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Green Strength Optimization of Injection Molding Process for Novel Recycle Binder System Using Taguchi Method

Mohd Halim Irwan Ibrahim[1*], Nur Hafizah Kamarudin[1], Noor Hasliza Kamarudin[1]

[1]Faculty of Manufacturing and Mechanical Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, BatuPahat, Johor, MALAYSIA

*Corresponding Author

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Abstract: Metal injection molding is a worldwide technology that world use as a predominant method in manufacturing. Optimizing the injection molding process is critical in obtaining a good shape retention of green components and improving manufacturing processes itself. This research focuses on the injection molding optimization which correlated to a single response of green strength which implementing orthogonal array of Taguchi L_9 (3^4). It involved the effect of four molding factors: injection temperature, mold temperature, injection pressure and injection speed, towards green strength. The significant levels and contribution to the variables of green strength are determined using the analysis of variance. Manual screening test is conducted in regards of identifying the appropriate level of each factors. The study demonstrated that injection temperature was the most influential factor contributes to the best green strength, followed by mold temperature, injection speed and injection pressure. The optimum condition for attaining optimal green strength was definitely by conducting injection molding at; 160 ℃ of injection temperature, 40 ℃ of mold temperature, 50 % of injection pressure and 50 % of injection speed. The confirmation experiment result is 15.5127 dB and it was exceeding minimum requirement of the optimum performance. This research reveals that the proposed approach can excellently solve the problem with minimal number of trials, without sacrificing the ability of evaluating the appropriate condition to achieve related response, which is green strength.

Keywords: Green strength, single response optimization, Taguchi method, Stainless Steel 316L metal injection molding

1. Introduction

Concerning the large tons of waste produced every day that leads to disposal problem, environmental pollution, affect health, and such on, an alternative way was introduce for this present research. One of the major wastes is waste plastic bag which are classified as the non-biodegradable where it is disposed in the landfill and involve the high cost of incineration and limited space [1]. Many researchers have a great attention on binder's system development that are based on recycled material purpose to enhance developing the "green metal injection molding" [2]. Thus, the authors focused on the waste disposal problems that are being crucial in the world due to the rapid development todays. This study is fundamentally to investigate the potential of employing waste plastic bag which acts as a source of High-Density Polyethylene), commonly abbreviated as a backbone binder. Authors believed that such waste has a great potential which to be converted into the more beneficial industrial components.

Previous literature of [3] used recycled ceramic powder in ceramic injection molding (CIM), which sourced from recycle porcelain as we known that the porcelain was so expensive. This such works, which recycling the all materials

*Corresponding author: mdhalim@uthm.edu.my

are claimed as a delicate effort. Vielma et al. said that the reuse of waste as a delicate effort which using inexpensive and environmentally friendly [4]. In 2012, Omar et al. was recycling the rejected gloves to be functioned as a binder for MIM [5]. It was agreed that the recycled materials are functioned well and proportionate to commercial binder. This was proven as the feedstock was injectable and achieving the 99 % density of its theoretical. Meanwhile, Nemade et al. using recycled plastic as an addition substance in bitumen mixture for road construction. It was proven that this addition is able to enhance road strength, higher water resistance and longer road life [6]. Previous literature of [7] exploited the waste plastic bag as an addition in road bitumen purposing to enhance the mechanical strength, prolonging the road life. The plastic coating promotes a better binding of the bitumen, which due to enhance of bonding and larger contact between polymers and bitumen. It was differing with Patel et al. which using the waste plastics to reduce bitumen usage [8]. Waste like cups, polymers, plastic bottles and much more are able to recycle and acts as an addition in road bitumen. It was found that the plastic addition enhances the melting point of the bitumen, makes the road retain its flexibility during winters resulting in its long life and the shredded plastic waste acts as a strong "binding agent" for tar making the asphalt last long. Meanwhile, previous literature of [9] applied sewage fat as a lubricant in metal injection molding. It was found that the feedstock acquires a good homogeneity and appropriate rheological behaviours. Hence, proving the great potential of sewage fat as a binder in MIM. Also, previous literature of [2] using waste polystyrene as a MIM binder system which act as a source of Low-Density Polyethylene. Vielma et al. stated that the HDPE is cheap and exhibit a high dimensional stability which is due to the crystallinity structure [4]. Li et al., Adames, Vielma et al., Huang and Hsu, Raza et al. and Ibrahim and Kamarudin claimed the effectiveness of commercial HDPE as a backbone binder system in MIM [10-14]. So, how about the waste plastic bag performance? The election process of the waste plastic bag as a binder for this MIM technology was made without sacrificing the ability of the binder itself to be functioned as a good binder that will tightly hold the metal powder particles before take place the sintering.

