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# Multiple Performance Optimization for the Best Metal Injection Molding Green Compact

[1]K.R. Jamaludin, [2]N. Muhamad, [2]M.N. Ab. Rahman, [3]S. Ahmad, [3]M.H.I. Ibrahim, [4]N.H.M. Nor, [5]M.R. Harun and [1]M.Y.M. Daud
[1]College of Science and Technology, Universiti Technologi Malaysia, Int. Campus 54100, Kuala Lumpur, Malaysia
[2]Faculty of Engineering and Architecture, National University of Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia
[3]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia
[4]Faculty of Mechanical Engineering, University Technology MARA, 40450 Shah Alam, Selangor, Malaysia
[5]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia, Melaka, 76109 Durian Tunggal, Melaka, Malaysia

**Abstract:** This study presents and demonstrates the effectiveness of optimizing multiple quality characteristics of the injection molding of the MIM green compacts via Taguchi method-based Grey analysis. The modified algorithm adopted here was successfully used for both detraining the optimum setting of the process parameters and for combining multiple quality characteristics into one integrated numerical value called Grey relational grade. The significant molding parameters were identified as (1) Injection Pressure (2) Injection Temperature (3) Powder Loading (4) Mold Temperature (5) Holding Pressure and (6) Injection Speed. In addition, the multiple quality characteristics required are: (1) less defects (2) strong and (3) denser compact. The result concluded that the powder loading (C) is very significant for the combination of the quality characteristics.

**Key words:** Metal injection molding, optimization, green compact, grey relational, taguchi method

## INTRODUCTION

Manufacturing a defect free Metal Injection Molding (MIM) compact with superior final density that is very close to the theoretical density is desirable. Besides that, the strength of the green compact is also desirable because stronger green compact is easy to be handled for the next processes. Many optimization of the MIM process parameter has been published by many authors (Omar, 1999; Ismail *et al*., 2005; Barriere *et al*., 2002; Chuankrerkkul *et al*., 2008) without using any of the statistical based Design of Experiment (DOE) methodology, ends with unsatisfactory results in a wide range of experimental settings. However, authors of literatures (Berginc *et al*., 2006; Jamaludin *et al*., 2007) use the Taguchi method as a DOE to optimize the green part quality. The Taguchi method has been extensively adopted in manufacturing to solve some confusing problems and to improve product/process design optimization with a single quality performance (Tsao, 2009; Park, 1996). In order to improve the flexibility and ability of the Taguchi method, Deng (1989) proposed a grey relational analysis to fulfill the crucial mathematical criteria for dealing with a poor, incomplete and uncertain system (Tsao, 2009). Grey relational analysis can effectively be recommended as a method for optimizing the complicated inter-relationships among multiple responses (Tsao, 2009; Kopac and Krajnik, 2007). Through the Grey relational analysis, a Grey Relational Grade (GRG) is obtained to evaluate the multiple performance characteristics. As a result, optimization of the complicated multiple response can be converted into the optimization of a single Grey Relational Grade (GRG). The Grey-Taguchi method was established for combining both Grey relational analysis and the Taguchi method. The Grey-Taguchi method was successfully applied to optimize the multiple responses of complicated problems in manufacturing processes. In this study, the

**Corresponding Author:** K.R. Jamaludin, College of Science and Technology, Universiti Technologi Malaysia, Int. Campus 54100, Kuala Lumpur, Malaysia

Grey-Taguchi method was used to optimize the injection molding process parameter. The multiple response included defect free, strong and dense green compact. This is by the fact that the optimum injection molding process parameter is crucial for making sure the final compact manufactured by this advanced manufacturing process is tremendous.

## MATERIALS AND METHODS

A 316L stainless steel gas atomized powder with pycnometer density of 7.93 g $cm^{-3}$ has been mixed with Polyethylene Glycol (PEG), Polymethyl Methacrylate (PMMA) and Stearic Acid (SA) as a binder. The binder composition is 73% PEG + 25% PMMA + 2% SA based on the weight fraction. A powder metal particle size distributions used is in a bimodal distribution consisting of 70% of coarse powder in a weight fraction.

