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Preliminary study of unmodified wax printing using FDM 3D-printer for jewelry

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Abstract

This paper proposes a preliminary study of making wax model from a customized FDM 3D- printer for jewelry application. Using external extrusion speed and heating control together with the XYZ gantry control of the original printer, two types of wax, injection grade and carving and milling wax were extruded through a plunger-cylinder extruder to form some basic shapes and Buddha statues. Flowability of waxes was investigated and the printing objects were observed. It was found that both waxes could be extruded at a temperature lower than their melting points. The modified FDM 3D-printer could produce 3D wax objects but the materials were easily spread outwards during printing. Further study focusing on printing parameters and material properties were required to improve the printing resolution and accuracy.

Keywords: FDM 3D-printer, Wax printing, Jewelry, Plunger-cylinder extrusion

1. Introduction

Fused deposition modelling (FDM) 3D-printer is a modern additive manufacturing process normally used for making model or prototype. Due to its price advantage and incomplexity, nowadays, the printer is used widely among makers. An FDM 3D-printer extrudes molten material through a small diameter nozzle, generally of 0.4 mm. to form lines and layers of material following the predetermined 3d-computer model profile. Materials used in FDM 3D-printer are mostly thermoplastics including PLA, ABS, PET, nylon, etc. and sometimes with various fillers added such as wood, carbon and copper to improve the printing parts' properties [1-4]. More and more types of materials can be used with FDM 3D-printer these days for specific purposes in the field of construction, food production as well as medical applications as a result of many attempts made by many researchers [5-10]. Among those, many literatures utilized plunger-cylinder extrusion for 3D printing of liquid- and gel-like materials [11-13].

Jewelry making is a process that requires skillful craftsmanship. It starts with an original artist's unique master design that includes various shapes of gemstones and metal parts. While the gemstones are cut into required shape by hands, the metal part can be cloned using one-time plaster mold made by lost wax casting process. In this process, the master prototype is used to make a silicone rubber mold. Then the prototype is removed and molten wax is poured into that mold in order to get a wax model similar to the master. Later, the model is craved and polished until the details are closed to the original master prototype so it can be used as an insert for plaster mold making. In an oven, the wax model is molten away leaving an empty plaster mold which then, finally, is used only once for molding. The lost wax process is complicated, time consuming and requires skillful workers. Recently, selective laser sintering (SLS) and digital light processing (DLP) technology are introduced to shorten the process and it is claimed that these technologies are accurate and repeatable. However, their price and maintenance cost are still high. [14]

To integrate the advantage of rapid prototype making from additive manufacturing and cost effectiveness from FDM 3D-printing, this paper proposes a preliminary study of making wax model made of original waxes used in jewelry process including injection-grade and carving and milling-grade waxes by using a modified FDM 3D-printer extrusion set. It is expected that the obtained results from this study are useful as a guideline for developing a new method for low-cost, FDM 3D-wax printing later.

2. Materials and methodology

2.1 Materials

Two types of wax including injection-grade and carving and milling-grade waxes were obtained from a Thai local jewelry maker. Normally, injection-grade wax is used to make general simple jewelry patterns while carving and milling-grade wax is suitable for more detailed patterns since the latter material can be filed, polished or CNC machined. In this study, an injection-grade wax, Blue New, from Siam Casting Powders LTD. and a carving and milling-grade wax, green Ferris File-A-Wax, from Freeman Company were used as the trial materials. Their properties are shown in Table 1.