Metal injection molding (MIM) was clarified as a global technology that used by manufacturers and researchers according to its flexibility and high productivity of small and complex components [14-16]. Fundamentally, the four major process of MIM technology are comprised of mixing, molding, debinding and sintering [17-18]. The process starts with mixing the fine metal powders with waxes and/or thermoplastic polymers in order to prepare homogeneous feedstock [15]. Next, the blended mixture was subjected to injection molding process to be transformed to a desire shape of metal component. However, the binders need to be removed from metal component without forfeiting the ability of fabricating the free defect brown component, so called the debinding process. Last, the brown component is sintered purposing to achieve the approximately to theoretical densities [19]. However, the manuscript only covered the second process of MIM, injection molding process.German and Bose claimed that the optimization stage for injection molding is necessary in producing the high quality of green component and ensure successful of debinding and sintering processes [18]. Defects which appeared in components during the debinding or sintering process, were not necessarily due to debinding or sintering but may have their origins defect since injection molding process [20-21]. This revealed that the optimization of injection molding was a crucial stage in MIM. Purposing to minimize cost, defect and time, Design of Experiment (DOE) is applied. Taguchi method is one of well-known optimization tool among researchers [22-27]. It was used to conduct an optimization stage of injection molding variables which considering the green component's performances (density, strength, surface quality, etc.), then reducing the number of trials needed compared to the trial-and-error method [28-34]. All the researchers worked on several injection factors in order to conduct the optimization stage, i.e., injection temperature, mold temperature, injection pressure, injection speed, holding time, cooling time and such on. However, the present authors only highlighted the four imperative factors; injection temperature (A), mold temperature (B), injection pressure (C) and injection speed (D), to be proceeded in optimization stage. Overall, the objective of this present study was to analyse the optimum injection molding parameters condition in order to produce maximum strength of the green components.

Table 1 – SS316L powder characteristics [36]

Characteristic	Details
Identification	SS316L, PF-10F
Tap density, g/cm^3	4.06
True pcynometer density, g/cm^3	8.0471
Powder size	d_{10}=2.87 μm, d_{50}=5.96 μm, d_{90}=10.65 μm

2. Experimentation

2.1 Material and experimental facilities

In this study, commercial stainless steel 316L supplied by Epson Atmix Japan, and the powder characteristics presented in Table 1. Waste plastic bag and palm kernel used as main binder components during MIM. The characteristics of binders; degradation temperature, melting temperature and etc. were studied in previous work of

[14,35]. Literature of Ibrahim et al. reported that the critical powder volume concentration (CPVC) for SS316L powder was approximately equal to 64.80 % [35-36], which outlines with statement of German & Bose which mentioned that optimal powder loading should be 2 % to 5 % lower than the critical loading [18]. Inasmuch, the powder loading applied for this research is 60 vol. %.

The materials were mixed using Rotary Plastograph Brabender at 135 °C with 30 rpm for 80 minutes. First, the waste plastic bag was added and it was mixed for 10 minutes. Then, it was followed by addition of metal powder by every little portion until finished of it. In 20 minutes, the palm kernel was added and mixed with the blended mixtures for 50 minutes. The mixed feedstock was leave for cooling before being crushed into pellet form. Next, the injection molding was proceeded by feeding the pellet feedstock via a hopper of horizontal injection molding machine; Model of Nissei 21, which accessible in Polymers and Ceramic Laboratory, UTHM. The feedstock was left to melt in the barrel. An amount of pressure is used to force the molten feedstock into mold cavity. Within a cooling time, the feedstock is solidified and the applied pressure was released to eject the part produced.

