

Defects Optimization of Green Part Ti-6Al-4V with Palm Stearin Binder using Response Surface Methodology



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ABSTRACT: Metal Injection Moulding (MIM) is an effective near-net-shape process for producing small, intricate parts in high volumes. Many optimizations of the MIM process parameter have been published without using any of the statistical based Design of Experiment (DOE) methodology and ends with unsatisfactory results in a wide range of experimental settings. This paper focuses on analysing the optimization of injection moulding process parameters for titanium alloy Ti-6Al-4V green parts using response surface methodology (RSM) to determine significant parameters. The feedstock is prepared by mixing Ti-6Al-4V powder with palm stearin (PS) and polyethylene (PE) binders in three different powder loadings: 63 vol%, 65 vol%, and 67 vol%. RSM is then used to create a Design of Experiment (DOE) to optimize parameters, including A: injection pressure, B: injection temperature, C: powder loading, D: mould temperature, and E: holding pressure. Analysis of variance (ANOVA) was performed to identify the significant parameters influencing defects in Ti-6Al-4V green parts. The study successfully identified the optimal conditions for producing Ti-6Al-4V components using PS and PE binders: A: 443.139 bars, B: 142.11 °C, C: 65.38 vol.%, D: 44.694 °C, and E: 629.561 bar. Scanning electron microscopy (SEM) from optimised of green part shows that the primary backbone polymer PE holds the green part and generates wetting for the feedstock and will ease moulding and shaping while the secondary backbone PS will act as a soft polymer that can provide the moisture to the feedstock.

KEYWORDS: Metal Injection Moulding, RSM, Defects, Ti-6AL-4V, green part

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I. INTRODUCTION

Metal Injection Moulding (MIM) is recognized as an effective method for reducing manufacturing costs while maintaining high-quality standards. It offers numerous significant advantages, particularly for the large-scale, efficient production of near-net-shape components, making it an increasingly popular choice in various industries (Singh et al., 2021b; Su et al., 2023). MIM not only enhances production efficiency but also significantly reduces the need for extensive machining and minimizes material waste, which are crucial for cost savings and environmental sustainability. The MIM process consists of four primary stages: material blending, injection moulding, binder removal, and sintering (Ali and Ahmad, 2020; Pandey et al., 2020). It starts with the blending of fine metal powders, typically titanium and its alloys, which are carefully selected for their particle size, generally in the micrometre range. These powders are mixed with binders in specific ratios to form a homogenous feedstock. This blending stage is essential, as the quality of the feedstock directly impacts the final component's integrity and performance.

Binders play a critical role in the MIM process as they act as lubricants during injection, ensuring a smooth flow of material, evenly coat the metal particles, and fill any voids between the powder particles. This helps in achieving a uniform and dense packing, which is vital for the strength and quality of the final product (Askari et al., 2019; Momeni et al., 2019). Polyethylene (PE) is commonly used as a binder due to its effective properties which make it highly suitable for providing structural cohesion and stability to composite materials.

However, alternatives like Palm Stearin (PS) are increasingly being utilized in multi-component binder systems for their environmental benefits and efficacy (Nor et al., 2013; Jamaludin et al., 2014; Li et al., 2014). Once the feedstock is prepared, it is introduced into a hopper, initiating the injection moulding process. This stage is governed by several key parameters, including injection pressure, temperature, powder loading, mould temperature, and holding pressure. The feedstock is then injected into a precisely designed mould cavity, forming what is known as a "green part"—a component that contains both metal and binder materials (Mohamad Nor et al., 2018; Askari and Momeni, 2021; Singh et al., 2021a).

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This study focuses on the injection of moulded parts using a mixture of Ti-6Al-4V powders with PE and PS, aiming to produce defect-free components. Since Ti-6Al-4V is a highly alloyed material, the mechanical and contamination properties are a concern. Therefore, a high final density is important for optimization of the desirable attributes. Among the four MIM processing steps, injection process is the most important step that affects the final density as well as the mechanical properties.

Previous studies (Mohamad Nor et al., 2011 and Nor et al., 2010) have shown that the important factors of the injection process are: injection pressure, injection temperature, powder loading, mould temperature and holding pressure. These factors can affect the microstructure, final density, and quality of sintered part. These in turn influence the mechanical properties of the sintered parts. An understanding of the effects of the injection factors on the quality of green part can be used further to optimize the sintering process.

