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Optimization of Injection Molding and Solvent Debinding Parameters of Stainless Steel Powder (SS316L) Based Feedstock for Metal Injection Molding

(Pengoptimuman Pengacuan Suntikan dan Penyahikatan Larutan bagi Bahan Suapan Berasaskan Serbuk Keluli Tahan Karat (SS316L) untuk Pengacuanan Suntikan Logam)

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ABSTRACT

In this study, injection molding parameters, including green strength, surface quality and green part density, were optimized using the L_{18} Taguchi orthogonal array. The L_{25} Taguchi method was used to optimize the green density of solvent debinding parameters. The feedstock consisted of stainless steel powder (SS316L), with powder loading fractions of 63, 63.5 and 64 v/o. The binder compositions used in the study were polyethelene glycol (PEG-73 wt. %), polymethyl methacrilate (PMMA-25 wt. %) and stearic acid (2 wt. %). The Taguchi method was used to optimize the injection parameters. The obtained optimum parameters were as follows: mold temperature of 65°C, injection temperature of 145°C, injection pressure of 650 bar, injection flow rate of 20 m^3/s, holding time of 5 s and powder loading of 64% v/o. Analysis of variance results showed that mold temperature has the greatest influence in the production of good green part surface quality and that powder loading gave the best green part strength. Immersion time and temperature were used to optimize for solvent debinding parameters. By optimizing the solvent debinding parameters, an immersion temperature of 61°C and immersion time of 5 h produced the highest density which is the optimum value gain in this study.

Keywords: Debinding; density; green compact strength; injection parameters; metal injection molding; Taguchi method

ABSTRAK

Dalam kajian ini, parameter pengacuanan suntikan logam bagi kekuatan jasad hijau, kualiti permukaan dan ketumpatan jasad hijau dioptimumkan menggunakan Kaedah Ortogon Taguchi $L_{18.}$ Taguchi L_{25} pula digunakan bagi mengoptimumkan parameter penyahikatan larutan bagi ketumpatan jasad hijau. Bahan suapan yang digunakan terdiri daripada serbuk keluli tahan karat (SS316L) dengan pecahan pembebanan serbuk sebanyak 63, 63.5 dan 64 v/o. Bahan pengikat yang digunakan pula terdiri daripada polietelina glikol (PEG-73 wt. %), polimetil metaklirat (PMMA-25 wt. %) dan asik stearik (2 wt. %). Kaedah Taguchi digunakan bagi mendapatkan nilai optimum dalam kajian ini. Parameter optimum bagi penyuntikan yang diperoleh adalah seperti berikut: Suhu acuan pada 65°C, suhu penyuntikan pada 145°C, tekanan penyuntikan pada 650 bar, kadar alir pada 20 m^3/s, masa padatan pada 5 s dan pembebanan serbuk pada 64 v/o. Berdasarkan analisis ANOVA, suhu acuan memberikan pengaruh yang paling tinggi bagi mendapatkan jasad hijau yang mempunyai ketumpatan yang tinggi serta kualiti permukaan yang baik manakala pembebanan serbuk memberikan kekuatan jasad akhir yang terbaik. Pengoptimuman bagi penyahikatan menunjukkan suhu rendaman pada 61°C dan masa rendaman selama 5 jam memberikan ketumpatan jasad yang tertinggi dalam kajian ini.

Kata kunci: Kaedah Taguchi; kekuatan jasad hijau; ketumpatan; parameter penyuntikan; pengacuan suntikan logam; penyahikatan

INTRODUCTION

Metal injection molding (MIM) is a near-shape molding process that combines injection and powder metallurgy procedures (German & Bose 1997). It is a cost effective process for producing high volumes of small, complex and precise parts (Liu et al. 2003). The processes involved in MIM include mixing metal powders with a binder, injecting the mixture to the molding, debinding and sintering (Huang & Hsu 2009). The optimization of injection parameters is necessary in producing high-quality green components before going through the debinding and sintering processes (Ibrahim et al. 2008).