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Table 1 Some properties of the injection-grade wax (Blue New) form Siam casting powers LTD. and carving and milling-grade wax, green Ferris File-A-Wax, from Freeman Company

Properties	Injection-grade wax (Blue New)	Carving and milling-grade wax (Ferris File-A-Wax)
Melting point	68-72°C	243ºF (117ºC)
Hardness (Shore D)	N/A	57
Specific gravity	0.8-0.9	0.92
Flash point	N/A	585ºF (307ºC)

2.2 Modified FDM 3D-printer extruder

The original designed 3D-printer consists of a heating nozzle and a moving bed that can be moved accordingly along an XYZ-axis. To make a 3D-plastic shape, the present equipment utilizes a stepper motor to push continuous line of solid filament into the heating nozzle and other 3 stepper motors to control the nozzle and bed movement so that the plastic lines can be layered as wanted. Since solid wax is more brittle than the plastic filament and its melt viscosity is very low, using the current extrusion system is not possible. It was decided to heat the wax and then inject the molten material instead. The new extrusion unit was made as shown in Figure 1. A plunger-cylinder type extruder made of 6063 aluminum was attached with a 300W heater band and at the nozzle tip, a type-K thermocouple was installed to monitor and control the molten wax temperature. To inject the wax, a 12V, 1.7A stepper motor with 150-mm linear slider set from Machifit was used.

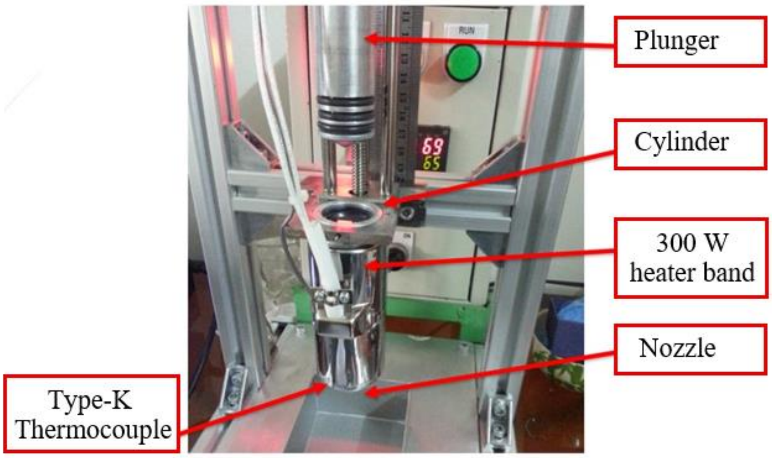


Figure 1 The modified extruder for wax injection

A microcontroller, Arduino Mega 2560, and a stepper motor driver, Microstep TB6600, were used to signal the step motor. Extrusion speed can be varied by adjusting the controlled pulse width (period) from the microcontroller by means of changing the duration of high output signal time, *t1*. As shown in Figure 2 and Equation 1-3, the extrusion speed (mm/s) depends on numbers of pulse per duration time (Times), and can be found according to the system configuration.

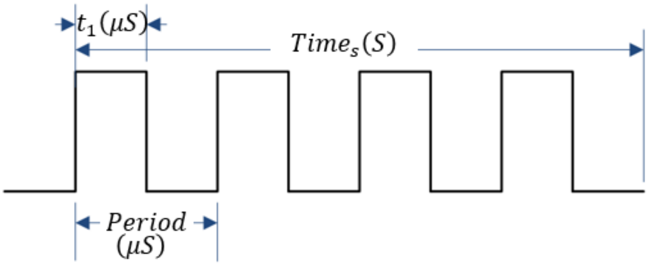


Figure 2 Parameters to control stepper motor and extrusion speed

$$Period = 2t_1 \quad (1)$$

$$Pulse = \frac{Time_s}{Period \times 10^{-6}} \quad (2)$$

$$speed_e = screw_p\left(\frac{1.8 \times 10^6}{360period}\right) = screw_p\left(\frac{1.8 \times 10^6}{360 \times 2t_1}\right) \quad (3)$$