## RESULTS AND DISCUSSION

The Design Of Experiment (DOE) includes six controllable injection parameters at three level and coded values are tabulated in Table 1. The experimental frame is a region determined by the lower and upper limits of parameters settings that are of major interest. The range of the injection pressure (A) and injection temperature (B) is limited by the rheological result of the feedstock as presented in the previous publications (Jamaludin *et al*., 2008; Jamaludin *et al*., 2010). The powder loading (C) was selected based on the critical powder loading (Ismail *et al*., 2005)of the metal powder used in this study while other parameters were based on the preliminary experiment done prior to the optimization using the DOE.

As shown in Table 2 the Taguchi orthogonal array of $L_{27}$ $(3)^{13}$ has been employed to explore the process interrelations within the experimental setting. The orthogonal array has 13 columns and 27 rows; each injection molding parameter was assigned to a column, according to standard linear graph (Park, 1996; Jamaludin *et al*., 2009a). The mean of the quality performance (response) of the experiment parameter is as shown on the right hand side of the Table 2, green appearance, flexure strength and density of the injection molded green compacts are to be optimized in this study.

Table 1: Injection parameters and their levels

| Process parameter | Symbol | Level 0 | Level 1 | Level 2 |
|---|---|---|---|---|
| Injection pressure (bar) | A | 350 | 450 | 550 |
| Injection temperature (°C) | B | 130 | 140 | 150 |
| Powder loading (% volume) | C | 64 | 64.5 | 65 |
| Mold temperature (°C) | D | 45 | 48 | 51 |
| Holding pressure (bar) | E | 700 | 900 | 1100 |
| Injection speed (ccm/s) | F | 10 | 15 | 20 |

Further, they are linear normalized according to the type of response. In the context of Taguchi method, the green compact surface appearance is the lower-the-better performance response whilst on the other hand the green compact density and strength is the higher-the-better performance. The Grey Relational Grade (GRG) shown in Table 2 was obtained from the average of the Grey Relational Coefficient (GRC) of the normalized response (Tsao, 2009; Kopac and Krajnik, 2007). If the expected data sequence is of the form "the-higher-the-better", then the original sequence can be normalized as:

$$x_i^*(k)=\frac{x^\circ_i(k)-\min x^\circ_i(k)}{\max x^\circ_i \min x^\circ_i(k)} \quad (1)$$

where, $x_i^\circ$ is the original sequence, $x^*$ (k) the sequence after the data preprocessing, max $xi^\circ$ (k) the largest value of $xi^\circ$ (k) and min $xi^\circ$ (k) implies the smallest value of $xi^\circ$ (k) for the i th experimental run. Note that the complete experiments result is not presented in this study, however the max $xi^\circ$ (k) and min $xi^\circ$ (k) was obtained from the data replication of each experiment run, i based on the Taguchi's orthogonal array. The larger normalized results correspond to better performance and the best normalized result should be equal to 1 (Deng, 1989).

When the form "the-smaller-the-better" becomes the expected value of the data sequence, the original sequence can be normalized as:

$$x_i^*(k)=\frac{\max x^\circ_i-\min x^\circ_i(k)}{\max x^\circ_i \min x^\circ_i(k)} \quad (2)$$

The Grey relational coefficients are calculated to express the relationship between the ideal (best) and the actual experimental results. The Grey relational coefficient, $\zeta_i$ (k) can be expressed as:

$$\zeta_i(k)=\frac{\Delta\min+\zeta\Delta\max}{\Delta_{oi}(k)+\zeta\Delta\max} \quad (3)$$

