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ORIGINAL ARTICLE

Development of injection molding tooling with conformal cooling channels fabricated by optimal process parameters

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Abstract

Wax patterns can be used in precision casting. Developing a low-cost approach to rapid fabrication of customized wax patterns with complex geometry is an important research issue. In this study, a wax filament with low melting point is developed for fabricating wax patterns using additive manufacturing technology. The optimal process parameters for producing wax pattern were investigated using the Taguchi design method. The results show that the most important control factor affecting the form accuracy of the fabricated wax patterns is the flow of nozzle, followed by print speed. The form accuracy of the fabricated wax patterns has the lower impact for the nozzle temperature and bed temperature. The optimal process parameters for producing wax patterns are nozzle temperature of 64 °C, print speed of 60 mm/s, bed temperature of 40 °C, and flow of nozzle of 100%. An injection molding tooling is fabricated by wax conformal cooling channels fabricated by the optimal process parameters.

Keywords Injection molding tooling · Wax · Conformal cooling channel · Taguchi method

1 Introduction

Additive manufacturing (AM) refers to manufacturing physical models directly from computer-aided design data [1]. Physical models allow engineers to verify their product design at the research and development stage. The current competitive market needs to lower product manufacturing cost and faster product development speed. Thus, rapid tooling technologies are developed. Wax patterns can be used for fabricating metal components by investment casting inexpensively and swiftly [2, 3]. Generally, wax injection molding is widely employed to fabricate wax patterns. However, the fabricated wax patterns are limited to geometric shapes due to complexity of the wax injection mold. The production rate can be improved significantly by the wax injection mold with conformal cooling channels [4]. Based on green manufacturing technology [5], it is important to develop green manufacturing processes for rapid tooling technologies. Wax conformal cooling channels can be easily removed during rapid tooling manufacturing process. Wax conformal cooling channels with high geometric complexity can be easily fabricated by additive AM. Thus, developing wax filaments for fabricating conformal cooling channels using AM technology is an important research issue.

The L_9 (3^4) orthogonal array has been widely used to determine the signal-to-noise (S/N) ratio in the Taguchi method. Akıncıoglu et al. [6] applied the L_9 orthogonal array to investigate the effects of cryogenically treated tools in turning of Hastelloy C22 super alloy on surface roughness. Choi et al. [7] used the Taguchi method to select the optimal conditions of electrochemical polishing of the stainless steel. Pinar et al. [8] employed the Taguchi method to study the different cooling methods in the pocket milling of AA5083-H36 alloy. Gong et al. [9] applied the Taguchi method to enhance the tensile strength of injection-molded fiber-reinforced composites. Zhou et al. [10] used the Taguchi method to investigate the effects of a special nozzle structure on its outlet velocity uniformity. Azadeh et al. [11] employed the Taguchi method to select the optimum maintenance policy. Costa et al. [12] applied the Taguchi method to optimize the process parameters for steel turning process. Effertz et al. [13] applied the Taguchi method to optimize the process parameters for friction spot welded aluminum alloy. Jorge et al. [14] used the Taguchi

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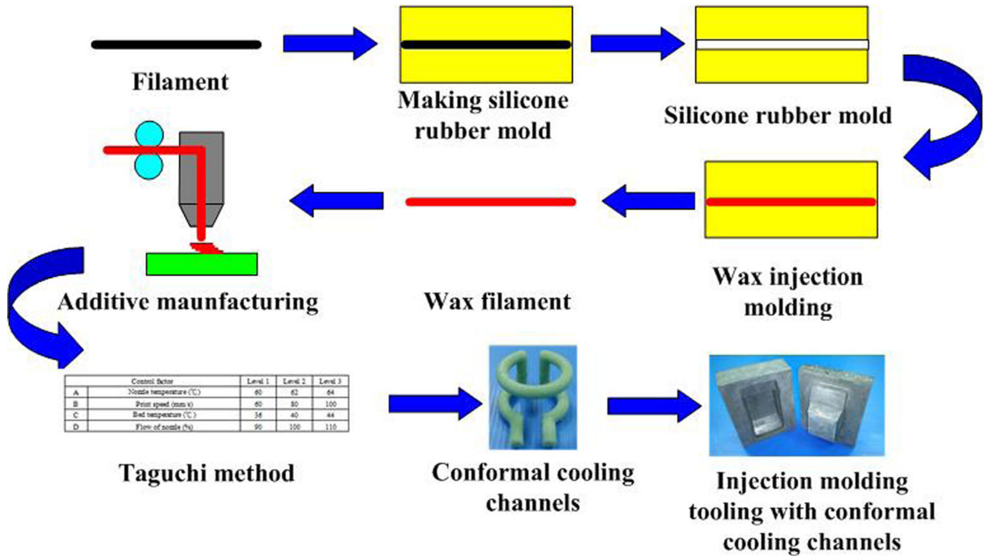


Fig. 1 Research methodology of this study

method to optimize the process parameters for a medical device cutting process. Adnan et al. [15] applied the Taguchi method to study the springback behavior of AA6061 strip with non-uniform thickness. The main purpose of this study is to develop wax filaments for fabricating wax patterns. In addition, the optimal additive manufacturing process parameters for producing wax conformal cooling channels are also investigated experimentally using the Taguchi method.