The Taguchi method optimizes injection parameters by considering the surface quality and the strength of the green compact, thus minimizing the number of experiments needed compared to the trial-and-error method. A component is considered high density when it has better strength and limitless defect (Li et al. 2007). The mold temperature and packing time have the greatest influence on green compact surface quality, as reported by Jamaludin et al. (2009). Tatt (2009) also reported that mold temperature has the greatest influence on green compact surface quality, density and strength. Solvent debinding is an intermediary process that helps achieve the required high density component (Yulis 2008), which was optimized by an immersion temperature of 59°C and immersion time of 6 h. The objectives of this study were to optimize the injection molding parameters for optimum density, surface quality and mechanical strength for the injected part while for solvent debinding parameter aimed to increase the density.

METHODS

In the experiment, SS316 L, water-atomized stainless steel powder with a pycnometer density of 7.93 g/cm^3 was mixed with 73 wt. % of polyethylene glycol (PEG 4000), 25 wt. % of polymethyl methacrylate (PMMA) and 2 wt. % of stearic acid as a surfactant. Sigma blade mixer is used for mixing three composition of SS316L powder loadings (63, 63.5 and 64 v/o) and acetone was added into the feedstock with ratio of 4 mL acetone for each gram of PMMA used in the mixture to improve the feedstock mixing result. Rheology analysis of the feedstock was performed by using Shimadzu to identify which flow characteristic of the feedstock was suitable for the injection processes. A Battenfeld BA 250 CDC injection molding machine, with single cavity standard tensile bar shaped cavity, was used as the mold. An INSTRON Universal Tester 5567 was used to perform the three-point bending test to determine the strength of the injected component. Feedstock was injected using design of experiment DOE by the L_{18} Taguchi method to determine the optimized injection parameters (Table 1). After obtaining the optimized injection parameters, the feedstock was again injected using the optimized injection parameters. Three testing criteria were considered: The injected part surface quality, the injected part strength and the injected part density.

Optimized injected components were used in the solvent debinding process. The L_{25} Taguchi method was used to determine the optimum solvent debinding parameters, which were immersed in five different immersion temperatures and times (Table 2). The sintering cycle phase diagram used in the current study was based on the optimum sintering cycle proposed by Jamaluddin (2009) which pre-heating at 380°C and sintering at 1320°C.

RESULTS AND DISCUSSION

Figure 1 shows the feedstock rheology analysis results. Three feedstock powder loadings, namely, 63, 63.5 and 64 v/o, exhibited pseudoplastic characteristic with flow index $n < 1$ (Table 3). The viscosity and shear rate values fell within the acceptable ranges of 10 to 1000 Pa.s and 10^2 s^{-1} to 10^5 s^{-1}, respectively. The value ranges indicate the flowability of the feedstock in the MIM process. The ideal rheology properties are produced by 64% powder loading, which generated the highest values. Higher flowability index values result in more stable feedstock reactions to temperature changes, thus leading to reduced green part distortion and cracking (Khakbiz et al. 2005).

Figures 2 and 3 show the optimized injection parameters using the Taguchi method. The surface quality and green part strength are defined as the evaluation factors. The optimal injection parameters for surface quality are as follows: Mold temperature of 65°C, injection temperature of 145°C, injection pressure of 700 bar, holding time of 5 s and powder loading of 64 v/o (Figure 2). The mold temperature has a great effect on the surface quality, because temperature keeps the surface constantly heated and maintain the surface structure. The optimal injection parameters for green part strength are as follows: Mold temperature of 60°C, injection flow rate of 20 m^3/s, injection temperature of 145°C, injection pressure of 650 bar and holding time of 15 s (Figures 3 and 4). The green part strength required a compaction between the binder and the metal powder which the injection flow rate needs in order to be optimum so the particles compress tightly meanwhile the green part surface quality required the suitable mold temperature. Given that powder loading is a

TABLE 1. Factor and level of injection molding parameters

No	Factor Column	Factor	Level		
			0	1	2
1	A	Injection Pressure (bar)	600	650	700
2	B	Injection Temperature (°C)	145	150	155
3	C	Mold Temperature (°C)	55	60	65
4	D	Injection Time (s)	4	7	-
5	E	Holding Time (s)	5	10	15
6	F	Powder Loading (%)	63	63.5	64