The traditional approach to experimental work is to vary one factor at a time, holding all other factors fixed. This method does not produce satisfactory results in a wide range of experimental settings. By optimizing process parameters and selecting suitable materials, these defects can be minimized, ensuring high-quality production outcomes. Additionally, this paper explores the use of Response Surface Methodology (RSM) to analyse and characterize the optimal green part. The technique involves optimizing injection moulding parameters to achieve the best results (Pereira, Milan and Tapia-Blácido, 2021).

In this study, Design of Experiment (DOE) within Response Surface Methodology (RSM) was utilized to optimize the injection parameters. Researchers have utilized Response Surface Methodology (RSM) in the Metal Injection Moulding (MIM) process to optimize various parameters like binder composition, temperature, pressure, and sintering conditions. Sulaiman et al. (2016) optimize the parameters of the MIM process, such as feedstock preparation, injection moulding, and debinding. They investigated how the feedstock composition (metal powder and binder ratios) and processing conditions affect the density and mechanical properties of the final sintered parts. Raza et al. (2020) focused on using RSM to optimize sintering parameters for titanium-based MIM components. They explored how sintering temperature, holding time, and heating rate impact the density and shrinkage of MIM parts. Their study demonstrated how RSM could be applied to minimize defects such as porosity and distortion. Zhang et al. (2014) applied RSM to optimize injection moulding parameters like injection temperature, pressure, and time to minimize defects such as warping and incomplete filling in stainless steel MIM parts. Their work highlights the efficiency of RSM in determining the optimal combination of process parameters. Additionally, Analysis of Variance (ANOVA) was employed to identify the contributing factors influencing the quality characteristics (Huang et al., 2022; Sundaraselvan et al., 2023).

Through ANOVA analyses, it's possible to predict the optimal combination of process parameters. Subsequently, a confirmation experiment is carried out to validate the optimal process parameters obtained from the parameter design

(Santhosh et al., 2021). Common defects encountered during the MIM injection process include weld lines, flashing, jetting, and binder separation, which can affect the structural integrity and appearance of the final product (Mohamad Nor et al., 2011). Therefore, optimizing process parameters such as injection pressure, temperature, and powder loading is crucial to achieving high-density and defect-free parts.

II. MATERIAL AND METHODOLOGY

A. Characterization of Material

The Ti-6Al-4V metal powder utilized in this study was gas atomized powder supplied by TLS Technik GmbH. Table 1 presents the characteristics of the powder, while Table 2 outlines its chemical composition. Figure 1. shows the morphology of the Ti-6Al-4V alloy powder. The particles are spherical, with a pycnometer density of 4.38 g/cm³. The binder system employed in this study consisted of Palm Stearin (PS) as a primer binder and Polyethylene (PE) as a backbone binder, with a binder weight fraction ratio of PS:PE set at 60:40.

Table 1: Characteristics of Ti-6Al-4V Powder

Particle shape	Sphere
Size	<22 μm
Pycnometer Density	4382.7 kg/m ³
Melting	1650 °C

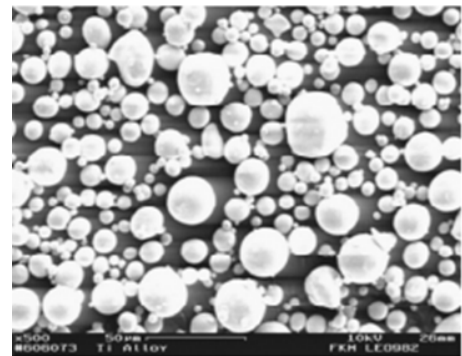


Figure 1: Scanning electron micrograph showing the morphology of the Ti-6Al-4V

Table 2: Chemical Composition of Ti-6Al-4V powder

Al	V	C	Fe	O	N	H	Ti(wt%)
5.99	4.08	0.005	0.043	0.185	0.004	0.002	Bal

B. Binder

In this study, the binder comprises PS as the primary binder and PE as the secondary binder or backbone. PS is a potential binder system due to its low cost and high availability in Malaysia. Other advantages of palm stearin include providing capillary pores to remove backbone binder during thermal debinding (Arifin et al., 2015). It is believed to be a viable

binder component because it contains fatty acids, which are commonly used as surface active agents in many binders. The density of PS utilized was 0.891 g/cm³, while that of PE was 0.91 g/cm³. The composition of the binder, consisting of 60% PS and 40% PE, was determined based on mass percentage. This composition was selected due to its stability, as demonstrated in a previous study by Omar et al. (2011), which employed the binder with spherical powder of 316L stainless steel.