2 Experimental details

A cylindrical rod with a dimension of 10 and 10 mm in height was designed with the Pro/ENGINEER CAD software and used as a master model in this study. The edge of the printed cylindrical rod has an obvious stair-stepping effect that can be used for evaluating the form accuracy of wax patterns. A set of horizontal cross-sections can be generated by slicing process using slicing software (Ultimaker Inc.). Four factors affecting the implementation feasibility of wax patterns, i.e., nozzle temperature, print speed, bed temperature, and flow of nozzle, are selected as control factors in this study. To investigate the effects of additive manufacturing process parameters on the form accuracy of wax patterns, an L_9 orthogonal array was designed based on the Taguchi method. The-smaller-the-better was chosen because the minimum peak-to-valley (P-V) value of the fabricated wax pattern stands for better surface quality. The P-V value, i.e., form accuracy of the wax patterns, was examined using an optical microscope (M835, Microtech Inc.).

The research processes of this study were shown in Fig. 1. It includes nine major steps. A polylactic acid (PLA) filament was used as a master model to make an elastic mold. Figure 2 shows an elastic mold fabricated by a liquid silicone rubber (KE-1310ST, Shin Etsu Inc.) for

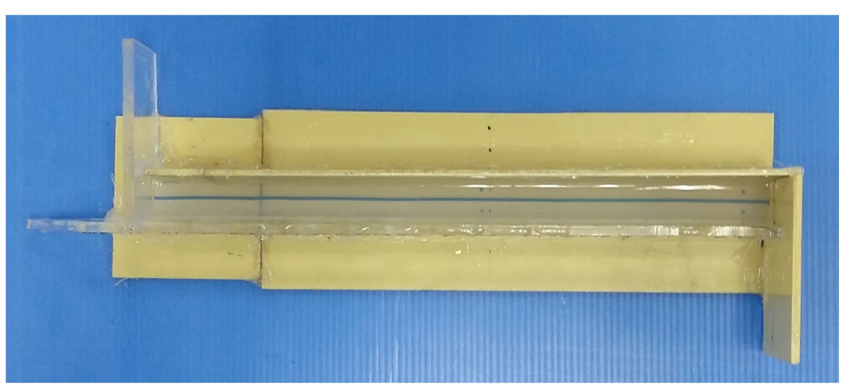


Fig. 2 An elastic mold for producing wax filaments using a low-pressure wax injection molding machine

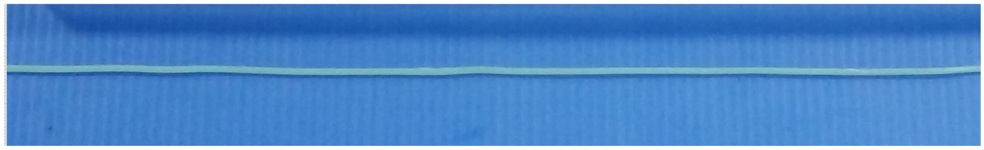


Fig. 3 Wax filament fabricated by the developed silicone rubber mold

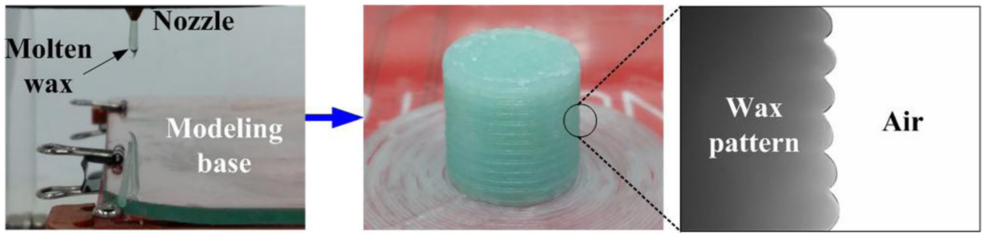


Fig. 4 A typical wax pattern fabricated by AM

fabricating wax filament through a low-pressure wax injection molding machine (0660, W&W Inc.). The silicone rubber was mixed with a curing agent thoroughly with a stirrer. The silicone rubber and curing agent were mixed in a weight ratio of 10:1. It is easy to make a mistake to determine the amounts of hardener and liquid silicone rubber precisely by a human. In order to reduce human error, a program was developed using a visual basic program to determine the amounts of both hardener and liquid silicone rubber. A vacuum machine (F-600, Feiling, Inc.) was used to extract the air bubbles resulting from the mixing process under vacuum conditions. The diameter of the PLA filament is 1.75 mm. The process parameters for producing wax filaments are degassing time of 7 s, injection temperature of 85 °C, injection time of 5 s, and injection pressure of 0.7 kgf/cm^2.