TABLE 2. Immersion time and temperature for solvent debinding

Parameters	Test Range
Immersion Time (h)	2,3,4,5,6
Immersion Temperature (°C)	55,57,59,61,63

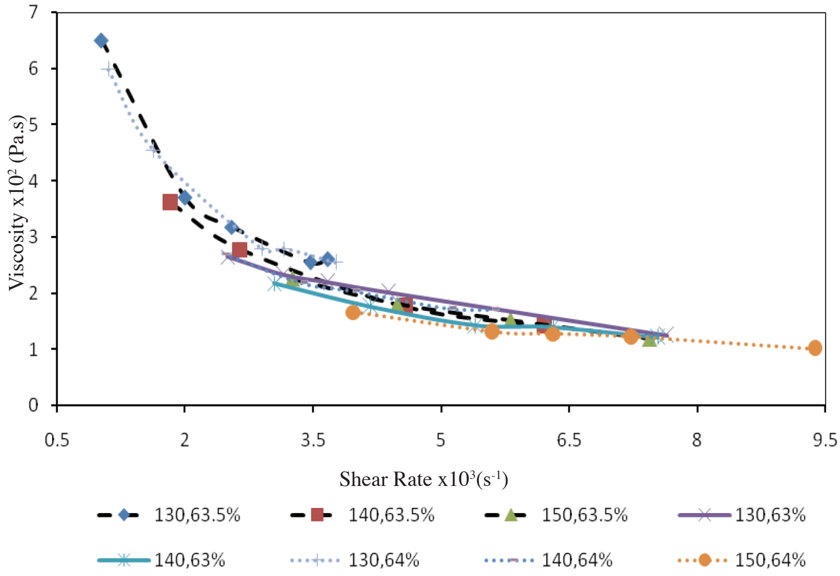

FIGURE 1. Viscosity against shear rate at different temperatures and powder loadings

TABLE 3. Flow index *n* of feedstocks at various temperatures

Powder Loading (%)	Temperature (°C)	Flow index, *n*
63	130	0.33
	140	0.37
63.5	130	0.27
	140	0.23
	150	0.24
64	130	0.28
	140	0.44
	150	0.46

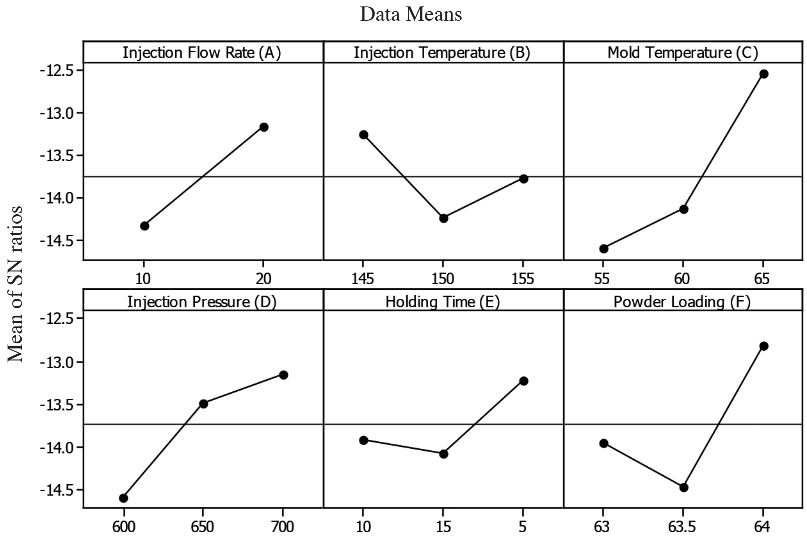

FIGURE 2. S/N ratios for surface quality at various levels of injection parameters