where, $\Delta_{oi}$ is the deviation sequence of the reference sequence ($x_o$) and the comparability sequence ($x_i$), i.e., $\Delta_{oi} = \| x_o(k)-x_i(k)\|$, where $x^\circ$ (k) is the ideal result (=1) and $\zeta$ is the distinguishing coefficient set between zero and unity; in this study, it was set to $\zeta$ = 0.9 (Kopac and Krajnik, 2007). $\Delta$ max is the largest value of $\Delta_{oi}$ and the $\Delta$ min is the smallest value of $\Delta_{oi}$. Next, the Grey relational grade $\zeta(x_o, x_i)$ is computed by averaging the Grey relational coefficient corresponding to each quality characteristic is defined as:

$$\zeta(x_o,x_i)=\frac{1}{n}\sum_1^n \zeta_i(k) \quad (4)$$

Table 2: The design of experiment

| Run | A: Inj. Pressure (bar) | B: Inj. Temp. (°C) | C: Powder Loading (% Vol.) | D: Mold Temp. (°C) | E: Holding Pressure (bar) | F: Injection Speed (ccm $s^{-1}$) | Appearance | Strength (Mpa) | Density (g $cm^{-3}$) | GRG, $\zeta$ ($x_o$, $x_i$) | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 4.3 | 10.59 | 5.2988 | 0.853045 | 5 |
| 2 | 0 | 0 | 1 | 1 | 1 | 1 | 4.2 | 9.88 | 5.286 | 0.839653 | 9 |
| 3 | 0 | 0 | 2 | 2 | 2 | 2 | 3.7 | 8.00 | 5.3362 | 0.821583 | 11 |
| 4 | 0 | 1 | 0 | 1 | 2 | 2 | 2.7 | 10.72 | 5.3552 | 0.857328 | 3 |
| 5 | 0 | 1 | 1 | 2 | 0 | 0 | 3.1 | 9.7 | 5.3212 | 0.749238 | 27 |
| 6 | 0 | 1 | 2 | 0 | 1 | 1 | 3.7 | 11.03 | 5.5064 | 0.772202 | 25 |
| 7 | 0 | 2 | 0 | 2 | 1 | 1 | 1.3 | 9.32 | 5.2552 | 0.854463 | 4 |
| 8 | 0 | 2 | 1 | 0 | 2 | 2 | 3.7 | 0.84 | 5.368 | 0.866454 | 2 |
| 9 | 0 | 2 | 2 | 1 | 0 | 0 | 5.0 | 8.92 | 5.299 | 0.785998 | 21 |
| 10 | 1 | 0 | 0 | 1 | 1 | 2 | 5.3 | 9.37 | 5.1578 | 0.778194 | 23 |
| 11 | 1 | 0 | 1 | 2 | 2 | 0 | 5.5 | 10.24 | 5.3078 | 0.84672 | 8 |
| 12 | 1 | 0 | 2 | 0 | 0 | 1 | 2.9 | 10.76 | 5.5212 | 0.774405 | 24 |
| 13 | 1 | 1 | 0 | 2 | 0 | 1 | 2.1 | 9.84 | 5.2458 | 0.849141 | 7 |
| 14 | 1 | 1 | 1 | 0 | 1 | 2 | 4.1 | 10.94 | 5.358 | 0.920098 | 1 |
| 15 | 1 | 1 | 2 | 1 | 2 | 0 | 3.7 | 9.87 | 5.2902 | 0.788079 | 20 |
| 16 | 1 | 2 | 0 | 0 | 2 | 0 | 3.5 | 11.07 | 5.3578 | 0.780528 | 22 |
| 17 | 1 | 2 | 1 | 1 | 0 | 1 | 4.3 | 10.13 | 5.3352 | 0.800798 | 19 |
| 18 | 1 | 2 | 2 | 2 | 1 | 2 | 3.9 | 7.32 | 5.2462 | 0.818791 | 12 |
| 19 | 2 | 0 | 0 | 2 | 2 | 1 | 2.6 | 9.06 | 5.1248 | 0.81532 | 13 |
| 20 | 2 | 0 | 1 | 0 | 0 | 2 | 2.2 | 11.45 | 5.4242 | 0.835588 | 10 |
| 21 | 2 | 0 | 2 | 1 | 1 | 0 | 4.1 | 8.41 | 5.103 | 0.803745 | 18 |
| 22 | 2 | 1 | 0 | 0 | 1 | 0 | 5.3 | 10.31 | 5.3196 | 0.806147 | 16 |
| 23 | 2 | 1 | 1 | 1 | 2 | 1 | 3.4 | 10.31 | 5.3248 | 0.808885 | 15 |
| 24 | 2 | 1 | 2 | 2 | 0 | 2 | 6.1 | 7.51 | 5.1308 | 0.803825 | 17 |
| 25 | 2 | 2 | 0 | 1 | 0 | 2 | 4.1 | 9.53 | 5.2522 | 0.852087 | 6 |
| 26 | 2 | 2 | 1 | 2 | 1 | 0 | 4.3 | 8.08 | 5.1888 | 0.811411 | 14 |
| 27 | 2 | 2 | 2 | 0 | 2 | 1 | 5.9 | 11.15 | 5.421 | 0.75124 | 26 |