3 Results and discussion

Figure 3 shows a wax filament fabricated by the developed silicone rubber mold. The melting temperature of the developed wax filament is less than 70 °C, which is lower than that of commercially available wax filament. Low power consumption in the process is consistent with green manufacturing technology. The developed wax filament has excellent toughness and can be used to fabricate wax patterns using AM technology. In addition, the cost of the developed wax filaments is cheaper than commercially available wax filaments. It was found that the cost of the developed wax filament is only New Taiwan dollar (NTD) 0.3/g while the cost of the commercial wax filament is NTD 6/g. The wax filament was delivered to a three-dimensional printing machine by two rollers. Figure 4 shows a typical wax pattern fabricated by

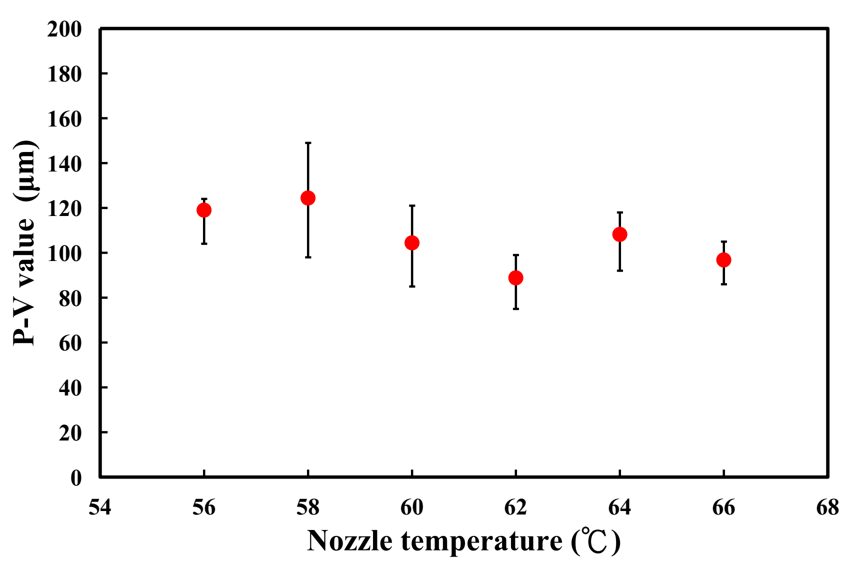


Fig. 5 Effects of the nozzle temperature on the form accuracy of wax patterns

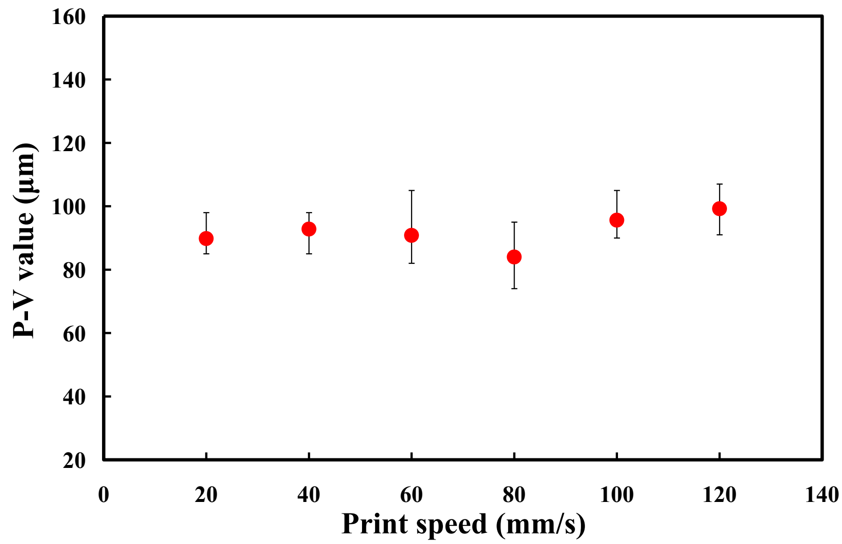


Fig. 6 Effects of the print speed on the form accuracy of wax patterns

AM. This result means that the developed wax filaments provide the capability to fabricate wax patterns using AM technology.

Figure 5 shows the effects of the nozzle temperature on the form accuracy of wax patterns. Results show that the nozzle temperature of 62 °C has the lowest P-V value. Thus, nozzle temperature of 62 °C was selected as level 2 of control factor 1. The nozzle temperature of 60 and 64 °C was selected as level 1 and level 3 of control factor 1, respectively. Figure 6 shows the effects of the print speed on the form accuracy of wax patterns. Results show that the print speed of 80 mm/s has the lowest P-V value. Thus, print speed of 80 mm/s was selected as level 2 of control factor 2. The print speed of 60 and 100 mm/s was selected as level 1 and level 3 of control factor 2, respectively. Figure 7 shows the effects of the bed temperature on the form accuracy of wax patterns. Results show that the bed temperature of 40 °C has the lowest P-V value. Thus, bed temperature of 40 °C was selected as level 2 of control factor 3. The bed temperature of 36 and 44 °C was selected as level 1 and level 3 of control factor 3, respectively. The extruded wax is about 3.2 mm^3/s when the nozzle flow rate is 100%. Figure 8 shows the effects of the flow of nozzle on the form accuracy of wax patterns. Results show that the flow of nozzle of 100% has the lowest P-V value. Thus, the flow of nozzle of 100% was selected as level 2 of control factor 4. The flow of nozzle of 90 and 110% was selected as level 1 and