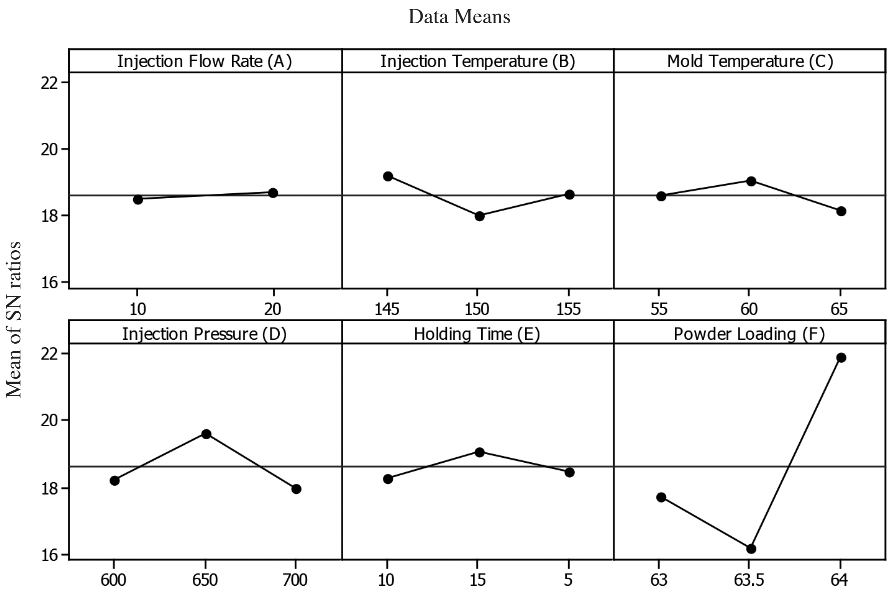

FIGURE 3. S/N ratios for strength at various levels of injection parameters

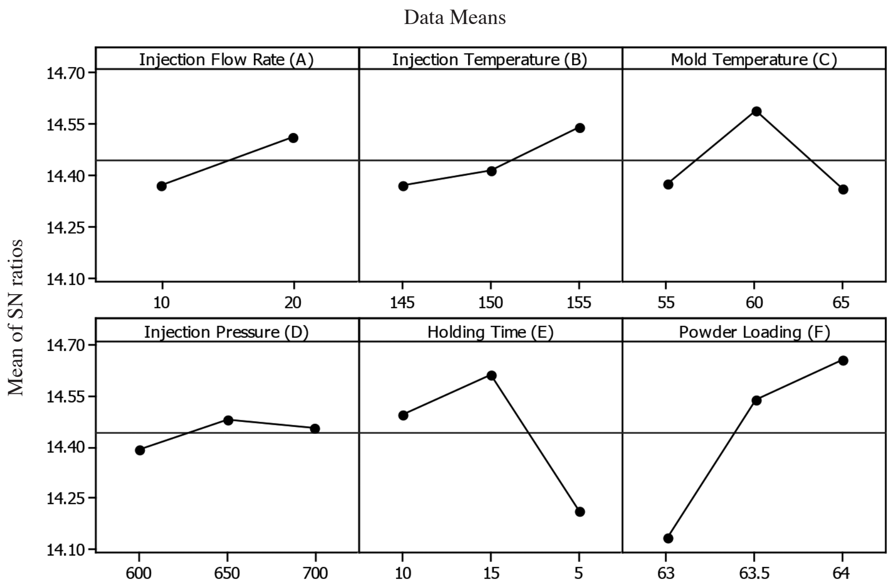

FIGURE 4. S/N ratios for density at various levels of injection parameters

major factor in green strength evaluation, higher amounts of added powder resulted in higher green part produce strengths (Yimin et al. 2007).

Table 4 shows the combination of the optimized parameters for the evaluation criteria, while Table 2 shows the optimized combination of injection parameters. Analysis of variance was performed to determine the most significant contribution factor. Mold temperature and powder loading are the most influential parameters for green part surface quality and injected part strength and density, respectively (Table 4). High mold temperature provides enough flowability for the feedstock to occupy all the cavity area (Liu et al. 2003). According to Huang and Tai (2001), high mold temperature decreases the shear rate between the feedstock surface and the cavity surface areas. Furthermore, the powder loading factor has the greatest influence on strength evaluation criteria. According to German and Bose (1997), adding more metal powder results in greater injected part strength because of the compaction between the metal particles. Figure 5 shows a part that has been injected with optimum parameters in the present work. The injected parts with optimized parameters exhibited better surface quality and higher green strength values compared with injected parts that have not been optimized.

