International Journal of Advancements in Mechanical and Aeronautical Engineering– IJAMAE
Volume 2: Issue 1 [ISSN : 2372-4153]
Publication Date : 30 April, 2015

Quality Feedstock Preparation for Metal Injection Molding Using Taguchi Design of Experiment

Nurun Nahar[a], Altab Hossain[b], Imtiaz Ahmed Choudhury[c], Azuddin Bin Mamat[d]

***Abstract*—Preparation of quality feedstock is critically important for production of quality product through metal injection molding (MIM). This study deals with the optimization of mixing parameters to ensure the homogeneity in feedstock of aluminum powder and high density polyethylene based binder. Experimental design and feedstock preparation was carried out considering three parameters such as powder concentration, mixing temperature and mixing speed. Feedstock rheological characteristic 'viscosity' was analyzed through alpha analytical rheometer. The Taguchi analysis was performed for this 'viscosity' to find the combination of optimum level of parameters. The results show that 58:42 powder-binder ratio, 120 ^{0}C mixing temperature and 43 rpm mixing speed give satisfactory quality of feedstock i.e. minimum feedstock viscosity. A well fit of the optimized parameters was observed through analysis of variance (ANOVA) with higher accuracy using a confidence level of 95%.**

Keywords—*Metal injection molding, feedstock, optimization, viscosity.*

I. Introduction

Metal injection molding (MIM) is an age-old practice of manufacturing area where very fine metallic powder is mixed with suitable binder system in selected proportion to prepare feedstock. This feedstock is then injected into the mold cavity of desired shape and size to obtain green part. In further processing, the green part is debinded in order to remove the binder and finally sintered in order to produce the brown part. Micro parts of the complex and complicated shape can be manufactured by this process with high precision at relatively low cost. The quality of the final parts depends on number of parameters like particle size, binder system, injection temperature, injection time, holding pressure, powder loading [1, 2]. Better surface finish as well as higher aspect ratio can be maintained in the final part using smaller sized powder particles. Bigger particle size of metal powder allows greater amount of powder in powder-binder mixture [3]. In MIM process, lower percentage of powder in the powder-binder mixture improves mold filling attributes but it causes higher shrinkage in the final part [1]. Again, higher powder content in feedstock does not allow sufficient amount of binder leading viscous feedstock as well as incomplete mold filling while it is helpful in reducing shrinkage [4, 5]. Therefore, powder loading effects the injection molding of metal powders vastly. Again, the phenomena like powder-binder separation, inhomogeneous mixing happens due to very high mixing temperature [6]. Supati et al. [6] also reported that mixing speed controls shear rate which has an inverse relation with viscosity. Statistical methods such as diagonal recurrent neural network (DRNN) [7], back propagation neural network (BPNN) [8], Taguchi parameter design method [8, 9], response surface methodology [10], genetic algorithm [7, 10], six sigma methods [9] etc. have been used to optimize parameters as well as to develop a prediction model.

This study focuses on three mixing parameters: (i) powder concentration, (ii) mixing temperature, and (iii) mixing speed to obtain good quality feedstock as well as to set up an optimum mixing condition. Experimental design and optimization were carried out using Taguchi design of experiment (DOE) and impact of optimum parameters was analyzed using analysis of variance (ANOVA).

II. Materials and Methods

A. *Materials*

Silver gray colored aluminum powder of 99.80% purity, 19.82 µm particle sizes and relative density 2.699 g/cm^3 was used in this experiment. Binder system consisting of high density polyethylene (HDPE), paraffin wax (PW) and stearic acid (SA) were used in the ratio of 50/46/4 to prepare feedstock [2, 11]. The characteristics and composition of starting powder and binder components are listed in Table I.