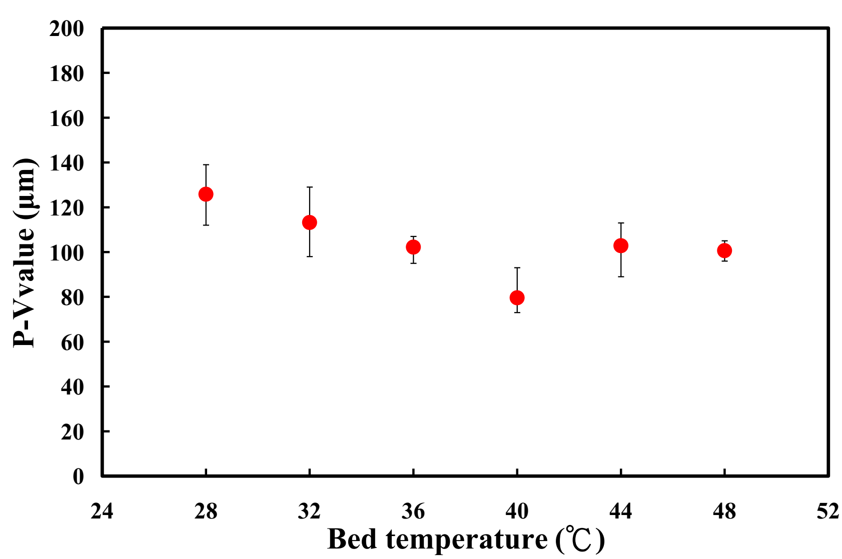


Fig. 7 Effects of the bed temperature on the form accuracy of wax patterns

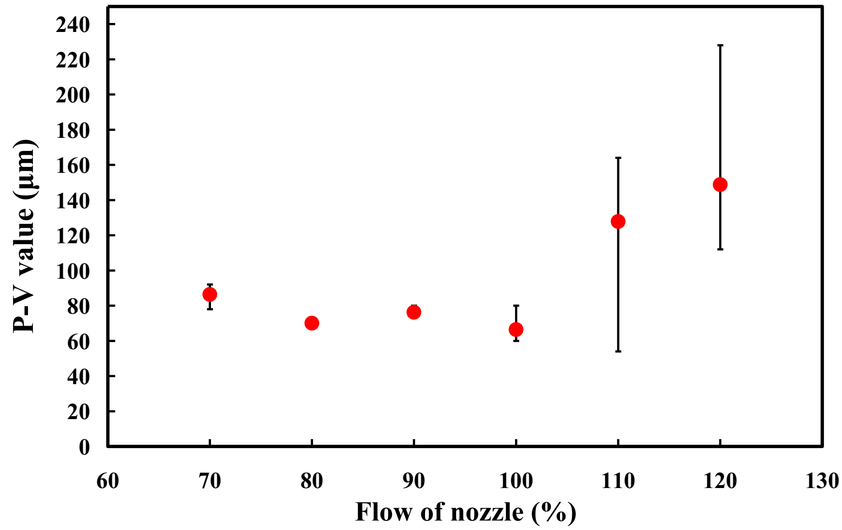


Fig. 8 Effects of the flow of nozzle on the form accuracy of wax patterns

Table 1 Process control factors and their levels

Control factor		Level 1	Level 2	Level 3
A	Nozzle temperature (°C)	60	62	64
B	Print speed (mm/s)	60	80	100
C	Bed temperature (°C)	36	40	44
D	Flow of nozzle (%)	90	100	110

level 3 of control factor 4, respectively. According to the experimental results described above, four process control factors and their levels were listed in Table 1.

The L_9 orthogonal array (OA) was chosen in this study because it is suitable for the four process control factors with three levels. To investigate the optimal additive manufacturing process parameters of wax patterns with highest form accuracy, three levels were used in this study. The experimental results of the depth error based on L_9 OA were listed in Table 2. Figure 9 shows the wax patterns fabricated by different parameters. The quality characteristics can be classified into three types, i.e., the-bigger-the-better, the-nominal-the-best, and the-smaller-the-better in the Taguchi design method. In this study, the-smaller-the-better is chosen because a lower P-V value stands for a better form accuracy of the fabricated wax patterns. The corresponding S/N ratio can be calculated based on the-smaller-the-better quality characteristics, as shown in Table 3.