Figure 6 shows the optimized debinding parameters obtained using the Taguchi method with the L_{25} orthogonal array. The density of green part strength was used as the

TABLE 4. Optimum parameters and contribution percentage of the factors

Factor	Optimum parameter	Contribution percentage, %		
		Surface quality	Strength	Density
Injection flow rate (A)	20 m^3/s	25.63	0.33	9.47
Injection temperature (B)	145^{0}C	6.03	3.50	4.71
Mold temperature (C)	65^{0}C	29.40	1.94	10.02
Injection pressure (D)	650 bar	14.82	7.38	1.34
Holding time (E)	5 s	5.28	1.65	26.77
Powder loading (F)	64%	18.84	85.20	47.67
Error		0.01	0.01	0.01

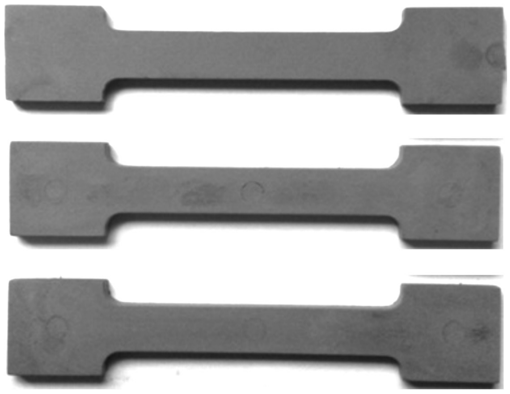

FIGURE 5. Parts injected at optimized injection molding parameters

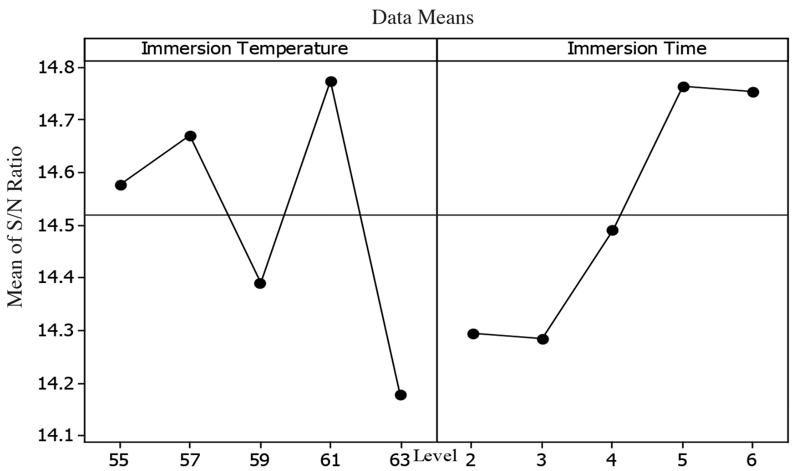

FIGURE 6. S/N ratios for green density at various level of debinding parameters

evaluation factor. The optimized debinding parameters are as follows: Immersion temperature of 61°C and immersion time of 5 h. Higher immersion temperatures resulted in faster PEG% decomposition; however, most of the green parts with temperatures higher than 61°C exhibited swelling and reduced green densities (Figure 7). Higher immersion temperatures create a large void between the powder and binder particles because of the decomposition of the PEG in the green part. Most of the PEG passed through the void to exit between the powder and PMMA and a large number of water molecules entered during this process, affecting the bonding between the powders and leading to swelling.

The morphology structure for the debinding process shows that the void occurred in an area dominated by a large group of binders. Figure 8(a) and 8(b) shows decomposition of PEG. Furthermore, the PEG decomposed during the joining of the particles when they exited the green part.