In this single response optimization, the only green strength was examined as an evaluation performance of green component. The flexural test for green components was determined by referring to ASTM Standard SI 10, which according to Metal Powder Industries Federation 15. The test was conducted by using Universal Testing Machine, model of Testometric 100 kN that available at Mechanic Testing Laboratory, UTHM. This testing is beneficial for measuring unsintered compacted powder metallurgy strength's by exposing them to a uniformly increasing transverse loading below defined parameters. Green strength is defined as a stress that necessary to break a simple beam of powder metallurgy component, and it was determined using equation 1:

$$S = \frac{3PL}{2t^2W} \quad (1)$$

Where:
S – Strength of injected component (MPa)
P – Amount of force which required for rupture (N)
L – Length of component span of fixture (mm)
t – Injected component thickness's (mm)
w – Injected component width's (mm)

2.2 Taguchi Method

The orthogonal array experiment is arranged using the employment of Taguchi method. The method was able to minimize the number of trials which purposing to recognize the significant variables. The experimental is designed in L_9 (3^4) orthogonal array. Four vital factors were implemented; i.e., injection temperature (A), mold temperature (B), injection pressure (C) and injection speed (D). The four factors are considered each time and each factor takes three levels, as shown in Table 2. Taguchi advocated the signal to noise ratio (S/N) as an objective function for matrix experiments. It was implemented purposing to quantify the quality characteristics and significant machining factors via Analysis of Variance (ANOVA). Taguchi organizes objective function into three categories, i.e., smaller the better, larger the better, nominal the best. Thus, this research suits the objective function of the larger the better, which applied to compute the process variables.

Inasmuch, the manual screening test was necessary to be conducted in order to determine the appropriate level of each factor. The complete graphical of green component produce was illustrated the all defects and the factor levels that were used is stated. The interaction variables are ignored due to the insignificant interaction factors during the screening test (not covered in this manuscript).

Table 2 – Injection molding factors of orthogonal array of Taguchi L_9 (3^4)

Factor	Indicator	Level		
		1	2	3
Injection temperature (ºC)	A	160	170	180
Mold temperature (ºC)	B	40	45	45
Injection pressure (%)	C	40	45	45
Injection speed (%)	D	40	45	45

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

3. Results and discussion

Manual screening test was conducted in order to fix the appropriate range value of each factor before it was proceed to statistical approach of Taguchi Method. According to this, literature of German and Bose specified that the injection temperature should be lower than the minimum degradation point and higher than the utmost melting point

[18]. Attempts to this, the injection temperature should be greater than 124.25 °C which is the high melting point of the backbone binder [14,35]. Along this line of consideration, authors decided to implement the injection temperature of 130 °C, injection pressure of 20 % and injection speed of 20 %. The medium value of injection pressure and speed applied to ensure the sufficient pressure and speed to force out the molten feedstock during molding.