TABLE I: STARTING POWDER & BINDER COMPOSITION AND CHARACTERISTICS

Properties	**Al powder**	**HDPE**	**PW**	**SA**
Composition (wt%)	58	21	19.32	1.68
	62	19	17.48	1.52
	66	17	15.64	1.36
Density (g/cm^3)	2.699	0.95	0.75	0.84
Melting point (^{0}C)	660	122	57	72
Melting Range (^{0}C)		115-135	42–62	74–83

[a, b, c, d] Manufacturing System Integration (MSI), Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia

B. *Taguchi Method*

Taguchi method is a statistical method of design of experiment. This method is used in industrial engineering design and product manufacturing in order to obtain high product quality at minimal cost [12]. In Taguchi method, six-steps such as problem formulation and response identification, control factors and their level selection, creating an orthogonal array (OA) design, run the experiment and record the result, Taguchi statistical analysis, and finally run confirmatory experiment to validate the Taguchi analyzed result [12]. The Taguchi method uses S/N ratio approach to evaluate the quality characteristics. There are four categories of standard S/N ratio in quality engineering: (i) Smaller-the-better, (ii) Nominal-the-best and (iii) Larger-the-better, and (iv) Operating window [13]. The category selection for S/N ratio depends on expectation on quality characteristics. Complete technical line of Taguchi optimization flowchart is shown in *Fig. A.1* of Appendix *A*.

C. *Experimental Design and Mixing*

Taguchi L9 orthogonal array of three-level design was created in Minitab 16 by utilizing three mixing parameters such as powder concentration (PC), mixing temperature (T_M), and mixing speed (N_S) whose units as wt%, ^{0}C, and rpm, respectively. Taguchi orthogonal array design including parameters' value is shown in Table II.

The materials (powder and binder stuffs) were weighted according to the selected ratio (as mentioned at Table 1) using Adventurer Analytical Balance (AR 2140, USA). To prepare feedstock, a total of nine mixing experiments were carried out in two steps. Firstly, the powder and binder components were mixed using Retsch Planetary Ball Mill (PM 100, Germany) at a constant mixing speed of 300 rpm and mixing time of 5 hours at room temperature. Then, further mixing was accomplished in a custom made mixing machine (as shown in *Fig. 1*) where heat is added to the mixing chamber through a concentric heater surrounding the chamber. The mixing speed and mixing temperature were varied according to the Taguchi orthogonal design (Table II).

D. *Rheological Analysis*

For metal powder feedstock, viscosity is the most important rheological property which is the function of

powder concentration (ϕ), temperature (T), shear rate ($\dot{\gamma}$), and binder compositions [14]. The feedstock of aluminum powder were analyzed using Physica alpha analytical rheometer MCR 301 (Antom Paar GmbH, Austria) to determine its viscosity using a measuring plate of 15 mm diameter. By increasing the speed of piston, shear rates were varied within the range of 100 to 10000 s-1. A change in viscosity of feedstock was observed with the change of powder concentration and shearing rate but in the inverse manner.

TABLE II: Taguchi L9 (3^3) Orthogonal Array with parameters

Exp. No.	**PC (wt.%)**	T_M **(^{0}C)**	N_S **(rpm)**	**Viscosity (η) (pa.s)**	**S/N ratio (dB)**
1	58	120	35	10.25	-20.7962
2	58	130	43	10.96	-20.6120
3	58	140	51	10.73	-20.2145
4	62	120	43	12.05	-22.7661
5	62	130	51	13.75	-22.2588
6	62	140	35	12.97	-21.6197
7	66	120	51	14.93	-23.7898
8	66	130	35	15.47	-23.5218
9	66	140	43	15.00	-23.4812

Figure 1: Custom made mixture machine

III. Results and Discussion

A. *Rheological Analysis*

Fig. 2 shows the rheological property 'viscosity' corresponding to powder-binder ratio, mixing temperature and mixing speed. During rheology test, the value of viscosity was observed to vary in the acceptable range of 10 to 1000 pa.s for shear rate range of 100 S^(-1) to 10,000 S^(-1) [15].

The viscosity of the feedstock was observed to increase with the increase of powder loading (*Fig. 2 (a)*) throughout the shear rate range. Li et al. [5] have mentioned that feedstock flowability can be obtained with the addition of adequate quantity of binder to it as binder components assist in lowering feedstock viscosity. Therefore, increasing powder concentration facilitate less quantity of binder which results in highly viscous feedstock.