C. Feedstock Preparation

Three different powder loadings of feedstock were prepared, namely 63, 65, and 67 vol.%. The spherical Ti-6Al-4V particles with a density of 4.38 g/cm³ were mixed with 60 wt% PS and 40 wt% polyethylene (PE). This mixture was processed in a sigma blade at 150 °C for 1 hour. The resulting feedstock was injected using a Battenfeld BA 250 CDC injection moulding machine (Nor et al., 2010).

D. Injection Moulding Process

Injection was executed using the Battenfeld BA 250 CDC injection moulding machine. The injected body takes the form of a tensile bar, as illustrated in Figure 2. The injection process began once the preset parameters were achieved. Each combination of parameters was tested with a single sample injection (Jamaludin et al., 2015).



Figure 2: Dimension of Tensile bar (mm)

E. Response surface methodology (RSM)

RSM is a set of mathematical and statistical methods used to design, improve, and optimize complex problems using stochastic models (Hwang et al., 2016; Balajii and Niju, 2021). Central composite design (CCD) is a response surface method used to develop a second-order (quadratic) model for a response variable without needing a full three-level factorial experiment. It is widely used for formulation and process optimization in injection moulding. A CCD includes an embedded factorial or fractional factorial design (two levels) with centre points, enhanced by axial (star) points created through screening analysis, which enable the estimation of surface curvature in the resulting model (Darwish et al., 2021). Central composite design (CCD) has several advantages over other statistical designs, including desired properties such as orthogonality, rotatability, and uniformity. It provides high-quality predictions across the entire design space with a low number of experimental runs, making it suitable for injection moulding development (Latha et al., 2017). The main objective of this paper was to fit quadratic mathematical models and analyse the results obtained from injection moulding of the green part. It aimed to investigate the defects and interactions of each parameter. Therefore, Injection Pressure (A), Injection

Temperature (B), Powder Loading (C), Mould Temperature (D), and Holding Pressure (E) were considered as the factors during the CCD process.

Table 3 presented five variables at three levels used in the CCD for the injection moulding process of the green part. The two levels, low and high, were represented as -1 and 1, respectively. The values for the five variables, shown in Table 3, were designed using CCD with the objective of optimizing defects. Using regression techniques, second-order polynomial mathematical models for optimizing defects have been established, as shown in the Equation 1 (Veza et al., 2023).

$$Defect = \beta_0 + \beta_1A + \beta_2B + \beta_3C + \beta_4D + \beta_5E + \beta_6AD - \beta_7AE - \beta_8BC + \beta_9BE + \beta_{10}CE + \beta_{11}A^2 + \beta_{12}B^2 + \beta_{13}C^2 + \beta_{14}D^2 + \beta_{15}E^2 \quad (1)$$

Table 3: Factors and level

Level	Injection pressure (bar) A	Injection Temp (°C) B	Powder Loading (vol%) C	Mould Temp (°C) D	Holding Pressure (bar) E
-1	350	130	63	40	500
1	550	150	67	50	700

F. Analysis of variance

In the study, the defect of the green part was considered the response. A prediction model for the defect of the green part was created using the least squares method and established based on ANOVA (analysis of variance). ANOVA was used to analyse the regression equation and identify the interactions between the variables and the response. Then, the desirability function was used to determine the optimal levels of each independent variable to achieve the minimum defect rate of the green part as shown in Table 4.

Table 1: Rating for defects











Defects	Rating
Weld lines	1
Incomplete filling	3
Binder separation	0.5
Binder burnout	0.5
Green broken during mould opening	3
Slumps	3
Deflection	3
Chipping at gate	2
Flashing	0.5
Green broken during ejection	3

Table 5 show the example of defect green part during injection moulding. Table 6 displayed the total of 29 runs predicted by ANOVA, designed to investigate the effects of the five independent variables on the response (Bayuo el al., 2020). The Design Expert software conducts statistical optimization, primarily using RSM to optimize operating parameters in the injection moulding process. Table 4 shows the classification of rating for the defects of green part.