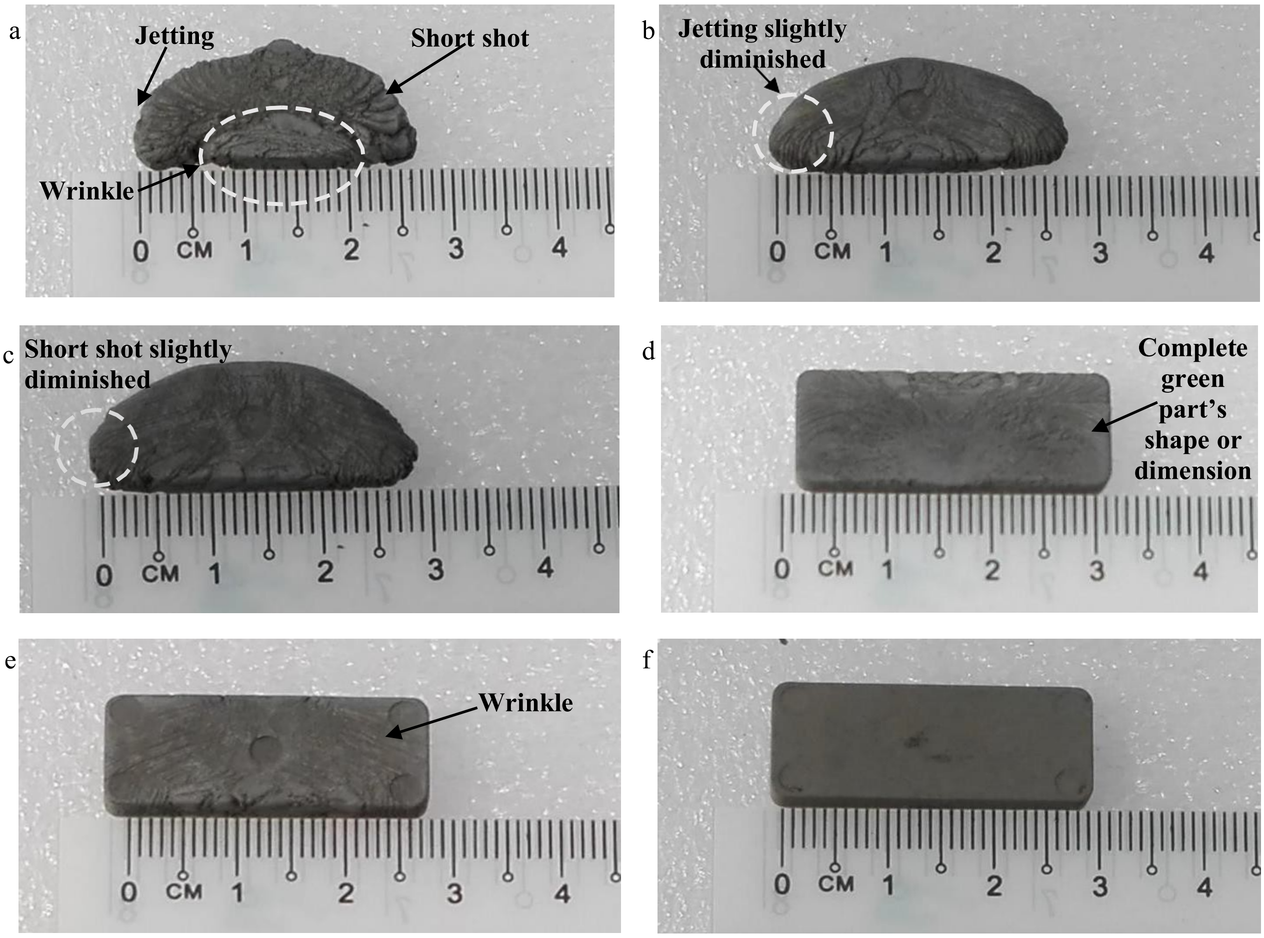

Fig. 1 – Green component that produced when used (a) injection temperature: 130 °C, injection pressure: 20 %, injection speed: 20 %; (b) injection temperature: 130 °C, injection pressure: 30 %, injection speed: 30 %; (c) injection temperature: 140 °C, injection pressure: 30 %, injection speed: 30 %; (d) injection temperature: 150 °C, injection pressure: 30 %, injection speed: 30 %; (e) injection temperature: 160 °C, injection pressure: 30 %, injection speed: 30 %; (f) injection temperature: 160 °C, injection pressure: 40 %, injection speed: 40 %

Fig. 1 (a) shows the defect of green component that produced, involving jetting, short shot and wrinkles. Presumably, the defects were occurred due to the lack injection pressure and injection speed to force out the molten feedstock for filling up the mold cavity. Thus, the injection pressure and injection speed were increased up to 30 %. It was found that the jetting and wrinkle are slight diminished compared as before, referring to Fig. 1(b). Unfortunately, the short shot still occurred at 130 °C due to the low injection temperature that may cause uncompleted melt of feedstock. Hence affected the flow ability of the molten feedstock to fill up the mold cavity.

Next, the injection temperature is increasing up to 140 °C, in order to enhance the feedstock flow ability. Attempts to this, the aforementioned defects are significantly diminished and this improvement automatically enhances green component's size, as shown in Fig. 1 (c). Again, the injection temperature increased up to 150 °C. As expected, the complete dimension of green component was produced. However, the wrinkle and jetting were still observed on the component surface, as illustrated in Fig. 1 (d).