Fig. 2 (b) illustrates that feedstock viscosity increases with the increase of mixing temperature until 130 ^{0}C but decreases with the further increase of temperature. This happens as binder components initiate to be softer with the increase of temperature. Hence, before being melted, binder components coagulate powder particle in its surrounding. Therefore, powder-binder agglomeration appears for a while which causes an increase in viscosity. On the contrary, binder components melt with successive increase of temperature which results in breakdown of powder-binder agglomerate and feedstock viscosity decreases. Again, feedstock viscosity decreases as mixing speed increases and become lowest at 43 rpm while an increasing phenomena was observed in the rage of 43-51 rpm (*Fig. 2 (c)*).

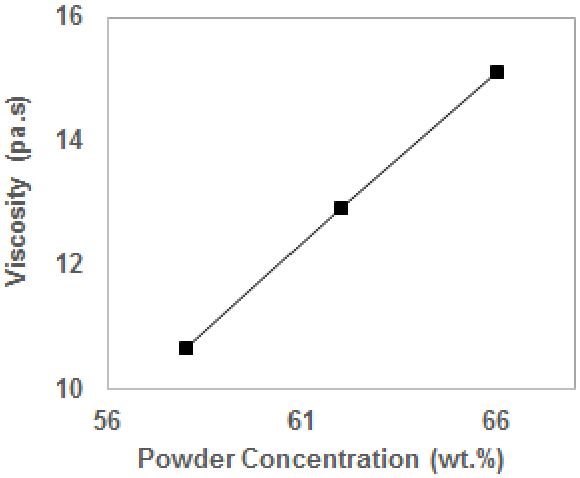

Figure 2(a): Response for viscosity corresponding to Powder Concentration

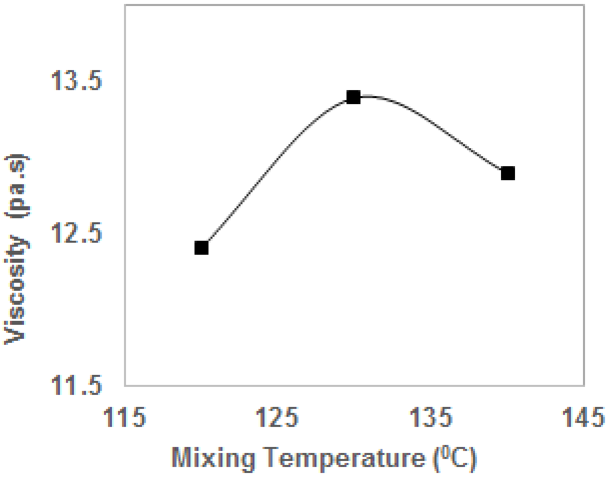

Figure 2(b): Response for viscosity corresponding to Mixing Temperature

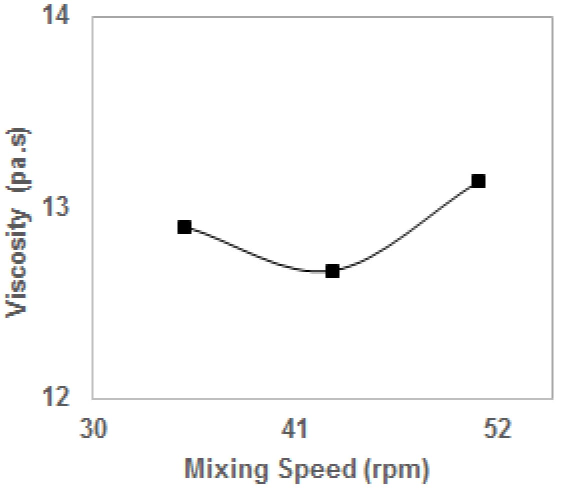

Figure 2(c): Response for viscosity corresponding to Mixing Speed

B. *Optimization of Mixing Parameters*

The measured response for this study is viscosity which is expected to be smaller. Hence, ‘Smaller is better’ approach was chosen to determine the signal-to-noise ratio for the output ‘viscosity’ which can be expressed mathematically as follows:

$$S/_N = -10\log[MSD] = -10\log {}^1/_n \sum_{i=1}^{n} y_i^2 \qquad (1)$$

where *MSD* is the mean square deviation, *y* is the measured response, and n is the number of observation and unit of *S/N* is dB. The means of *S/N* ratios for viscosity corresponding to parameters are shown in Fig. 3. From analysis of Taguchi design, smaller S/N ratio as well as low viscosity was observed at 58 wt% powder loading, 120 ^{0}C mixing temperature and 43 rpm mixing speed. Hence, these are the optimum conditions for powder-binder mixing i.e. for feedstock preparation. The results of the present study are found to be in close agreement with the mixing conditions proposed by Supati et al. [6] (54% powder loading, mixing temperature 90 ^{0}C (binders’ melting temperature was ~ 90 ^{0}C), and 30 rpm rotor speed) and Kong et al. [4] (66% powder loading).

The optimized result was analyzed using analysis of variance (ANOVA) to evaluate the effect of parameters on viscosity. A confidence level of 95% was considered during this analysis [16]. From ANOVA, powder concentration is found as most significant parameter among three mixing parameters with 92.2% impact on feedstock viscosity while the two other parameters (mixing temperature and mixing speed) were observed as less significant.

C. *Confirmation Experiment*

The accuracy of the result of Taguchi optimization was checked by executing confirmation experiment using optimum level of parameters. The experiment was repeated for three times. The results ‘viscosity’ from rheology test and S/N value of confirmation experiment (calculated using 1) are shown in Table III.

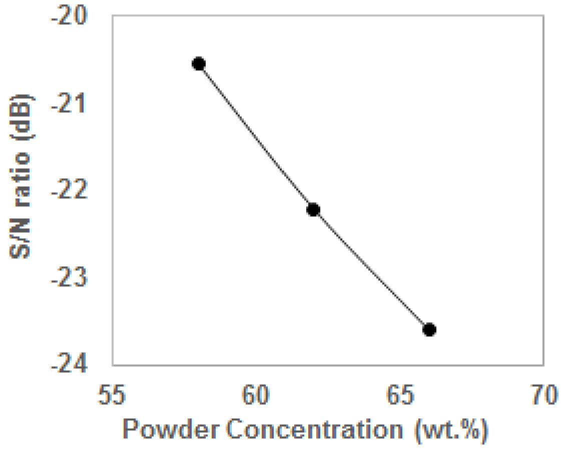

Figure 3(a): Response for S/N ratio corresponding to Powder Concentration

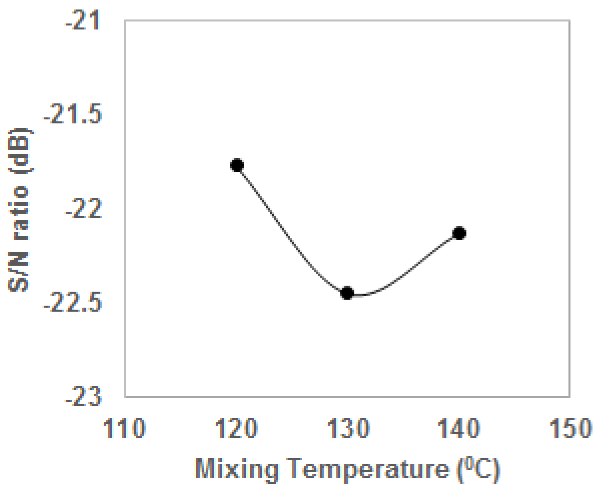

Figure 3(b): Response for S/N ratio corresponding to Mixing Temperature

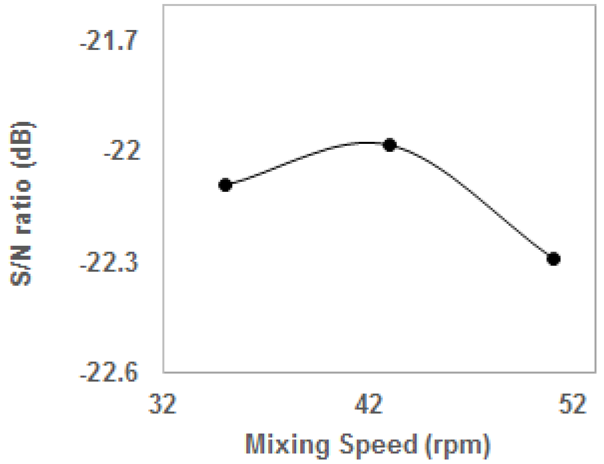

Figure 3(c): Response for viscosity corresponding to Mixing Speed.