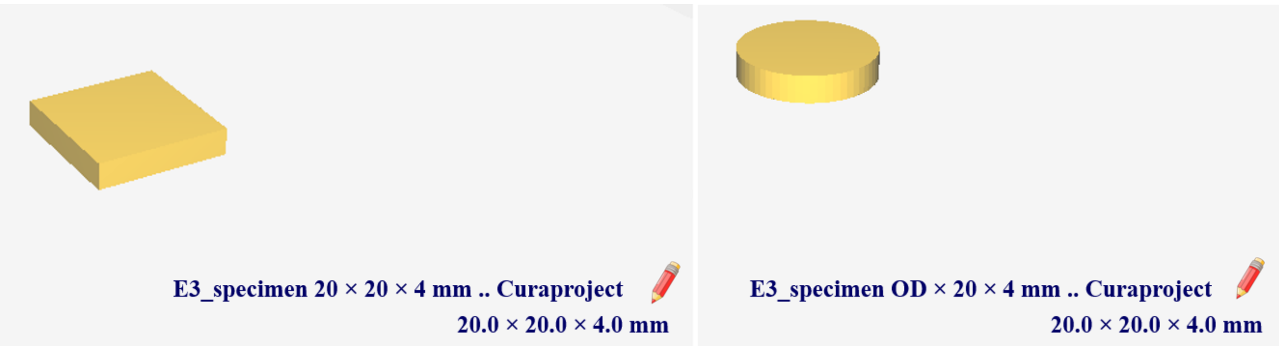
where
$speed_e$ is extrusion speed (mm/s)
$screw_p$ is linear slider screw pitch (mm).

2.3 Extrusion experiments

To obtain a 3D shape from FDM 3D-printer, the extruder must be able to extrude a continuous line of semisolid material. In this experiment, the modified extruder was set up to inject both grades of wax at 10 various extrusion speeds and at 4 various temperatures below or near to their melting points. It was intended to use the same nozzle size of 0.4-mm diameter however, from the initial experiment, the results suggested that the injection-grade wax could be extruded through 0.4-mm diameter nozzle very well while the carving and milling-grade wax could be extruded through a larger nozzle of 1.0-mm diameter. At 0.4-mm diameter nozzle, the carving and milling-grade wax was more viscous and turned to solid faster that the injection-grade wax hence the nozzle was clogged eventually even at the highest extrusion speed setting. This was due to its higher density and faster solidification. The higher melting temperature made it easily solidify at room temperature especially for a small amount of material being injected from 0.4-mm nozzle. Changing to l.0-mm nozzle for more material injection could prolong the time of material to solidify and solve the nozzle clog up. However, this would affect the model appearance and accuracy later. The solid-liquid phase versus material temperature should be investigated thoroughly to point out the suitable injection temperature range and temperature control for semisolid line in the future. Since this paper proposed preliminary study, At the present, the flow amount at various extrusion speed was investigated according to these conditions.