Thus, the injection temperature was raised up to 160 °C but the wrinkles were still clearly observed on the top surface of green component, by referring Fig. 1 (e). Often, the wrinkle defect is significantly producing when the low injection pressure and the low injection speed are used [24]. Finally, the free defect of green component was produced by implementing the higher injection pressure and speed of 40 % for each, please refer Fig. 1 (f). It shows that the minimum range value of the variables are; i.e., injection temperature of 160 °C, injection pressure of 40 % and injection speed of 40 %, were necessary to produce a free defect of green component. This claim was supported by the literature of [33,37-39] which found that mold temperature should be implemented in maximizing the surface quality of injected component. However, too high injection temperature, high injection pressure and high injection speed were led to powder binder separation phenomenon, flashing, sink mark, short shot and such on [24].

German and Bose found that the injection molding optimization was necessary stages in producing high quality of green component, and ensure successful of debinding and sintering processes [18]. Defects which appeared in components during debinding or sintering were not necessarily due to that processes, but may have their origins defect since the process of injection molding [20,40]. In this research, the single response of green strength is measured and evaluated as an indicator of injection molding performance, by implementing Taguchi L_9 (3^4) Orthogonal Array. Green strength is defined as a mechanical property that required to endure the mechanical procedures and force subjected after pressing and before sintering, without detrimental its sharp edges and fine minutiae. Taguchi methods explained "Signal" as a desirable's value (mean) for the output characteristic whereby the term "Noise" refer to the undesirables' value (S.D) of output characteristic. Correlates to this, the S/N ratio used to measure the quality characteristic diverge from the desired value. Equation 2 is formulated for obtaining the green strength of S/N ratio. The experimental result of green strength characteristic was presented in Table 3. The four replications were made for each trial, purpose to obtain the high accuracy outcome.

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

Where:
y_{ij} = Amount of score for the quality measured
N = Total number of shot for each trial

Table 3 – Taguchi L_9 (3^4) expresses the experimental data of injection molding when optimizing green strength

Trial	Factors				S/N ratio: Larger is better	
	A: Injection temperature (°C)	B: Mold temperature (°C)	C: Injection pressure (%)	D: Injection speed (%)	Average green strength (MPa)	S/N ratio
1	1	1	1	1	5.93	15.47
2	1	2	2	2	5.75	15.20
3	1	3	3	3	5.83	15.32
4	2	1	2	3	5.67	15.06
5	2	2	3	1	5.65	15.03
6	2	3	1	2	5.47	14.75
7	3	1	3	2	5.65	15.05
8	3	2	1	3	5.67	15.08
9	3	3	2	1	5.54	14.87
					$\sum$	135.82
					$\overline{T}$	15.09

Figure 2 depicts a graphical in presenting the main effects plot (data means) for the S/N ratio, where the optimum factor will be based on the highest peak at each factors of A, B, C and D. As a consequence, the optimum configuration for obtaining optimal green strength would be A_1, B_1, C_3 and D_3. Next analysis was proceed to analysis of variance (ANOVA). As known, ANOVA is a standard statistical technique to provide a measure of confidence and it was shown in Table 4. Also, it was sufficient in implementing the ANOVA purposing to measure the factor's statistically contribution percentage. Injection temperature (A) was giving the highest contribution which valued by 64.23 and it was supported with the previous works of [18,35,41] that similarly attained to that finding. This value was achieved the high significance level which is the 99.90 % confidence level, or it was also called as at α=0.001. Then, the second factor that contribute most was the mold temperature (B) with significance level of 99.90 % (α=0.001) and the percentage contribution of 16.78 %. Injection pressure (C) and injection speed (D) achieved lower contribution towards green strength characteristic which valued by 2.86 % and 9.53 %, respectively. The all controlled factors achieved the 99.90 % confidence level which indicating the all factors were given significant effects toward the studied single response.

