Parameter Optimization of WC-TaC-6Co Green Part in Injection Moulding using Taguchi Method

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Abstract. This study represents the injection moulding parameters optimization via Taguchi method on density and porosity of the green part of cemented carbide WC-TaC-6Co. The experiment commences with the preparation of WC-TaC-6Co feedstock mixed with 60 % palm stearin (PS), and 40 % of low-density polyethylene (LDPE). The important parameters for this study are the percentage of grain growth inhibitor (GGI), temperature of injection, injection pressure and injection speed. Utilizing orthogonal array L9(3^4), signal to noise ratio (S/N) was used to determine the significant levels and its contribution to the responses of density and porosity. The study signified that for density and porosity response, injection pressure and GGI is the most influential parameters. Based on that, it was found that the best parameter combinations for density and porosity is, GGI at 1.2 wt. %, temperature of injection at 155°C, injection pressure at 55% and 50%, and injection speed at 40% and 30%. Thus, it is determined that by controlling the setting of the best parameter, the optimal quality of the desired product can be accomplished and sustained without much complications during the process.

1. Introduction
Metal injection moulding (MIM) is a process of producing a near net-shape moulding products in which combining the procedure of both injection and powder metallurgy [1]. It is usually considered as a new processing technology used in powder metallurgy processing industries. This process is considerably beneficial and cost effective specifically for manufacturing large quantities of small parts and complex components. This process has a promising potential as in present time, most researchers implement this method in producing small and intricate part with better production cost [2-5]. During the process of injection moulding, several green parts were identified in terms of densities, tensile strength, defects such as shrinkage, and warpage among others. Adjustment of moulding process parameters in an intelligent way will lead to the acceptable way of maximizing or minimizing the characteristics required. Impartial optimization methods or the integration of it with other methods proposed a highly operative practices in finding the best development parameter values in which leads to least defects such as warpage, shrinkage, distortion and other associated defects [5-8].

Tungsten carbide (WC) is known as alloy with excellent combination of hardness and wear resistance. The average of its grain size usually is in between 0.2 μm and 20 μm and the normal
proportion of carbide phase is in between 70% to 97% of the total weight of the composite. Meanwhile, Tungsten carbide and Cobalt (Co) alloy are the most common hard phase and binder metal phase respectively. The underlying reasons for the main role of Cobalt are some of the exceptional properties of Co and the Co-W-C ternary system. It was known that the solubility of WC in Co is considerably high, and it varies strongly depending on the applied temperature. Moreover, the use of Co alloy in hard metals properties is controlled by crucial properties including the high hardness, yield stress, toughness, and strength of Cobalt [9]. The basic cemented carbide structure and grade are formed by the two stated materials, which is often based on this concept which referred to as the straight grades in a simplified term. Titanium Carbide (TiC), Tantalum Carbide (TaC) or Niobium Carbide (NbC) and others might successfully act as a grain growth inhibitor in cemented carbide.

Taguchi parameter design is a tool of importance for this robust design. The simple and systematic method of the design is vital in optimizing design for cost, performance and quality. In robust design, signal to noise ratio and orthogonal array are used as dominant tools. Signal to noise ratio (S/N) concentrate on determine quality with the stress on variation and orthogonal arrays, which simultaneously hold various design factors [10]. Design of experiment (DOE) technique contribution the researchers to identify the quality parameter which demands to be controlled. Based on the studies by Ji et al. [11], the investigation of the consequence of sintering factors on the properties of sintered part was found to be the main factors for their studies. Khairur et al. [12] on the other hand discovered the effects of injection parameters on the green part quality characteristics such as green density, strength and defects and utilized classical Design of Experiment (DOE) approach. The other researchers who have also used Taguchi as a channel to optimize their parameter are Ghani et al. [10], Ahmad et al. [13], Chen et al. [14], Tuncay et al. [15] as well as Oktem et al. [16].

