Development of a Powder Material Deposition Unit and Process Parameters Identification for Selective Vacuum Manufacturing Rapid Prototyping

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ABSTRACT

Selective vacuum manufacturing (SVM) is an inexpensive, rapid prototyping technique that applies sand casting and powder sintering processes to fabricate a prototype layer by layer. Poly-lactic acid (PLA) powder, a biodegradable polymer, was considered for part material of SVM, in particular for tissue scaffold fabrication. Previous studies illustrated a problem with incomplete PLA powder deposited in the created cavity due to clogging at the nozzle's tip. The objective of this paper was to develop a new powder material deposition unit for SVM. A pneumatic cylinder was adopted to provide vertical vibration that can prevent the clogging problem more effectively. The nozzle size and the air pressure used for its operation were varied to identify the suitable process parameters. The results illustrated that using a nozzle size of 18G (internal diameter 0.90 mm) and air pressure of 0.5 bar could provide an average flow rate of 4.312 ± 0.555 mg.s^{-1} without flow problems.

Keywords: material deposition, poly-lactic acid, powder, rapid prototyping, selective vacuum manufacturing

INTRODUCTION

Selective vacuum manufacturing (SVM) is a rapid prototyping technique that adopts two simple manufacturing processes—sand casting and powder sintering—to create a prototype (Phattanaphibul *et al.*, 2014). Instead of using a physical pattern and filling the created cavity with molten material like the conventional sand casting process, a vacuum nozzle is used to create a thin cavity profile which is subsequently filled with powder material. Lastly, the powder is sintered to form a solid layer. By repeating these steps, the prototype can be created one layer at a time. Figure 1 presents the steps of SVM process.

Besides manufacturing applications, SVM has been researched for temporary scaffold fabrication (Irwansyah *et al.*, 2010). The scaffold is a structure for cells to live on during a tissue regeneration period (Verrier and Boccaccini, 2000). After the damaged tissue has completely recovered, the scaffold must be degraded and absorbed by the human body without leaving any toxic by-products. Therefore, many biodegradable polymers including poly-lactic acid (PLA) have been considered for this application. For SVM, PLA has been successfully applied as part material to fabricate the scaffolds with the results illustrating that the fabricated scaffolds could be considered for soft tissue application (Phattanaphibul and

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Koomsap, 2012). However, some suggestions were also addressed for further improvement. In this paper, the problem of incomplete PLA powder deposited in the cavity profile was studied. Due to its low flowability, PLA powder tends to agglomerate at the nozzle's tip which gives poor material deposition and low packing density in the cavity as shown in Figure 2 (Irwansyah, 2008). As a result, this affects both the strength and accuracy of the fabricated scaffolds. This issue has led to the development of a new material deposition unit for polymeric powder that voids this flow problem.

DEVELOPMENT OF POWDER MATERIAL DEPOSITION UNIT

Flowability and flow problems

Prescott and Barnum (2000) defined *flowability* as the ability of powder to flow in equipment in a desired fashion, that is *first-in first-out*, called mass flow. Accordingly, *last-in first-out* is an undesirable fashion, which is called funnel or core flow. Normally, flow problems are caused by funnel flow. Figure 3 presents three possible phenomena of flow problems—ratholing, bridging

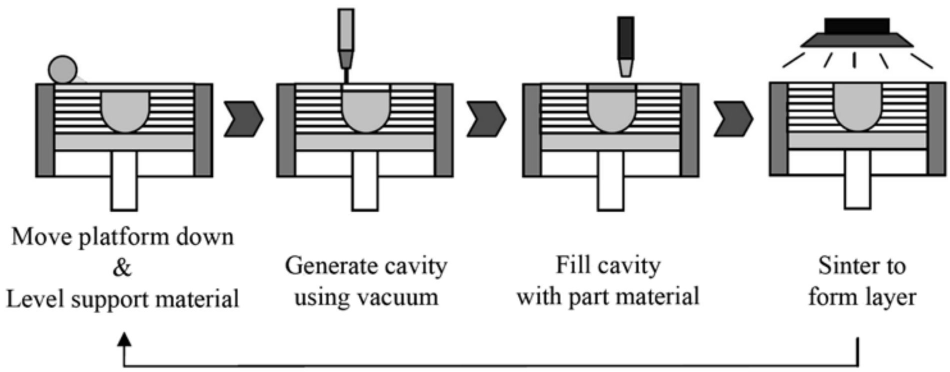

Figure 1 Steps of selective vacuum manufacturing process (Sourced: Phattanaphibul and Koomsap, 2012).