Figure 10 shows the S/N ratio effects of each process control factor. As can be seen, a set of optimal combination of process control factors and levels can be determined because a higher S/N ratio means a better quality characteristic. The optimal combination is A3, B1, C2, and D2. The optimal process parameters for producing wax patterns using additive manufacturing technology are nozzle temperature of 64 °C,

Table 2 Experimental results of depth error

Experiment no.	Control factor				Form accuracy (μm)			σ^2	S/N (dB)
	A	B	C	D	1	2	3		
1	a1	b1	c1	d1	74	75	73	1.5	− 37.385
2	a1	b2	c2	d2	72	65	62	43.278	− 36.452
3	a1	b3	c3	d3	80	81	74	19.278	− 37.886
4	a2	b1	c2	d3	64	74	73	57.111	− 36.961
5	a2	b2	c3	d1	75	68	77	37.944	− 37.318
6	a2	b3	c1	d2	67	68	59	32.611	− 36.23
7	a3	b1	c3	d2	59	60	64	9.5	− 35.712
8	a3	b2	c1	d3	82	76	71	46.444	− 37.669
9	a3	b3	c2	d1	68	74	72	18.444	− 37.071

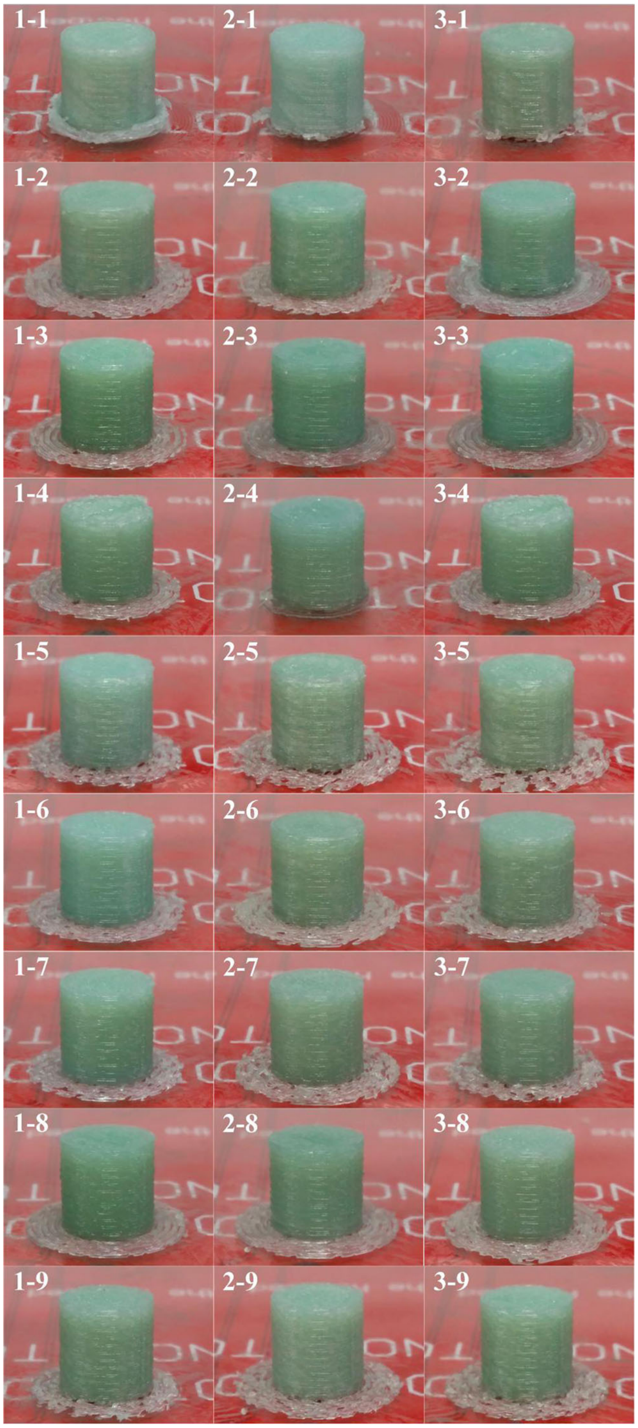


Fig. 9 Wax patterns fabricated by different parameters

print speed of 60 mm/s, bed temperature of 40 °C, and flow of nozzle of 100%.

In order to investigate the results of the experimental designs, the analysis of variance (ANOVA) was carried out. The percentage contribution of each control factor was employed to measure the corresponding effect on the quality characteristic. The results of ANOVA were listed in Table 4. The percentage contribution of each control factor can be calculated. It was found that the percentage contributions for the control factors *d*, *b*, *a*, and *c* are 79.87, 8.95, 8.52, and 2.66%, respectively. This shows that the flow of nozzle is the most significant control factor affecting the form accuracy of the fabricated wax patterns. Figure 11 shows the schematic illustration of the percentage of contribution.

The verification test is essential in engineering analysis to validate the better form accuracy of the wax patterns fabricated by the optimal process parameters. Therefore, the final step of the Taguchi method is to carry out a verification test for examining the form accuracy of the fabricated wax patterns using the optimal process parameters. Table 5 presents the results of verifying the optimal process parameters. These results were consistent with expectation. It is clear that the form accuracy of the wax patterns fabricated by the optimal process parameters is better than that fabricated by the general process parameters. Thus, the optimal process parameters can be used for fabricating wax conformal cooling channels.