Regression analysis using the least squares method was performed on the results, and the prediction model for optimize defect was determined as shown in Equation 2. Where, defect was the response; A, B, C, D, E represented the five independent variables, respectively.

$$Defect = 1.7 + 0.2083A + 0.0833B + 0.2917C + 0.1250D + 0.2083E + 0.25AD - 0.1250AE - 0.1875BC + 0.1250BE + 0.125CE + 1.19A^2 + 0.5027B^2 + 0.6902C^2 + 0.2527D^2 + 0.2527E^2 \quad (2)$$

Table 5: Example of defects of green part

				
Weld lines	Incomplete filling	Binder separation	Binder burnout	Green broken during mould opening
				
Slumps	Deflection	Chipping at gate	Flashing	Green broken during ejection

To validate the effectiveness of the regression equation and the impact of different variables on the defect, variance analysis was employed to analyse the regression equation. Table 6 presented the ANOVA results for the injection moulding process of the green part regarding the calculated defect results. From Table 7, the high F-value and low P-value indicate that the established regression model was statistically significant with a confidence level of 95%, suggesting that the model's level of accuracy was high (Hossain et al., 2019). The lack of fit's P-value being greater than 0.05 suggests that the degree of mismatch is not significant. Additionally, the regression model shows stability and validity, as the predicted R-squared value matches the adjusted R-squared value. Furthermore, all values of determination (R-squared), adjusted R-squared, and predicted R-squared are greater than 0.9, indicating a strong correlation between the independent variables and the response defect rating (Asfaram et al., 2019).

In addition to the regression model, the effects of independent variables and their interactions on the defect of the

green part were also analysed through ANOVA. Based on Table 7, considering the F-values, all five variables had a significant impact on the defect of the green part. The order of influence was observed as injection pressure and powder loading being the most influential, followed by holding pressure, mould temperature, and injection temperature. The interaction effects of different combinations of independent variables were also assessed. Additionally, as indicated in Table 7, certain combinations, such as injection pressure and mould temperature, injection pressure and holding pressure, injection temperature and powder loading, injection temperature and holding pressure, as well as powder loading and holding pressure, showed greater significance in minimizing defects compared to other treatment combinations. Moreover, the square effects of injection pressure, powder loading, mould temperature, and holding pressure also significantly contributed to reducing defects.

Table 2: Result injection moulding for defects

Run	Injection pressure (bar)	Injection Temperature (°C)	powder loading (Vol%)	Mould Temperature (°C)	Holding Pressure (bar)	Defect Rating
	A	B	C	D	E	
1	550	130	67	50	500	5.5
2	450	160	65	45	600	4
3	450	140	65	35	600	2.5
4	350	150	63	50	700	4.5
5	350	150	63	40	500	4
6	450	140	65	45	600	1.5
7	550	150	63	40	700	4.5
8	350	130	63	50	500	3.5
9	450	140	65	55	600	3
10	350	130	63	40	700	4
11	550	150	67	50	700	5.5
12	550	130	63	40	500	4
13	450	140	65	45	600	1.5
14	350	150	67	50	500	4
15	550	130	63	50	700	4.5
16	450	140	65	45	800	3
17	450	140	65	45	600	2
18	350	130	67	50	700	5
19	450	140	65	45	400	2.5
20	350	130	67	40	500	4.5
21	550	150	63	50	500	5
22	650	140	65	45	600	7
23	350	150	67	40	700	5.5
24	550	150	67	40	500	4
25	450	140	69	45	600	5
26	450	120	65	45	600	3.5
27	250	140	65	45	600	6
28	550	130	67	40	700	5
29	450	140	61	45	600	4