2. Methodology

2.1. Starting Materials

WC-6%Co were used as the main metal powder combined with 0.4 wt. %, 0.8 wt. % and 1.2 wt. % of TaC as Grain Growth Inhibitors. The characteristics of the metal powder is as illustrated in Table 1.

| Powder          | WC-Co                  | TaC                  |
|-----------------|------------------------|----------------------|
| Manufacturer    | US Research Nanomaterials, Inc. | US Research Nanomaterials, Inc. |
| Grain Size      | 40-80 nm               | 950 nm               |
| Morphology      | Nearly spherical       | Cubic                |
| True Density    | 14.7 g/cm³             | 13.9 g/cm³           |

A multicomponent binder system was utilized in preparing the feedstock. The characteristics of the binder components are as stated in Table 2. In this study, major fraction (60%) of the binder system consists of palm stearin (PS) and minor fraction (40%) consists of polyethylene (LDPE).

| Type            | Density (g/cm³) | Melt Temperature (°C) | Decompose Temperature (°C) |
|-----------------|-----------------|------------------------|-----------------------------|
| Palm Stearin    | 0.891           | 54.3                   | 398.5 – 598.8               |
| LDPE            | 0.95            | 127                    | 389.6 – 501.6               |

Figure 1 and Figure 2 shows the powder microstructure for WC-6Co and TaC that was evaluated via Scanning Electron Microscopy (SEM). From the SEM, the powder particles for WC-6Co and TaC are exhibit irregular shapes and some agglomerations.
2.2. Feedstock Preparation
In this study, Brabender Plastograph mixer is used to mix the composition of WC-6Co-TaC with the powder loadings of 43%. The duration taken for this process is 1 hour at 140 ºC and 40 rpm of speed until a homogenous mixture was obtained. Shimadzu is used to perform the rheology analysis of the feedstock to identify which flow characteristics of the feedstock are suitable for injection processes. Nissei NP7-1F type are chosen as the injection moulding machine.

2.3. Design of Experiment (DOE)
In this research, L9 (3^4) orthogonal array which consists of 4 columns and 9 experiment trials are utilized as DOE with four parameters involved are GGI (A), injection temperature (B), injection pressure (C), and injection speed (D). Table 3 and 4 present Taguchi’s orthogonal array which demonstrates the parameter of this study. There are 27 samples for 9 trials were injected to be tested.

Green strength optimization in MIM is a significant process as it focuses on investigating the performance and superiority of the green part. The data of signal to noise ratios were obtained by using Statistical software-Minitab version 16. In line to achieve the optimal factors, the signal to noise response graph were constructed to determine the highest level based on density and porosity. The optimum value of the SN ratio stipulates the best setting for the selected factors. The ranks of the most prominent factors have also been obtained from the software.

For an engineering analysis, S/N ratio characteristics normally can be divided into three; the smaller-the better, the nominal-the better, and the larger-the better. In this study, the smaller-the better and larger-the better are used to find the optimal parameters.
Table 3. Injection Parameters of Taguchi Design

| Level | GGI (%) | Injection Temp. (°C) | Injection Pressure (%) | Injection Speed (%) |
|-------|---------|----------------------|------------------------|---------------------|
| A     | 0       | 0.4                  | 145                    | 45                  | 30                  |
| B     | 1       | 0.8                  | 150                    | 50                  | 35                  |
| C     | 2       | 1.2                  | 155                    | 55                  | 40                  |

** Unit conversion: 1 % of injection pressure equal to 1.61 MPa, 1 % of injection speed equal to 3.50 rpm

Table 4. Orthogonal Array (OA)

| Level / Trials | GGI (%) | Injection Temperature (°C) | Injection Pressure (%) | Injection Speed (%) |
|----------------|---------|---------------------------|------------------------|---------------------|
| A              | 0.4     | 145                       | 45                     | 30                  |
| B              | 0.4     | 150                       | 50                     | 35                  |
| C              | 0.4     | 155                       | 55                     | 40                  |
| D              | 0.8     | 145                       | 50                     | 40                  |
| E              | 0.8     | 150                       | 55                     | 30                  |
| F              | 0.8     | 155                       | 45                     | 35                  |
| G              | 1.2     | 145                       | 55                     | 35                  |
| H              | 1.2     | 150                       | 45                     | 40                  |
| I              | 1.2     | 155                       | 50                     | 30                  |

The deficiencies of the composite including the porosity, shrinkage and warpage, unwanted particulates in the deposition process were determined by the Taguchi’s method implementing S/N ratio for smaller-the-better quality. The logarithmic function which is mainly constructed through the mean square deviation [12] derived from the equation which is used to calculate the signal-to-noise ratio for the smaller-the-better quality characteristics of the composite. The S/N ratio equation:

\[ S/N = -10 \log MSD \]

The equation mean square deviation for a smaller-the-better characteristic can be written as:

\[ MSD = \frac{y_1^2 + y_2^2 + \ldots + y_n^2}{n} \]