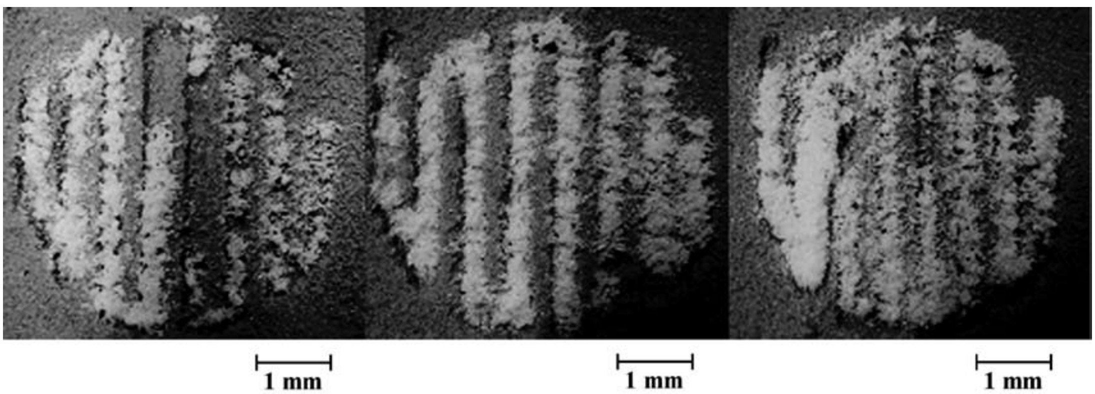

Figure 2 Examples of incomplete powder deposited in the cavity profile with scale bar = 1 mm (Sourced: Irwansyah, 2008).

and flooding (Royal and Carson, 1991). When the powder is fed into the nozzle's tip, some of it starts accumulating and forms a (rat) hole. The powder can flow through this formed hole until it is blocked by a bridge. With flooding being when the hole and bridge collapse and form repeatedly, which gives uncontrolled flow.

Powder material deposition units in selective vacuum manufacturing

During the material deposition step of SVM, the part material should have good flowability to be fed through a small nozzle into the created cavity and packed closely. Figures 4a and 4b present two previous powder material deposition units. The first model, designed by Nachaisit (2004), was used for high, apparent-density polymeric powder such as poly-vinyl chloride (PVC) and poly-amides (PA or nylon). By providing slight vibration on top of the unit, the powder could flow without clogging. However, this model could not be used for powder that had low flowability like PLA powder. The powder tended to agglomerate at the nozzle's tip. Ratholing and bridging always appeared. The next model was further developed by adding a sub-unit to break the clogged powder at the nozzle's tip. The temperatures of the PLA powder and the

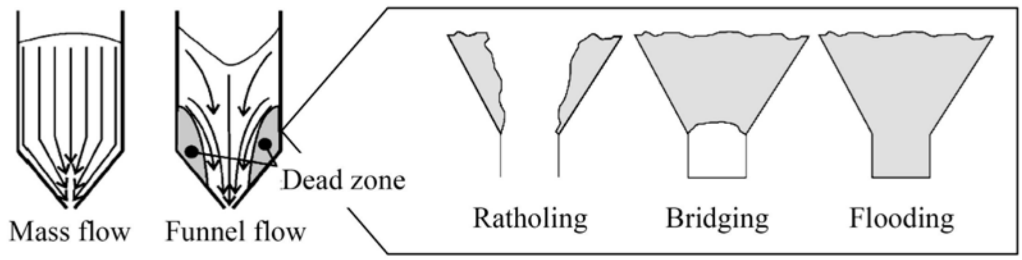

Figure 3 Flow pattern and flow problems (Sourced: Royal and Carson, 1991; Holdich, 2002)