Overall observation was made. The authors found that the green strength are increased as the injection temperature is increased [41]. But, a too high injection temperature and pressure will lead to component defects such as flashing, wrinkle and such on.

$$CI = \pm\sqrt{\frac{F_\alpha(f_1, f_2)\times V_e}{N_e}} \quad (3)$$

Where:
F_α (f_1, f_2) = Variance ratio for DOF of f_1 and f_2 at level of significance α. The confidence level is (1-α)
f_1 = DOF of mean (usually equal to 1)
f_2 = DOF of error
V_e = Variance of error
N_e = Number of equivalent replication which given as ratio of number of trials (1 + DOF of all parameters used in the estimate)

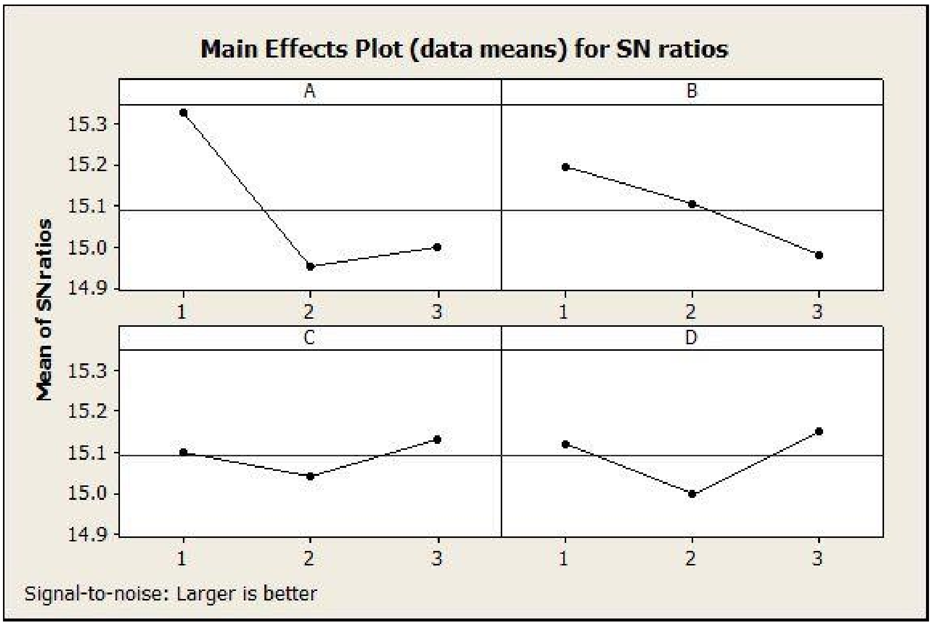

Fig. 2 - Main effects plot (data means) of S/N ratio when optimizing the green strength

Table 4 – ANOVA table of green strength optimization

	DF	SS	Variance	F	Critical F value	Percentage contribution (%)
A	2	0.4367	0.2183	171.38	F(0.001)=9.0194	64.23
B	2	0.1160	0.0580	45.52	F(0.001)=9.0194	16.78
C	2	0.0219	0.0110	8.60	F(0.001)=9.0194	2.86
D	2	0.0670	0.0335	26.29	F(0.001)=9.0194	9.53
Error	27	0.0344	0.0013			6.60

Table 5 – Estimate of performance (Characteristics: Larger is better) when optimizing the green strength

Significance optimum parameter: $A_1B_1C_3D_3$	
Optimum performance calculation:	
15.09 + (15.53 – 15.09) + (15.19 – 15.09) + (15.13 – 15.09) + (15.15 – 15.09) = 15.53	
Current grand average performance	15.53
Confidential interval (CI) at 99 % confidence level	± 0.05
$\overline{T} + (\overline{A}_1 - \overline{T}) + (\overline{B}_1 - \overline{T}) + (\overline{C}_3 - \overline{T}) + (\overline{D}_3 - \overline{T})$	
Expected result at optimum performance, μ	15.58 < μ < 15.58

Table 6 – Confirmation experiment of injection molding for optimizing the green strength

Replication	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**S/N ratio larger is better is**
Green strength (MPa)	6.19	5.86	5.90	5.90	5.99	5.93	5.91	5.97	5.90	6.14	15.51

Later, the confident interval (CI) is calculated by applying Equation 3 and it was valued by ± 0.05. The expected range of optimum performance was shown in Table 5. Here, the analysis proceeded by predicting the quality characteristics according to its CI. The confirmation experiment was conducted using the optimum injection condition of A_1, B_1, C_3 and D_3. Noted that the confirmation result of S/N ratio should be within the range between 15.48 dB to 15.58 dB. By referring Table 6, it was proven that the confirmation test was valid since the acceptable S/N ratio (15.51 dB) was lies in the range of expected result at optimum performance, S/N ratio just 0.03 dB above the minimum level.