It potentially leads to inconsistencies of the surface quality if manual finishing is used [16]. In order to maintain the dimensional accuracy of the wax patterns, soaking wax patterns in hot water was used in this study. Figure 12 shows the form accuracy of the wax pattern soaking at different hot water temperatures with different duration. As can be seen, the surface qualities of the wax patterns soaking at temperatures of 55 and 60 °C with the soaking time of 15 s are improved significantly, but the soaking time is too long under the same surface quality of the wax pattern. The surface profiles of the wax patterns have been changed when the wax patterns were soaked at temperatures of 65 and 70 °C because water temperature is excessive. Based on the achieving integrity of geometry and soaking duration, the optimal process parameter for enhancing the form accuracy of the wax pattern is water temperature of 65 °C with soaking time of 10 s. Thus, a wax conformal cooling channel was treated with this condition to enhance the surface finish of the fabricated wax conformal cooling channels. The principal benefits of this method are that expensive facility, specific fixture, and

Table 3 Response table of S/N ratio based on the-smaller-the-better quality characteristics

Control factor	Level 1	Level 2	Level 3
Nozzle temperature (°C)	− 37.241	− 36.836	− 36.818
Print speed (mm/s)	− 36.686	− 37.146	− 37.062
Bed temperature (°C)	− 37.095	− 36.828	− 36.972
Flow of nozzle (%)	− 37.258	− 36.131	− 37.505

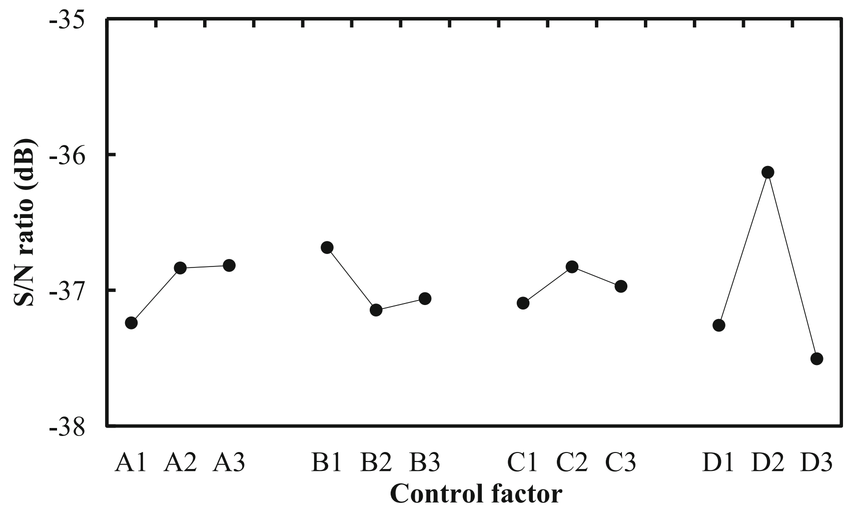


Fig. 10 S/N ratio effects of each process control factor

Table 4 ANOVA table

Control factor		Level1	Level 2	Level 3	SS	DOF	*V*	*ρ* (%)
A	Nozzle temperature (°C)	− 37.241	− 36.836	− 36.818	4.029	2	0.172	8.52
B	Print speed (mm/s)	− 36.686	− 37.146	− 37.062	4.029	2	0.180	8.95
C	Bed temperature (°C)	− 37.095	− 36.828	− 36.972	4.029	2	0.054	2.66
D	Flow of nozzle (%)	− 37.258	− 36.131	− 37.505	4.029	2	1.609	79.87

great sill are not required. In addition, it is not a time-consuming and expensive process.

An excellent cooling system design can shorten the cooling time. A reduction in the cooling time will increase the production rate. The cooling efficiency [17–19] of molds or dies is principally dependent on the surface finish of the inner cooling channels because it affects the flow of coolant during the cooling stage. Figure 13 shows the wax conformal cooling channels fabricated by general process parameters, optimal process parameters, and optimal process parameters with surface treatment. This means that the fabrication time of wax conformal cooling channels with smooth surface can be reduced dramatically. Thus, molds or die with excellent cooling efficiency