TABLE III: THE RESPONSES OF CONFIRMATION EXPERIMENT AND PREDICTED S/N RATIO

PC wt.%	T_M ^{0}C	N_S rpm	Average Visocsity (pa.s)	S/N ratio dB	Predicted S/N ratio dB
58	120	43	11.17	-20.9637	-20.0544

The predicted S/N ratio was calculated at optimum condition using 2 as shown in Table III.

$$S/N_{predict} = T + \sum (F_i - T) \qquad (2)$$

where T is the mean of total S/N ratio and F_i is the S/N ratio for optimum factor. The error between S/N ratio of confirmation experiment and predicted S/N ratio was found as 4.34% which satisfy 95% confidence level which supports the accuracy of the Taguchi optimization [17].

IV. Conclusion

The paper presents a brief description of investigation for optimum powder-binder ratio, mixing temperature and mixing speed for preparation of quality feedstock. Mixing Parameters were optimized using Taguchi DOE technique and impact of these optimized parameters on feedstock characteristic 'viscosity' was analyzed through ANOVA with a confidence level of 95%.

According to Taguchi design and optimization technique, optimum mixing parameters for quality feedstock are found to be powder-binder concentration in the ratio of 58:42 wt.%, 120 ^{0}C mixing temperature and mixing speed of 43 rpm. From ANOVA, Powder concentration is found as most significant parameter with a contribution of 92.2% on feedstock viscosity. Mixing temperature and mixing speed apparently do not have significant effect on feedstock viscosity.

Acknowledgment

The authors thank the Department of Mechanical Engineering, Faculty of Engineering, University of Malaya and University of Malaya Research Grant (UMRG) for their support under the grant [RP020-2012A and RP020-2012B].

Appendix A

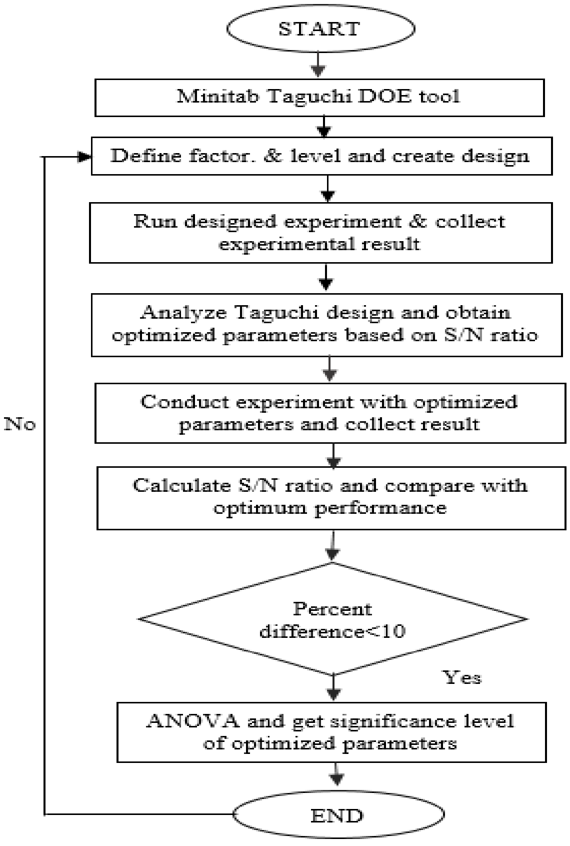

Figure A.1: Taguchi optimization flow line using Minitab

References

[1] P. Thomas, B. Levenfeld, A. Várez, and A. Cervera, "Production of Alumina Microparts by Powder Injection Molding," I. J. App. Ceram. Tech., vol 8, pp 617-626, June 2011.