Table 3: Response table for grey relational grade

| Process parameter | Symbol | Level 0 | Level 1 | Level 2 | Max-min | Rank |
|---|---|---|---|---|---|---|
| Injection pressure (bar) | A | 0.822218 | 0.817417 | 0.809805 | 0.012413 | 3 |
| Injection temperature ( °C) | B | 0.818695 | 0.817216 | 0.81353 | 0.005165 | 6 |
| Powder loading (% volume) | C | 0.827361 | 0.830983 | 0.791096 | 0.039887 | 1 |
| Mold temperature (°C) | D | 0.817745 | 0.812752 | 0.818944 | 0.006192 | 5 |
| Holding pressure (bar) | E | 0.830119 | 0.820952 | 0.79837 | 0.031749 | 2 |
| Injection speed (ccm/s) | F | 0.808979 | 0.819238 | 0.821224 | 0.012245 | 4 |

where n is the number of quality performance. The Grey Relational Grade (GRG) shows the correlation between the reference sequence and the comparability sequence. The evaluated GRG fluctuates from 0 to 1 and equals 1 if these two sequences are identically coincident. The GRG is ranked for each experiment. The higher GRG implies that the corresponding experimental result is closer to the ideal normalized value. In the other words, the larger the GRG, the better will be the multiple performance characteristic. Owing to the fact that experiment 14 has the highest GRG (0.920098), it has the best multiple performance characteristics among all experiments. The injection parameters are: (1) Injection Pressure, 450 bar; (2) Injection Temperature, 140°C; (3) Powder Loading, 64.5% Vol; (4) Mold Temperature, 45°C; (5) Holding Pressure, 900 bar; and (6) Injection Speed, 10 cm $s^{-1}$.

Table 3 shows the response table and graph of the GRG of each injection parameters at different level respectively. The response of the GRG shown in Table 3 indicates the powder loading, C is the most critical parameter for the best multiple performance characteristic, followed by the holding pressure (E), injection pressure (A), while the least important is the injection temperature (B). Although the injection pressure (A) and injection temperature (B) are not ranked as the first but they are still important to displace the melt into the mold cavity. Poor green compact appearance and density are predominantly resulted from the extreme injection pressure (A) and injection temperature (B). The influence of the extreme injection pressure (A) and injection temperature (B) has been discussed thoroughly from the rheological perspective of the feedstock by literatures (Jamaludin *et al.*, 2008; Jamaludin *et al.*, 2010; Mohamad Nor *et al.*, 2009).