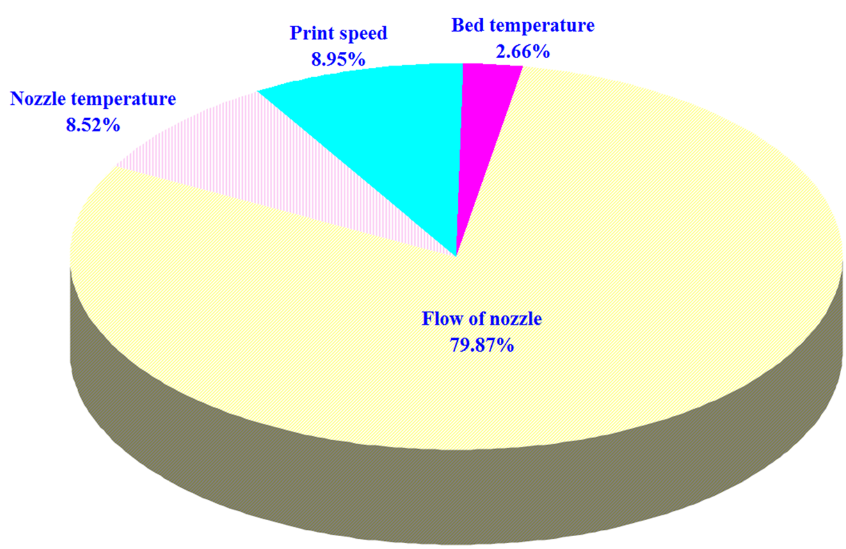
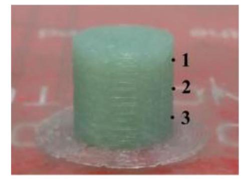
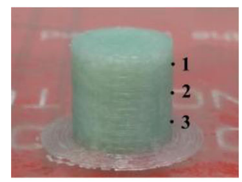
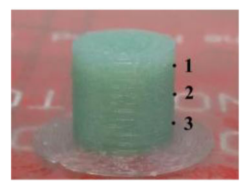
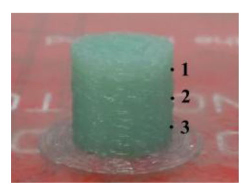


Fig. 11 Schematic illustration of the percentage of contribution

Table 5 Results of verifying the optimal process parameters

Process parameters	Form accuracy (μm)			Wax patterns
	Measurement point 1	Measurement point 2	Measurement point 3	
Nozzle temperature 64 °C Print speed 60 mm/s Bed temperature 40 °C Flow of nozzle 100%	69	67	68	
Nozzle temperature60 °C Print speed 60 mm/s Bed temperature 36 °C Flow of nozzle 90%	91	91	75	
Nozzle temperature 62 °C Print speed80 mm/s Bed temperature 40 °C Flow of nozzle 100 %	85	74	70	
Nozzle temperature 64 °C Print speed 100 mm/s Bed temperature 44 °C Flow of nozzle 110 %	116	89	123	

can be implemented by the use of wax conformal cooling channels treated by optimal process parameters with surface treatment. In addition, ultra-large wax injection molds with complex conformal cooling channels can be implemented swiftly by the use of aluminum-filled epoxy resins. In addition, the production costs for molds or dies

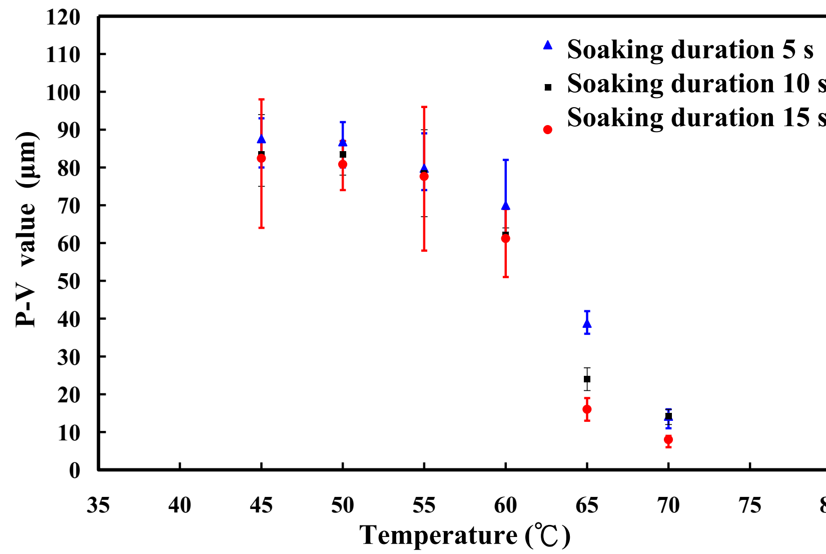


Fig. 12 The form accuracy of the wax pattern soaking at different hot water temperatures with different duration

with conformal cooling channels are lower than that fabricated by atom diffusion additive manufacturing (ADAM), electron beam melting (EBM) [20], selective laser melting (SLM) [21], selective laser sintering (SLS) [22], diffusion bonding (DB) [23], direct metal deposition (DMD) [24], or direct metal laser sintering (DMLS) [25] particularly for ultra-large molds or dies with conformal cooling channels. In general, molds with conformal cooling channels fabricated by ADAM, EBM, SLM, SLS, DB, DMD, or DMLS employed a hybrid machining process. Only the vital part with conformal cooling channels of a mold was fabricated by ADAM, EBM, SLM, SLS, or DB. The other part without conformal cooling channels of a mold was fabricated by conventional machining. The molds fabricated by hybrid machining process will result in coolant leakage from the connection