[2] K. H. Kate, V. P. Onbattuvelli, R. K. Enneti, S. W. Lee, S.-J. Park, and S. V. Atre, "Measurements of powder–polymer mixture properties and their use in powder injection molding simulations for aluminum nitride," The Journal of The Minerals, Metals & Materials Society, 64(9), 1048-1058, August 2012.

[3] I. Agote, A. Odriozola, M. Gutierrez, A. Santamarıa, J. Quintanilla, P. Coupelle, and J. Soares, (2001). "Rheological study of waste porcelain feedstocks for injection moulding," J. Eur. Ceram. Soc., vol. 21, pp 2843-2853, December 2001.

[4] X. Kong, T. Barriere, and J. Gelin, "Determination of critical and optimal powder loadings for 316L fine stainless steel feedstocks for micro-powder injection molding," J. Mat. Proc. Tech., vol. 212, pp 2173-2182, November 2012.

[5] Y. Li, L. Li, and K. Khalil, "Effect of powder loading on metal injection molding stainless steels," J. Mat. Proc. Tech., vol. 183, pp 432-439, March 2007.

[6] R. Supati, N. Loh, K. Khor, and S. Tor, "Mixing and characterization of feedstock for powder injection molding," Materials Letters, vol. 46, pp 109-114, November 2000.

[7] Y. Peng, W. Wei, and J. Wang, "Model Predictive Synchronous Control of Barrel Temperature for Injection Molding Machine Based on Diagonal Recurrent Neural Networks," Materials and Manufacturing Processes, vol. 28, pp 24-30, July 2012.

[8] W.-C. Chen, P.-H. Tai, M.-W. Wang, W.-J. Deng, and C.-T. Chen, "A neural network-based approach for dynamic quality prediction in a plastic injection molding process," Expert systems with Applications, vol. 35, pp 843-849, October 2008.

[9] W.-T. Lin, T.-A. Chiang, S.-T. Wang, M.-H. Li, C.-T. Huang, and S.-C. Dai, "Construction of a 3C product mold manufacturing process predictive optimization model," Materials and Manufacturing Processes, vol. 28, pp 195-199, February 2013.

[10] C.-C. Chen, P.-L. Su, C.-B. Chiou, and K.-T. Chiang, "Experimental investigation of designed parameters on dimension shrinkage of injection molded thin-wall part by integrated response surface methodology and genetic algorithm: A case study," Materials and Manufacturing Processes, vol. 26, pp 534-540, 2011.

[11] A. Hossain, I. A. Choudhury, N. Nahar, I. Hossain, and A. B. Mamat, "Experimental and Theoretical Investigation of Powder-Binder Mixing Mechanism for Metal Injection Molding," Materials and Manufacturing Processes, July 2014, DOI: 10.1080/10426914.2014.930955.

[12] J. Antony and F. J. Antony, "Teaching the Taguchi method to industrial engineers," Work Study, vol. 50, pp 141-149, November 2001.

[13] W. Y. Fowlkes, and C. M. Creveling, (1995). "Engineering methods for robust product design: Using Taguchi Methods in Technology and Product Development," Addison-Wesley, January 1995.

[14] B. Huang, S. Liang, and X. Qu, "The rheology of metal injection molding," J. Mat. Proc. Tech., vol. 137, pp 132-137, June 2003.

[15] R. M. German, and A. Bose, "Injection molding of metals and ceramics," January 1997.

[16] H. Oktem, T. Erzurumlu, and I. Uzman, "Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part," Materials & Design, vol. 28, pp 1271-1278, 2007.

[17] G. H. V. C. Chary , & M. G. Dastidar, "Optimization of experimental conditions for recovery of coking coal fines by oil agglomeration technique," Fuel, vol. 89, pp 2317-2322, September 2010.

About Author (s):

In the feedstock preparation for metal injection molding, powder concentration has the most significant effect on the viscosity.