The brown part morphology images are shown in Figure 8(c) and 8(d). The images were taken after the part underwent thermal debinding with a heating rate of

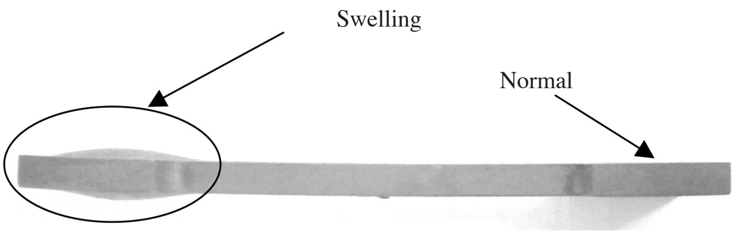

FIGURE 7. Swelling of green part at 63°C of immersion temperature

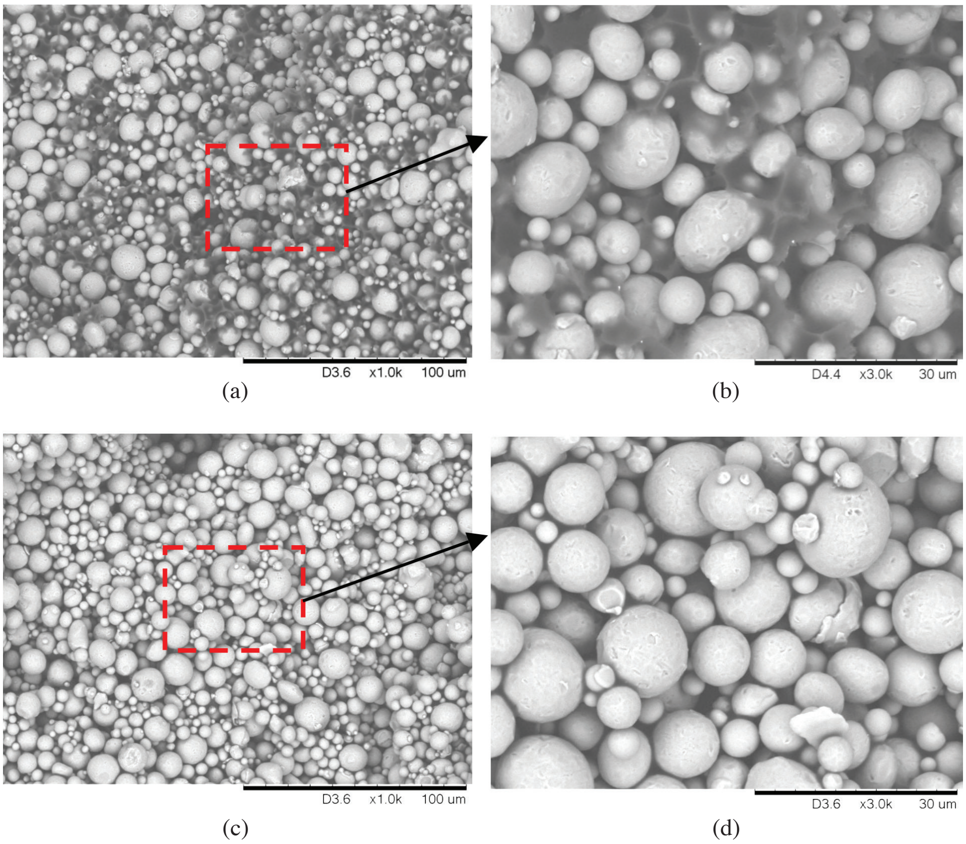

FIGURE 8. SEM images of (a) green part after 3 h immersion time and 61°C immersion temperature, (b) magnification of (a), (c) brown part after thermal debinding for 2 h at temperature 350°C and (d) magnification of (c)