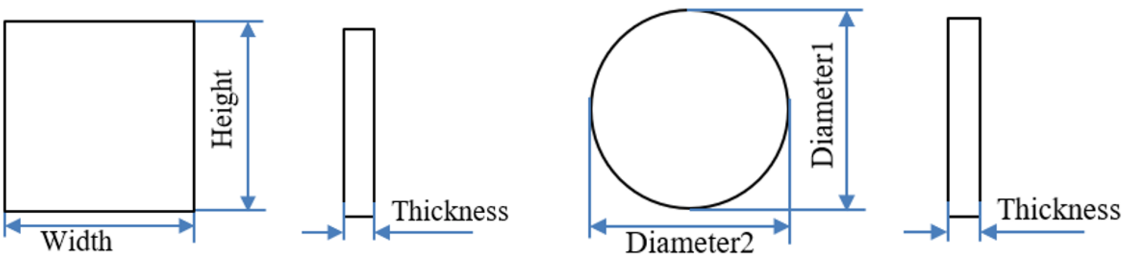
2.4 Simple shape experiments

The modified extruder was installed on Ender-3, a 3D-printer from Creality 3D to replace the original extrusion unit. Ultimaker's Cura 3.6 was used as slicer software to control only the gantry movement of the extrusion set and printer bed according to XYZ axis. Extrusion speed and wax temperature which could affect wax injection amount were controlled externally by Arduino Mega 2560 using some selected extrusion conditions obtained from the last experiment. During this, printer bed temperature was set at 60°C then shapes of wax were investigated in term of dimensions. Figure 3 shows the simple shape computer models, including 20 mm x 20 mm x 4 mm cuboid and 20 mm x 20 mm x 4 mm cylinder that were used for this experiment. The layer heights of 0.2, 0.3 and 0.4 mm for injection-grade wax and 0.6, 0.8 and 1.0 for carving and milling-grade wax with line fill-in and 100% infill were set for the tests. To achieve the layer settings, the nozzle was incrementally moved up to those specified heights after finish printing each layer by using Z-axis stepper motor. Setting lower layer height than nozzle diameter benefits stronger printing parts due to the excess material can be packed to fill in the gap between layer but too low layer height can cause dimensional error from the original design. Higher layer height than nozzle diameter is uncommon and should be avoided since it can cause weak layer attachment. At each setting, 3 repeated experiments had been conducted resulted in 3 printing examples and each was measured for their dimensions as shown in Figure 4. Overall width, height and thickness were one-time measured while diameter was measured twice in perpendicular direction using a vernier caliper. The measuring results were averaged and reported.



(a) (b)

Figure 3 Simple shape 3D-computer models (a) 20 mm x 20 mm x 4 mm cuboid and (b) ∅20 mm x 4 mm cylinder



(a) (b)

Figure 4 Simple shape measurement (a) cuboid shape and (b) cylinder shape

2.5 Preliminary 3D-wax model printing

Both wax materials were also extruded to form more sophisticated shape using selected settings from the last experiment. Roughly 60 mm x 30 mm x 80 mm, 3D model of buddha statue was selected as this is similar to the product made in local jewelry shop. It was aimed to preliminary assess if the wax could be injected smoothly when the extrusion unit was moving by observing the finishing wax models. Figure 5 show the model in Ultimaker Cura slicer program.

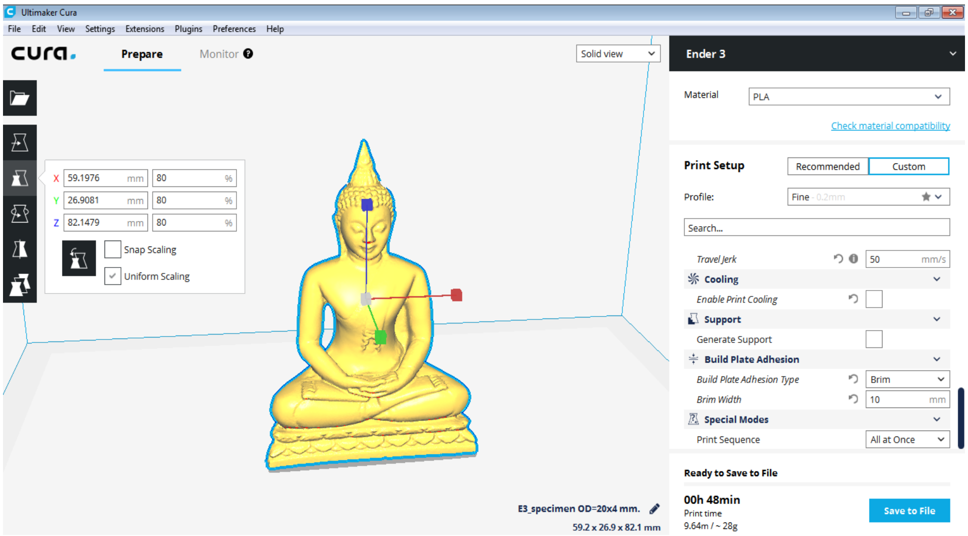


Figure 5 The 3D model of Buddha statue in Ultimaker Cura 3.6 [15]