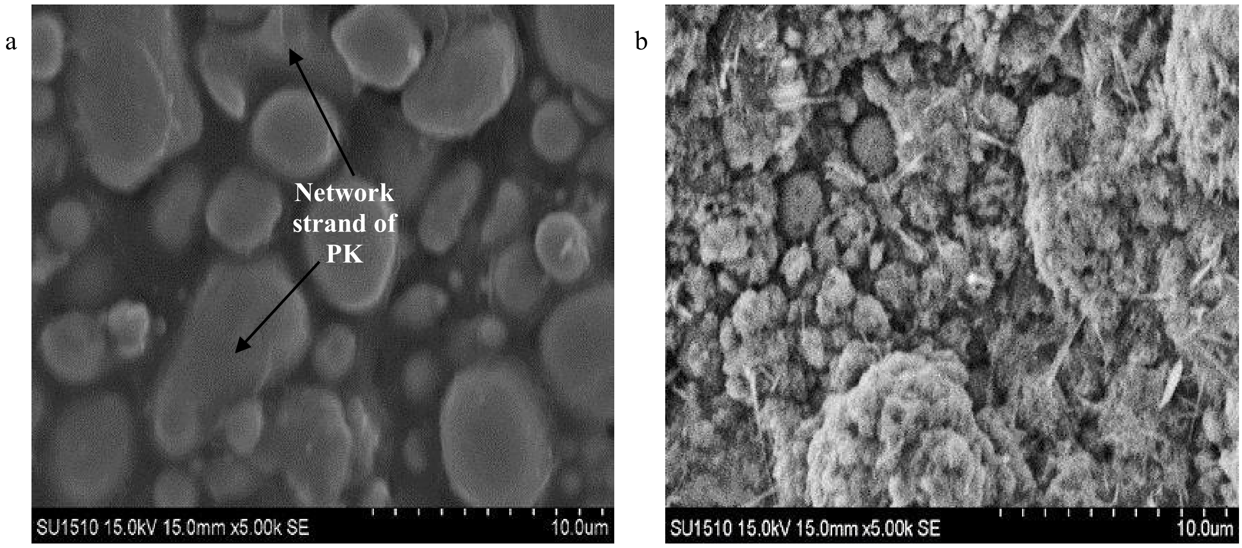

Fig. 3 - Microstructure of injected component; (a) surface and (b) cross section

Figure 3 (a) and (b) illustrate the green component's morphology after being injected using the optimal condition of obtaining the optimum green strength which given by injection temperature 160 °C (A_1), mold temperature of 40 °C (B_1), injection pressure of 50 % (C_3) and injection speed of 50 % (D_3). Different areas of the injected component were examined, including the top surface and fracture surface purposing to observe the binders and pore distribution. In both views, it was clearly seen that the network of WPB ligaments and a strand of PK was well coated and binding the SS316L particles. Figure 3 (b) shows the fracture surface of the green part at high magnification of 5000 which was also showing a good binders and pore distribution. Also, according to both micrographs, it was proven that the prepared feedstock has homogeneous dispersion of binder system between powder particles.

4. Conclusion

The optimization of injection molding process for green novel binder system of MIM using Taguchi orthogonal array with single response of green strength is discussed in this manuscript. From the experiment and analysis, the following conclusions can be drawn. It has been found that the combination of injection temperature of 160 °C, mold temperature of 40 °C, injection pressure of 50 % and injection speed of 50 % gave the maximum value of green strength. ANOVA shows that the injection temperature was found to be most effective factor in obtaining optimum green strength, followed by mold temperature, injection speed and injection pressure. All the variables have confident level above 99.9 % by using F-test. The optimum variables acquired from ANOVA are acceptable where the range of optimum performance between 15.48 dB and 15.58 dB. The results meet the requirement when S/N ratio (15.53 dB) from confirmation experiment is within the range and meet 99.9 % confident level. From the findings, it can be stated that Taguchi method is a powerful tool for evaluating single response performance in metal injection molding.

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