Table 7: ANOVA of defects

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	47.51	15	3.17	77.83	< 0.0001	significant
A-Injection Pressure	1.04	1	1.04	25.6	0.0002	
B-Injection Temperature	0.1667	1	0.1667	4.1	0.064	
C-Powder Loading	2.04	1	2.04	50.17	< 0.0001	
D-Mold Temperature	0.375	1	0.375	9.22	0.0096	
E-Holding Pressure	1.04	1	1.04	25.6	0.0002	
AD	1	1	1	24.58	0.0003	
AE	0.25	1	0.25	6.14	0.0277	
BC	0.5625	1	0.5625	13.82	0.0026	
BE	0.25	1	0.25	6.14	0.0277	
CE	0.25	1	0.25	6.14	0.0277	
A ²	34.75	1	34.75	854.1	< 0.0001	
B ²	6.2	1	6.2	152.37	< 0.0001	
C ²	11.69	1	11.69	287.23	< 0.0001	
D ²	1.57	1	1.57	38.51	< 0.0001	
E ²	1.57	1	1.57	38.51	< 0.0001	
Residual	0.529	13	0.0407			
Lack of Fit	0.3623	11	0.0329	0.3953	0.8752	not significant
Pure Error	0.1667	2	0.0833			
Cor Total	48.03	28				

IV. RESULTS AND DISCUSSION

A. Interaction effect of different variables

To better understand the effects of different independent variables and their interactions on defect optimization, three-dimensional response surface contours depicting two variables were presented in Figure 3 to Figure 7. These figures illustrated the interaction effects of injection pressure and mould temperature, injection pressure and holding pressure, injection temperature and powder loading, injection temperature and holding pressure, and powder loading and holding pressure, respectively.

1) Effect of injection pressure

In order to ensure full filling and components free of defects, injection pressure is essential for pushing molten plastic into the mould cavity. Excessive injection pressure can cause a number of problems, including flash, which is the formation of thin, undesired layers on the component when surplus material exits the mould cavity through parting lines or ejector pins. In addition, it may result in surface flaws, overpacking, elevated residual stress, and mould damage. Mould deterioration can result in cracked or worn-out mould components, which raises maintenance expenses. Warping, cracking, or component failure during or after ejection from the mould can be caused by an increase in residual stress. Parts that are thick and heavy from overpacking may have sink marks and distortion as a result of uneven cooling.

On the other hand, inadequate injection pressure can result in sink marks or voids because the material is unable to sufficiently adjust for shrinkage during cooling, leaving hollow or depressed regions, and incomplete filling (short shots), where the component is not entirely formed (Wang et al., 2022). Additionally, because of inadequate packing of the molten material against the mould surface, it may result in a poor surface quality and uneven or rough textures. Low pressure can cause dimensional instability, which can result in pieces that are too tiny or shaped incorrectly, as well as weld lines and weak places where two flow fronts meet and do not entirely fuse.

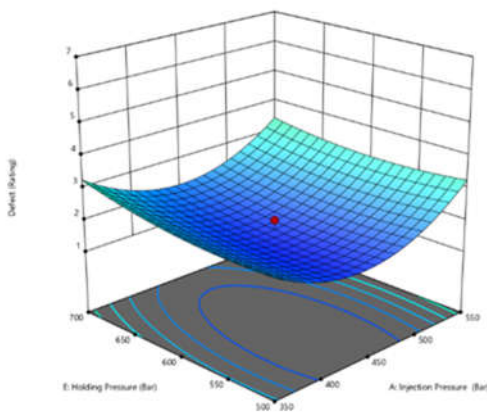


Figure 3: Interaction injection pressure and holding pressure

Figure 3 and Figure 4 demonstrate how crucial it is to optimise injection pressure in order to ensure consistent mould filling, appropriate material flow, low internal stresses, and high-quality products. A full and uniform filling of the mould cavity, sufficient packing to account for shrinkage of the material, reduced internal stresses and warping, superior surface smoothness, and dimensional correctness are all guaranteed by a properly balanced injection pressure. The ideal injection pressure must be carefully calibrated and monitored in order to produce products free of defects throughout the injection moulding process.