The S/N equation can be written as:

\[ \frac{S}{N} = -10 \log \left( \frac{y_1^2 + y_2^2 + \ldots + y_n^2}{n} \right) \]

Meanwhile, Taguchi’s S/N-Ratio for larger-the-better quality characteristics is applied for a desired output such as strength and critical current. The equation for the signal-to-noise ratio for the larger the better quality characteristic is written and applied similar to the smaller-the-better S/N formula [12]. The equation applied for the larger-the-better mean square deviation is written as follows:

\[ MSD = \frac{1/y_1^2 + 1/y_2^2 + \ldots + 1/y_n^2}{n} \]
The larger-the-better S/N equation can be written as:

\[
\frac{S}{N} = -10 \log \left( \frac{1/y_1^2 + 1/y_2^2 + \cdots + 1/y_n^2}{n} \right)
\] (5)

3. Result and Discussion

3.1. Density and Porosity Results

The performance and capabilities to obtain superior green part was investigated through green strength optimization in MIM process. The data of signal to noise ratios were attained to achieve the optimized factors by via Statistical software-Minitab version 16. The data obtained from the density and porosity which can be used to interpret the optimal level from the four factors and three levels by constructing the signal to noise response graph. The highest value of the SN ratio indicates the best setting for the selected factors. From the software, the ranks of the most influential factors successfully achieved.

The density and porosity of the samples were measured by using Archimedes method based on Metal Powder Industries Federation (MPIF) Standard 42 [17]. Figure 3 shows the experimental results for density where the optimum parameter will be based on the highest peak at each parameter. For the result, the optimal configuration for obtaining optimal density for green part would be A3 (1.2 wt. % of GGI), B3 (155 °C of injection temperature), C3 (55% of injection pressure) and D3 (40% of injection speed), respectively. The conditions were explained as below:

i. The injection temperature (B) selected must be sufficient to encourage smooth flow of the molten feedstock. This is due to the fact that the viscosity behaviour will be depended on the selected temperature, where high temperature of the feedstock will defer initial freezing at the early stage of the process before it fills up the cavity [1].

ii. Injection pressure (C) will largely affected the final properties as it has an imperative rule of increasing the green density of the samples. However, inappropriate selection of injection pressure will eventually leads to powder binder separation, thus leading to defected end product [1].

iii. Injection speed (D) is used as one of the parameter in producing good quality green parts. The ram will push the feedstock into cavity to fill up the mould with variable speed.
Figure 4 shows the main effects plot (data means) for S/N ratio for porosity where at each parameters, the optimal parameter is based on the highest peak. It was found that the optimum configurations for optimal density selection for green part was found in samples A\(_3\), B\(_3\), C\(_2\) and D\(_1\). It was inferred as 1.2 wt. % of GGI percentage (A), 155 °C of injection temperature (B), 50% of injection pressure (C) and 30% of injection speed (D). This is because the presences of pores will create voids between the particles that is considered as in the green body and will significantly reduce sintered strength. It was found that the GGI percentage and injection temperature resulted in the highest mean ratio. The selection of GGI at high percentage together with high injection temperature will act to cover smaller pores in the green part. The selection of high heat will facilitate in producing a defect-free green part by covering the pores. As the smaller pores filled the void, the size of pores will increase which lead to reduction of the porosity in the samples. This led to increment of the bulk density which improved the hardness value as the porosity volume fraction decreased [18]. Generally, the injection pressure and injection speed provide a moderate effect on the porosity response.

![Main Effects Plot for SN ratios](image)

**Figure 4.** Main effects plot (data means) for S/N ratio for porosity of green part

4. Conclusion
The objectives of this study were successfully achieved. Many factors might be affected the performance of quality of products and processes in Taguchi’s orthogonal array. Based on the results, it is concluded that for nominal density, the optimum parameters to be used are, GGI (1.2 wt. %), injection temperature (155°C), injection pressure (55%) and injection speed (40%). For ideal situation of this study, smaller-the-better was used to determine the least porosity in the green part. The best parameter that have been found is GGI (1.2 wt. %), injection temperature (155°C), injection pressure (50%) and injection speed (30%). Based on the findings, it is concluded that by controlling the optimum parameter setting, the optimum quality product desired can be continuously produced. The input from this research is hoped to be useful for further testing to be done in the future.

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