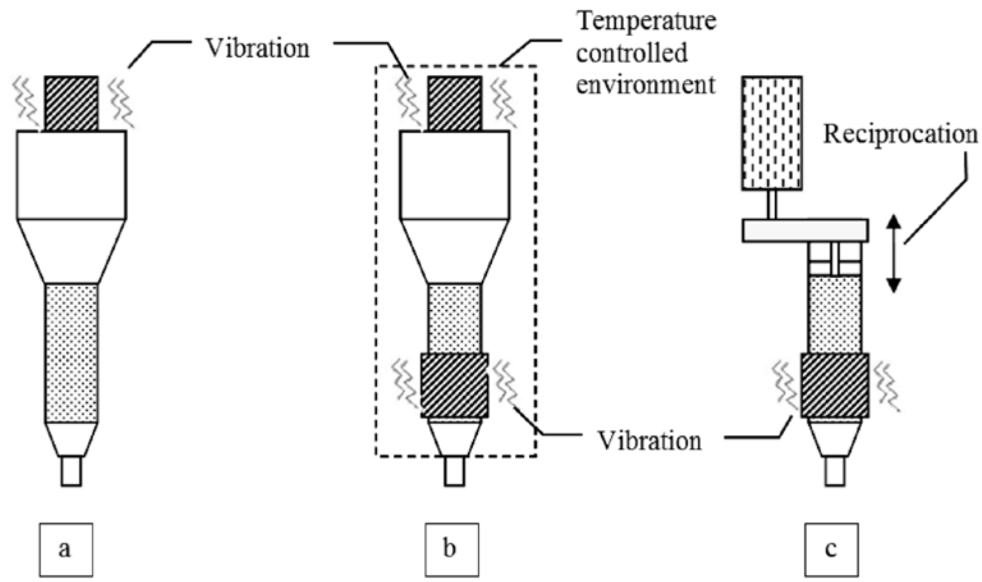

Figure 4 Powder material deposition: (a) First model, with vibration at the infeed; (b) Second model with vibration at the infeed and outfeed; (c) Developed model with a reciprocating infeed and vibration at the outfeed.

environment were also controlled to prevent any humidity effect that may cause flow problems (Phattanaphibul and Koomsap, 2012). However, the flow problem still existed due to difficulties with the temperature control device. This has led to a new model as presented in Figure 4c. The topmost vibration device was replaced with a new device driven by a pneumatic cylinder. While filling powder into the cavity, the piston rod reciprocates all the time. The clogged powder is sucked out of the nozzle's tip in the retract stroke which can break the rathole or bridge or both more effectively.

Unit construction

A prototype of the new powder material deposition unit was constructed as shown in Figure 5. Its components include a vibration device at the nozzle's tip, a powder loosening device on the top of the unit, and a filling nozzle (adopted from a flat-ended hypodermic needle). A 24 V direct current motor is used to generate vibration for the first component. The powder loosening device consists of a double-acting pneumatic cylinder, a 24 V direct current 5/2-way solenoid valve, a flow control valve, a pressure gauge and a LabVIEW-based control system (Version 2010; National Instruments Corporation; Austin, TX, USA). The flow control valve and pressure gauge are used to regulate the speed of the piston rod in the extend stroke. Using overspeed may result in spreading of powder deposited in the cavity. The reciprocating motion of the piston rod is controlled at the specified stroke via the operating cycle time of the solenoid valve and the control system. A cycle time to complete a full stroke (one extend and one retract stroke) is set at 0.1s.

PROCESS PARAMETERS IDENTIFICATION

Experimental setup

The experiment was conducted to identify the process parameters for the developed unit. Two factors of interest were the nozzle size and the air pressure used for extending the piston rod. The nozzle sizes were 18G (0.90 mm internal diameter; ID) and 20G (0.55 mm ID). The air pressure was varied at three levels (0.5, 1.0, and 1.5 bar). All six conditions, A-F, are presented in Table 1. According to Phattanaphibul *et al.* (2007), the PLA powder was prepared by spraying PLA solution in the water medium and screening the dried powder with a sieve number 200 (opening size ≤ 76 μm).

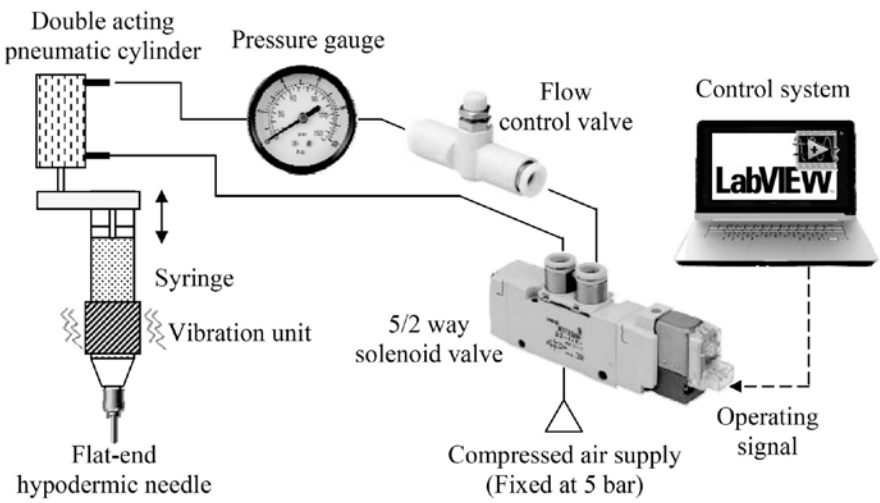

Figure 5 Components of new powder material deposition unit.