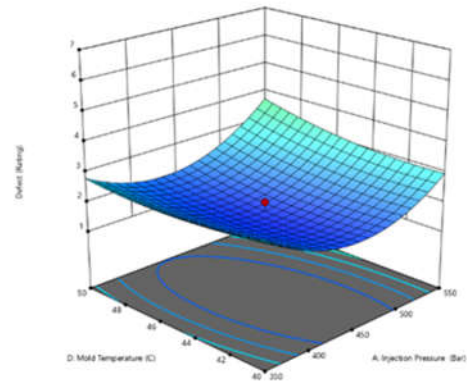


Figure 4: Interaction injection pressure and mould temperature

2) Effect of mould temperature

The final product's quality and quantities are largely determined by the temperature of the mould during the injection moulding process. Its main job is to control how quickly the molten plastic within the mould cavity cools down. Elevated temperatures in the mould can cause many flaws, such as warping, prolonged cooling periods, the development of flash, surface imperfections like burns or splay marks, and a greater amount of component shrinkage. On the other hand, low mould temperatures can lead to poor surface quality, increased brittleness, dimensional instability, inadequate filling of the mould cavity, and longer cycle durations overall. Achieving the ideal mould temperature balance is essential to guaranteeing consistent cooling, reducing internal tensions, and maximising component characteristics. The injection moulding process needs careful calibration and adjustment to prevent flaws and reliably yield high-quality products (Wu et al., 2019). Manufacturers may attain exact results, improving product quality and performance while optimising manufacturing efficiency, by precisely regulating the temperature of the mould. The interplay between injection pressure and mould temperature occurs to minimise the fault of the green component, as shown in Figure 4. As a result, controlling mould temperature is essential to the success of injection moulding processes as it affects both the efficiency of production and the quality of the final product (Liparoti et al., 2019).

3) Effect of holding pressure

Holding pressure has a major effect on the quality of the result in injection moulding; faults can arise from both excessive and inadequate pressures. Because the material is pushed into the mould too forcefully, high holding pressure can cause flash, overpacking, higher residual stress, surface defects, and longer cooling periods. On the other hand, inadequate material packing causes inferior mechanical qualities, sink marks, voids, inadequate surface polish, dimensional instability, and incomplete filling (short shots). It's critical to optimise the holding pressure according on the particular material, component shape, and mould design in order to prevent these problems.

In addition to compensating for material shrinkage, minimising internal tensions and warping, and maintaining ideal cycle durations without sacrificing component quality, proper balance also assures complete and uniform mould filling. Determining the optimal holding pressure for a high-quality, error-free injection moulding process requires careful calibration and testing (Wu et al., 2019). Figure 4 and Figure 5 demonstrate how the parameters that control holding pressure and other parameters interacted. Therefore, maintaining pressure is essential during injection moulding to produce a green component free of defects.

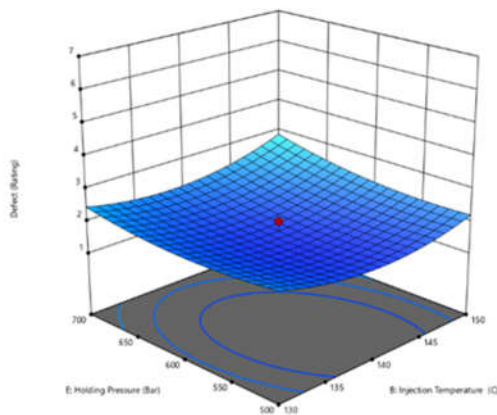


Figure 5. Interaction injection temperature and holding pressure

4) Effect of injection temperature

Figure 6 shows Injection temperature is a critical parameter in injection moulding, serving multiple essential functions in the process. It facilitates efficient material flow by ensuring the molten plastic reaches its optimal viscosity for filling intricate mould cavities accurately. Moreover, injection temperature plays a crucial role in maintaining the desired material properties, preventing premature degradation or overheating that could compromise the mechanical strength and structural integrity of the final product. Additionally, it influences the cooling rate of the plastic material within the mould, directly impacting the overall cycle time and part quality. However, deviations in injection temperature can result in various defects in the moulded product. Excessive injection temperature may

lead to material degradation, burn marks, flash formation, and extended cooling times, diminishing mechanical properties and manufacturing efficiency. Conversely, insufficient injection temperature can cause incomplete filling, poor surface finish, and increased internal stresses, leading to compromised part integrity and dimensional accuracy (Wang et al., 2022).