The combination of the A0 B0 C1 D2 E0 F2 is the optimal combination of the injection parameter for the best multiple performance characteristics and the optimal parameter is as shown in Table 4. The Taguchi method can not only provide the solid suggestion in recommending the dominant parameter for single quality

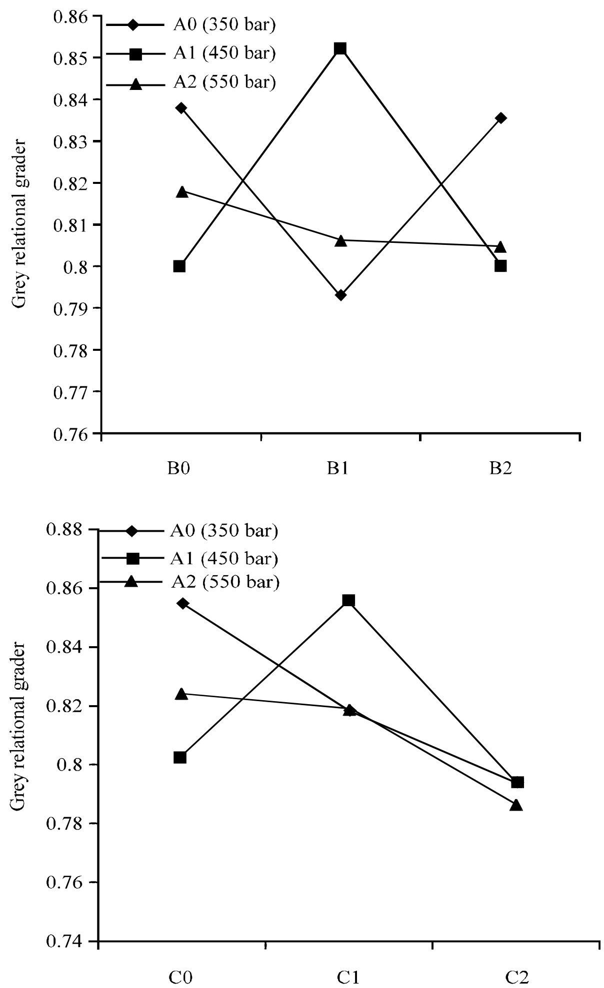


Fig. 1: The cross interaction between factors: Injection Pressure (A) Vs. Injection Temperature (B) and Powder Loading (C)

Table 4: Process performance at optimal parameter levels

| | |
|---|---|
| Injection pressure (bar) | 450 bar |
| Injection temperature (°C) | 140°C |
| Powder loading (% Volume) | 64.5%vol. |
| Mold temperature (°C) | 51°C |
| Holding pressure (bar) | 700bar |
| Injection speed (ccm/s) | 20ccm/s |
| GRG | 0.8789 |
| Upper and lower limit | 0.869844 <μ<0.887936 |

characteristics, but also offer an effective algorithm for clarifying the specific cross interaction between parameters. Consequently, the evaluated data can also be rearranged to indicate cross interaction between factors. Figure 1 illustrates the cross interaction between the injection pressure (A) versus injection temperature (B) and powder loading (C). As clearly shown in the figure, the factors had cross interaction between each other. The highest point indicates the optimum performance (A1×B1 and A1×C1). The cross interaction between the two parameters thus might mislead the regular Taguchi method recommendation and make it necessary to reconsider from a fresh perspective of optimizing the injection molding parameter. To further optimize the injection pressure, injection temperature and the powder loading, the highest Grey grade is to be considered and thus the new optimum injection molding parameter is A1B1 C1 D2 E0 F2.

A confirmation experiment is the last step for the Grey-Taguchi method to verify the improvement of the multiple performance characteristics at the optimal levels of selected injection molding parameters. The optimum combinations for the injection molding parameters combination were set and ten trials were conducted in the confirmation experiment and the result lies in the range of the optimum GRG. The optimum combination will be used for injection molded the green compact for the next process, debinding and sintering (Jamaludin *et al*., 2009b).

## CONCLUSION

Optimization of multiple MIM green compact quality performance using Taguchi method based Grey relational analysis was studied in this study. The calculation of the Grey relational grade helped to quantify the integrated quality performance required for the MIM green compacts. Accordingly, the optimum combination of the injection molding parameter to fulfill the requirement of the green part quality is A1B1 C1 D2 E0 F2 and the powder loading (C) is the most important parameter that needs to pay more attention during the injection molding process.

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