6°C/min until a temperature of 350°C was reached for approximately 2 h. Most of the brown part exhibited fragile characteristic structures because of the huge void. Thus, the brown part is not suited for mechanical or physical testing and must be sintered to obtain the final product. The strength gain from using optimized injection molding and water debinding parameters reached a higher average value of 892.7 MPa. The density of the sinter part also yielded successful results in average of 7.823 g/cm^3. This falls within 98.9% of the theoretical value. Therefore, the significant parameters in the current study influenced the good end product. The sinter part contributed to shrinkage in the demission after sintering. The contribution is less than 13% in MIM for a good feedstock powder loading fraction. As the shrinkage becomes higher, controlling the geometry and the physical and mechanical properties of the final product becomes more difficult (Loh et al. 2005). The final part produced in the current study exhibited a greater shrinkage of 11.75% as compared with the injected part of 63 v/o. The final part also decreased with the increase of powder loading percentages in terms of length and thickness, as shown in Tables 5 and 6, respectively. This situation coincides with the theory that adding more binder causes greater shrinkage in the MIM injection component (Omar & Ibrahim 2005). Figure 9 shows the difference of the injected part (a), brown part (b) and sinter part (c), in terms of dimensions.

CONCLUSION

Three feedstock powder loading formulations (63, 63.5 and 64 v/o) exhibited pseudoplastic flow behaviors and are suitable for MIM processes. The Taguchi method successfully optimized the injection parameters and only

TABLE 5. Shrinkage in term of length for different powder loadings

Powder loading (v/o)	Initial length, Li, (mm)	Final length, Lf, (mm)	Li-Lf, (mm)	(Li-Lf)÷Li, (mm)	Shrinkage percentage (%)
63	66.87	59.01	7.86	0.1175	11.75
63.5	66.88	59.05	7.83	0.1171	11.71
64	66.85	59.08	7.77	0.1162	11.62

TABLE 6. Shrinkage in term of thickness for different powder loadings

Powder Loading (v/o)	Initial Thickness, T_i (mm)	Final Thickness, T_f, (mm)	T_i-T_f, (mm)	(T_i-T_f)÷T_i, (mm)	Shrinkage Percentage (%)
63	3.14	2.87	0.27	0.0860	8.60
3.5	3.15	2.89	0.26	0.0825	8.25
64	3.14	2.90	0.24	0.0764	7.64

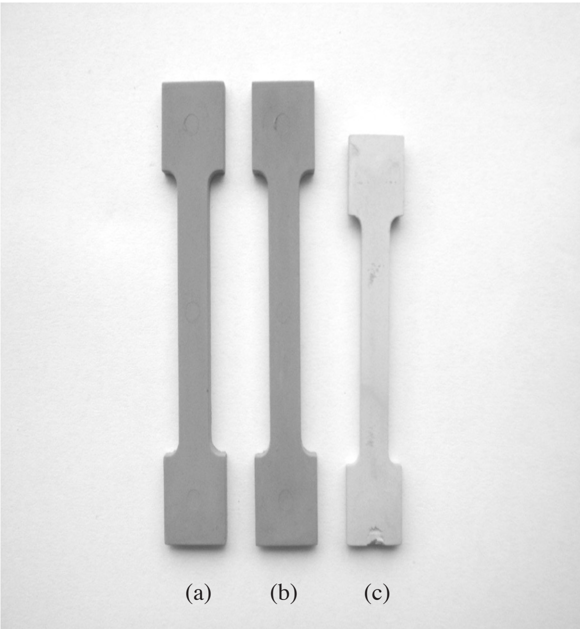

FIGURE 9. Shrinkage variation of (a) green part, (b) brown part and (c) sintered part

required a minimum number of experiments. Based on the results, mold temperature is the most significant factor for obtaining the best green part surface quality. Powder loading is a major factor of the green part strength and density evaluation criteria. The optimum injection molding parameters are as follows: Injection flow rate of 20 m^3/s, mold temperature of 65°C, injection temperature of 145°C, injection pressure of 650 bar and holding time 5 s. The optimum parameters for solvent debinding optimization show that an immersion temperature and time of 61°C and 5 h, respectively, give the highest density value for solvent debinding parts. The sinter part also resulted in a good end product when the end density and strength are near theoretical values. Shrinkage is also obtained in the MIM standard control. The current study successfully optimized the injection and solvent debinding parameters, thus achieving a good end product.

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