To mitigate these issues and ensure high-quality, defect-free parts, precise calibration and monitoring of injection temperature parameters are essential. By carefully adjusting and controlling the injection temperature, manufacturers can optimize material flow, maintain proper material properties, and regulate cooling rates effectively. This meticulous approach enables consistent production of parts with the desired quality standards while maximizing manufacturing efficiency. Thus, injection temperature management stands as a critical aspect of the injection moulding process, influencing both product quality and production performance.

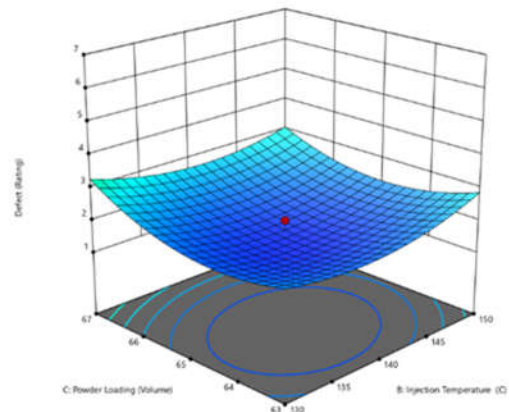


Figure 6: Injection temperature and powder loading

5) Effect of powder loading

When referring to the concentration of solid particles combined with a binder to create a feedstock for injection moulding, powder loading is important since it influences the material qualities and features of the finished product (Ali and Ahmad, 2020). According to the Figure 7, different powder loading levels 63%, 65%, and 67% by weight affect the moulded parts in various ways. At 63%, the feedstock has fewer solid particles, resulting in parts with lower density but potentially better flow properties. At 65%, there's a balance between density and flow, providing moderate mechanical strength and density, which is suitable for many applications. At 67%, the density and mechanical strength of the parts are higher, but the increased viscosity can make flow more difficult (Hnatkova et al., 2019). The powder loading choice is guided by specific application needs, enabling manufacturers to adjust feedstock composition for the best material properties and performance in the final moulded parts.

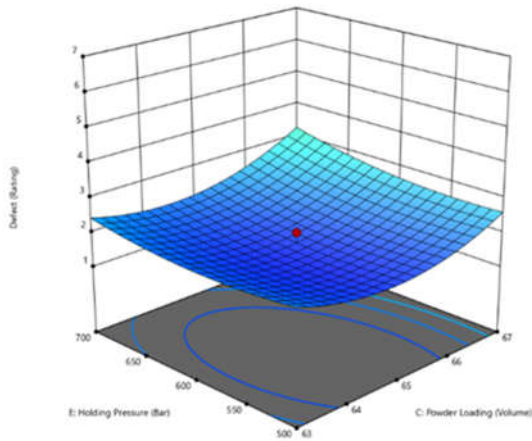


Figure 7: Interaction Powder loading and holding pressure

B. Optimal variable for defect optimization

The validity of the variant analysis that has been conducted was established through validation experiments. Ten green part samples that were injected using the parameters in Table 8 were used for validation experiments, and the green part's defect score was calculated. Table 9 indicates that the defect score value is within the optimal range. Figure 4 provides an example of a green part that is injected using the optimal parameters for a validation experiment on the green part's defect.

Table 3: The defects optimize value.

Injection pressure (bar)	Injection Temperature (°C)	powder loading (vol%)	Mould Temperature (°C)	Holding Pressure (bar)
A	B	C	D	E
443.14	142.11	65.38	44.69	629.56

Table 4: Result of validation experiment for defects of green part.

Experiment defects	1	2	3	4	5	6	7	8	9	10
Score	2	3	2	2.5	2	2	3	2.5	1.5	2

1) SEM Morphology of feedstocks

The optimised green part's morphology, made up of PS and PE, is shown in Figure 8. It demonstrates how the powder particles are evenly dispersed by the binder. The binding material is equally coating the powder particles as shown by the green portion that is formed. To facilitate moulding and shape, the initial backbone polymer, PE, was utilised to hold the green portion and produce wetness for the feedstock. The second PS backbone serves as a soft polymer that can give the feedstock moisture. For the subsequent debinding step, the PS

aids in creating a capillary pathway to the feedstock. The PE and PS polymer framework encircling the Ti-6Al-4V particle is clearly seen in Figure 9. The optimised green part shows no