The steps of the experiment were: 1) filling 15 cm^3 of PLA powder into a syringe, 2) inserting a plunger into the syringe, 3) connecting the plunger to the piston rod of the pneumatic cylinder, 4) operating both the vibrating and powder loosening device for two testing durations (5 s and 10 s to check the consistency of flow), and 5) weighing the discharged powder in a container using a high precision weight scale. Fifteen replications were done for each condition. The remaining powder was removed before beginning the next replication.

Three evaluation criteria were used—average flow rate, consistency of flow and characteristics of the discharged powder. The conditions were required to provide an average flow rate higher than 3.2967 $mg.s^{-1}$ (nozzle size, 3.00 mm ID) that was obtained from the first model of the powder deposition unit. (Phattanaphibul *et al.*, 2007). The difference in the average flow rate calculated from the two testing durations of 5 and 10 s was used as an indicator of flow consistency. Statistical analysis was carried out using the MINITAB software package (Version 14; Minitab Inc.; State College, PA, USA). A two-sample *t*-test was conducted with the hypothesis that H_o: μ_{5s}-$\mu_{10s} = 0$ and H_a: μ_{5s}-$\mu_{10s} \neq 0$ at the 95% confidence level ($\alpha = 0.05$). The results illustrated the consistency of the flow when H_o cannot be rejected ($P > \alpha$). Analysis of variance (ANOVA) was also applied to investigate the effect of the nozzle size and the air pressure on the flow rate. Lastly, the discharged powder was required to accumulate in the container to show the ability to control the flow during material deposition in an operational situation.

RESULTS AND DISCUSSION

The results showed that excluding condition D, the remaining conditions achieved the target average flow rate of 3.2967 $mg.s^{-1}$. However, considering only the flow rate may not reflect good flowability. Therefore, the consistency of flow and characteristics of the discharged powder were taken into consideration. The analytical results indicated that all conditions could pass the consistency of flow criteria because H_o cannot be rejected, that is, $P > 0.05$ as presented in Table 1. Figure 6 shows the residual plots for the flow rate. The normal probability plot and histogram in Figure 6 indicate that the data were distributed normally. The plots of the residual versus fitted values and the observation order present no apparent dependence

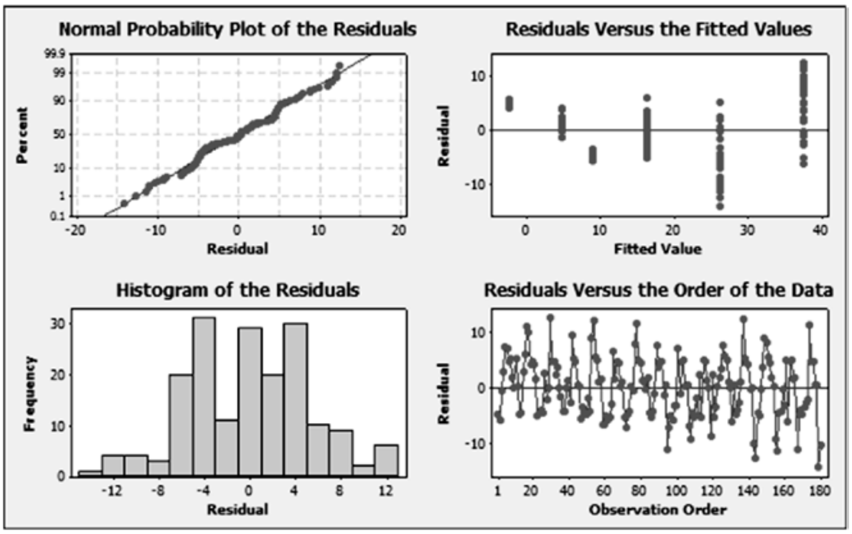

Figure 6 Residual analysis from the MINITAB software package.

in the residuals. Thus, ANOVA could be applied. As shown in Figure 7, the results illustrated that the flow rate was affected by the nozzle size and the air pressure due to the rejection of H_0 ($P < 0.05$). The larger the nozzle size or the higher the air pressure, the greater the flow rate will be. For the last criteria, the results were classified into 'accumulated' and 'spread' powder (Table 1) and Figure 8 shows some examples of each. High air pressure spread the powder over the container as was found in condition B, C, E and F. These four conditions were not applicable for practical application.