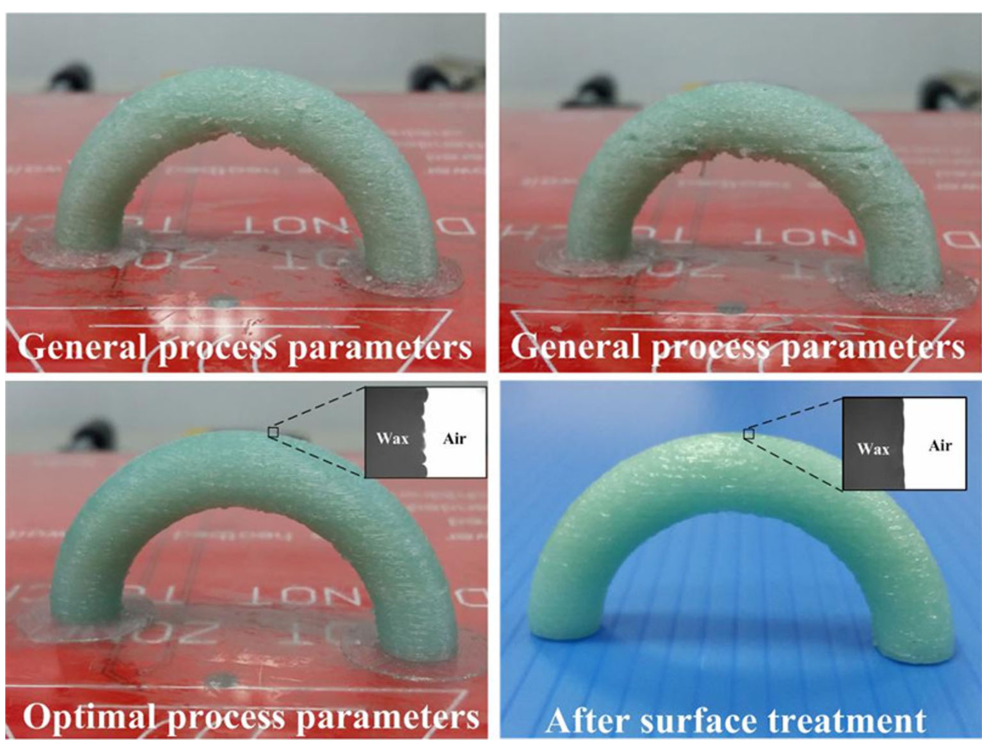


Fig. 13 Wax conformal cooling channels

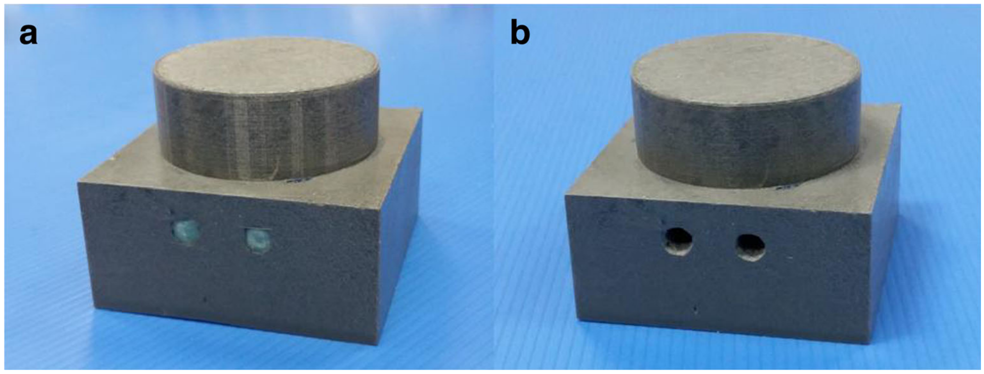


Fig. 14 An injection molding tooling with conformal cooling channel **a** before and **b** after removing the wax conformal cooling channels

locations of the mold during injection molding because the bonding strength is inferior to other parts of a mold. However, the specific advantage of this work is that the coolant will not result in leakage during injection molding for a long period of time under normal conditions because an injection molding tooling can be fabricated by one process manufacturing [26]. Figure 14 shows an injection molding tooling with conformal cooling channel.

This result reveals that an injection molding tooling with conformal cooling channels having smooth surface can be fabricated rapidly by the method proposed in this study. However, the mold strength fabricated with the aluminum-filled epoxy resin is inferior to the mold fabricated with conventional mold steels. Thus, enhancing the mold strength by a filler is needed. A future work is required to optimize the layout of conformal cooling channels by using computer simulation software because the cycle time is considered as a main factor affecting the productivity in the injection molding process.

4 Conclusions

AM has been widely employed in the area of new product development. Investment casting is a cost-effective method for manufacturing new metal parts using wax patterns. The aim of this work is to develop wax filaments for fabricating wax patterns using AM technology. The optimal process parameters are investigated using the Taguchi method. Based on the results discussed in this study, the following conclusions can be drawn:

1. The developed wax filament is very practical and provides the greatest application potential in both additive manufacturing and investment casting industries.
2. The optimal process parameters for producing wax patterns are nozzle temperature of 64 °C, print speed of 60 mm/s, bed temperature of 40 °C, and flow of nozzle of 100%.
3. The most important control factor affecting the form accuracy of the fabricated wax patterns is the flow of nozzle, followed by print speed.

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