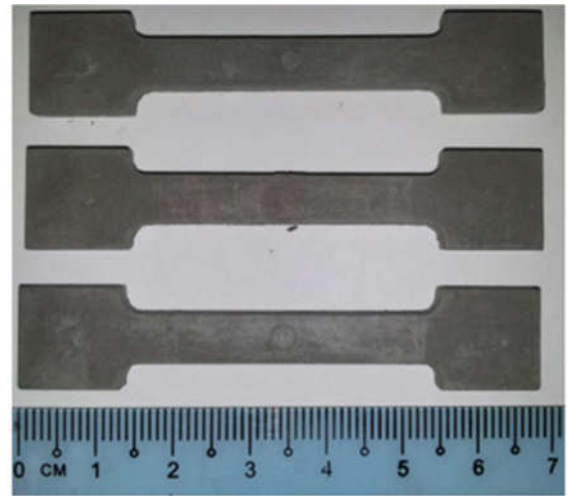


Figure 8: Example of green part injected using optimum parameter

powder-binder separation occurs, which can be attributed to the strong adhesion and excellent surface contact between the binder and the metal powder particles. This good contact ensures that the metal particles are uniformly coated and tightly held together, preventing issues like cracking, distortion, or damage during subsequent stages such as injection moulding, debinding, and sintering (Momeni et al. 2019). Adequate binder-powder interaction is crucial because it facilitates consistent material flow during moulding and prevents defects such as delamination or powder segregation, which could compromise the structural integrity and mechanical properties of the final component.

Furthermore, a well-formed binder-powder matrix ensures even shrinkage during sintering, reducing the likelihood of defects like warping or uneven density distribution in the final product. In this context, optimizing the binder composition and mixing conditions is essential to achieving a defect-free feedstock, as strong powder-binder cohesion plays a critical role in determining the quality and performance of the sintered parts (Zhang et al. 2014).

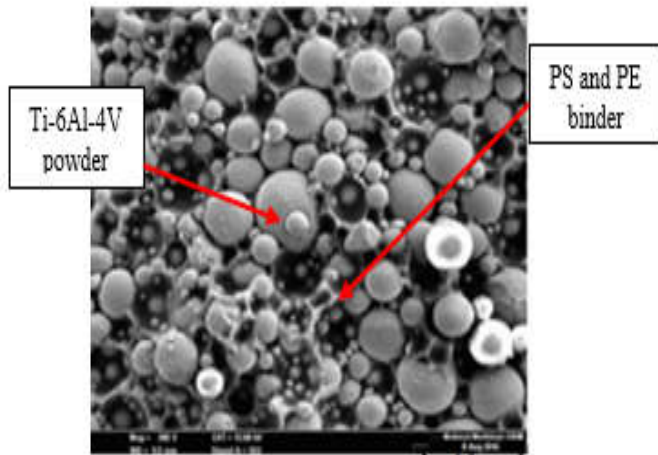


Figure 9: SEM morphology of optimum parameter green part

V. CONCLUSION

The study aimed to optimize defect ratings in green component injection moulding using a response surface methodology based on a five-factor central composite design. The effects of injection pressure (350–550 bar), injection temperature (130–150 °C), powder loading (63–67 vol%), mould temperature (40–50 °C), and holding pressure (500–700 bar) were analysed using Design Expert Software. Regression analysis and response surface modelling revealed that injection pressure had the greatest influence on defect ratings. After process optimization, experimental results aligned well with model predictions. The optimal parameters were 443.14 bar for injection pressure, 142.11 °C for injection temperature, 65.38 vol% for powder loading, 44.69 °C for mould temperature, and 629.56 bar for holding pressure, resulting in a defect rating of 2.5. The optimized green part shows no evidence of powder-binder separation, attributed to the strong adhesion and excellent surface contact between the binder and metal powder particles. This ensures a cohesive bond, preventing defects during subsequent processes.

AUTHOR CONTRIBUTIONS

J.B Saedon: Validation, Writing – review & editing. **N. H. Mohamad Nor:** Conceptualization, Methodology, Supervision, Writing – original draft. **S. Shawal:** Supervision, Writing – review & editing. **A. Arifin:** Software, Writing – review & editing. **M. A. Mifzal:** Experimental work, Writing – original draft. **Shaharudin Ahmad:** Writing – review & editing.

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