As a result, the most suitable condition that satisfied all the criteria was condition A (nozzle size 18G and air pressure 0.5 bar). The obtained average flow rate was 4.312 ± 0.555 $mg.s^{-1}$. The low standard deviation also indicated the consistency of the results, that is, the repeatability of condition A. In addition, condition D (nozzle size 20G and air pressure 0.5 bar) may be applied also due to the absence of any flow problems. However, the low flow rate may result in a longer fabrication time.

RECOMMENDATIONS AND CONCLUSION

A powder material deposition unit for an SVM machine was redesigned from previous models to be more applicable for PLA powder which exhibits funnel flow. The prototype of this new model was constructed and tested to determine suitable process parameters. The

Analysis of Variance for Flow rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Nozzle size	1	5823	5823	5823	201.76	0.000
Air pressure	2	26454	26454	13227	458.25	0.000
Error	176	5080	5080	29		
Total	179	37357				

S = 5.37254   R-Sq = 86.40%   R-Sq(adj) = 86.17%

Figure 7 Analysis of variance results for flow rate.

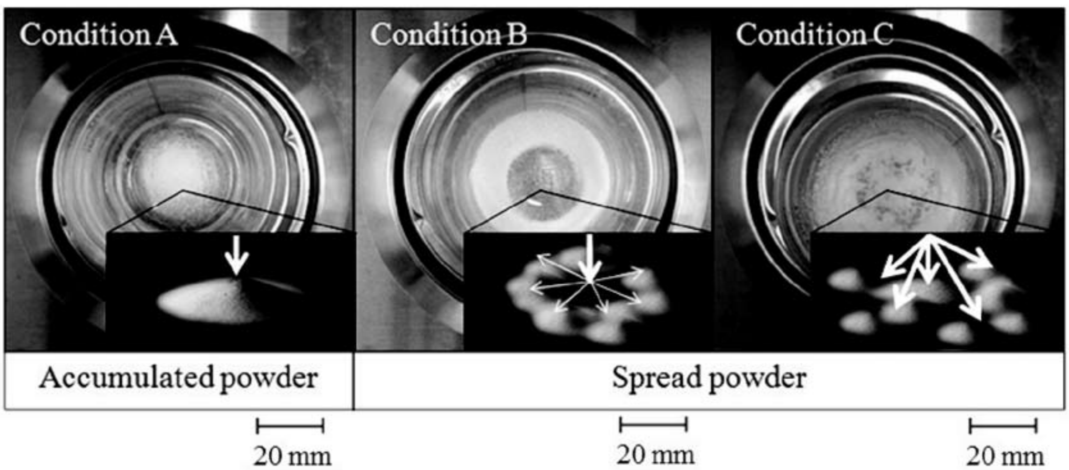

Figure 8 Examples of deposited powder in the container (plan view).

Table 1 Experimental and analytical results.

Condition	Nozzle size	Air pressure (bar)	Average flow rate ($mg.s^{-1}$)			P-value for testing H_o	Standard deviation of flow rate ($mg.s^{-1}$)			Characteristic of deposited powder
			5s	10s	Total		5 s	10 s	Total	
A		0.5	4.381	4.243	4.312	0.508	0.361	0.706	0.555	A
B	18G	1.0	15.070	15.630	15.350	0.583	2.323	3.199	2.762	S
C		1.5	43.070	43.420	43.245	0.859	4.544	6.121	5.300	S
D		0.5	2.467	2.327	2.397	0.326	0.458	0.287	0.382	A
E	20G	1.0	5.910	5.690	5.800	0.607	1.256	1.032	1.135	S
F		1.5	19.880	21.270	20.575	0.444	4.967	4.847	4.874	S

H_o: $\mu_{5s}-\mu_{10s} = 0$ ($\alpha = 0.05$) ; A = Accumulated; S = Spread.

experimental results suggested a 18G flat-ended hypodermic needle as the filling nozzle using an air pressure of 0.5 bar for the extend stroke of a double-acting pneumatic cylinder. Using these selected conditions, the PLA powder was able to flow through the filling nozzle at an average flow rate of 4.312 ± 0.555 $mg.s^{-1}$ without any flow problems. This design could be further improved for an actual powder material deposition unit. A hopper could be added to hold the PLA powder. As the PLA powder is fed into the syringe through a small pipe, a shutoff valve may be also used to control the amount of PLA powder being fed into the syringe. In addition, future studies will check the suitability of this unit with other powder materials which have a flow problem similar to PLA powder.

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