1-\alpha)$, f_1 is the DOF of mean (usually equal to 1) and f_2 is the DOF of 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 6. Confirmation experiments were conducted by running another ten replications at combined setting of A0, B1, C1, D2, E1 and F0. Table 6 shows the results and it was found that the average green strength obtained from the confirmation experiment fell within the prediction 95% confident interval.

4. CONCLUSIONS

Effect and optimization of process parameters in injection molding of Ti-4V-6Al powder and binders of palm stearin and polyethylene to produce green strength were successfully investigated through Taguchi Method. The data would give some insights on the scope of the parameter condition to be applied during injection molding practice in MIM. The binders of palm stearin up to 60wt% and polyethylene of 40wt% was successfully injected at the optimum injection parameter and were found to be 350 bar of injection pressure, 140^{o}c of injection temperature, 65vol.% of powder loading, 50^{o}c of mold temperature, 600 bar of holding pressure, and 10ccm/s of the injection rate. Based on ANOVA results regarding on green strength, mold temperature (Factor D) is the most significant effect which shows a contribution of 27.59%, followed by the powder loading (factor C) at 15.44% and injection pressure (factor A) at 12.30%. 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.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknologi MARA for the research grant, 600-IRDC/ST/FRGS 5/3/1300 and Ministry of Higher Education and Universiti Kebangsaan Malaysia for the PhD scholarship.

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