3. Results and discussions

3.1 Flow of waxes at different temperatures

The experiments were conduct in order to investigate the flow of materials and their flowability affected by the change of temperature and extrusion speed. Figure 6 showed the example of extrusion line of both waxes. Semisolid wax line injection was not successful at too high temperature, 68°C in the case of injection-grade wax and 110°C in the case of carving and milling-grade wax. At these points, it was observed that during extrusion both materials were runny at the nozzle tip and then formed inconsistent flow with bubbles and droplets instead of continuous semisolid line even though at the slowest extrusion speed setting. This showed too high extrusion speed causing turbulent and uncontrollable flow at their current viscosity. Again, material temperature related to solid-liquid phase and viscosity also played an important role here. To be able to inject consistent flow line, too high extrusion speed for low viscosity material should be avoided.

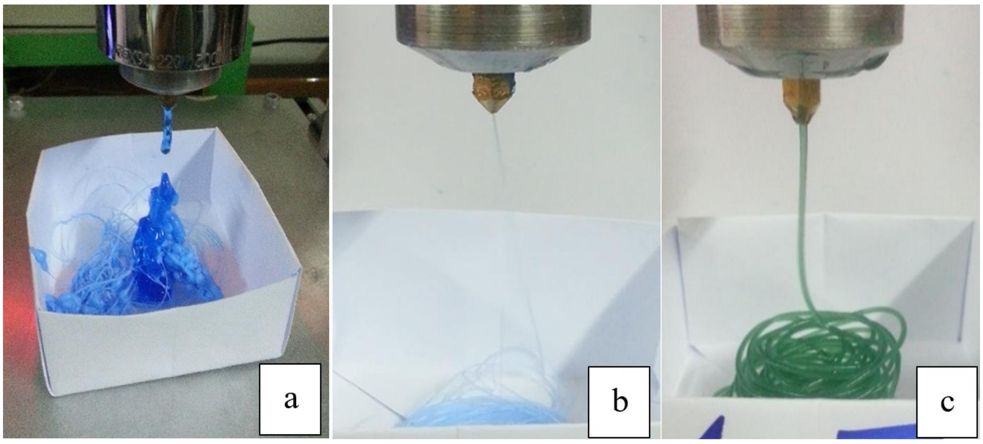


Figure 6 Extrusion line of injection grade wax and carving wax (a) droplet formed at too high temperature, (b) injection-grade wax line extruded from 0.4 mm nozzle and (c) carving and milling-grade wax line extruded from 1.0 mm nozzle

Flows of injection-grade wax and carving and milling-grade wax at various extrusion speed and temperature were plotted and shown in Figures 7 and 8. For both materials, it was shown that the more amount of wax could be extruded at higher extrusion speed as well as at higher temperature. At higher motor speed means higher power or back pressure exerts on molten materials while higher temperature also enhances the materials flowability due to their lower viscosity. Note that at 68°C the injection-grade wax could not successfully form a continuous line since it was in turbulent flow condition but the material was still injected at the same trend of other settings. This showed enough motor power to inject the material. Due to the viscosity effect, as expected, it can be seen that the injection-grade wax is easier to inject than the carving and milling-grade wax as shown by the higher flow amount at most of extrusion speed settings. At the speed of more than 0.18 mm/s, the higher temperature began to take more effect on easing carving and milling wax flow. This might be because of more internal friction heat accumulation caused from high extrusion speed applied to viscous material. The heat helped reducing viscosity of material inside the nozzle. Nevertheless, this internal friction should be kept minimal to prevent material degradation. To increase the flow, a higher speed from more powerful motor and a new nozzle internal shape design can help increasing the extrusion back pressure and reducing internal friction accordingly. It can be concluded that using plunger type extrusion is possible for wax injection however the suitable flow should be considered together with the printer gantry movement and must be carefully determined during 3D printing experiment.

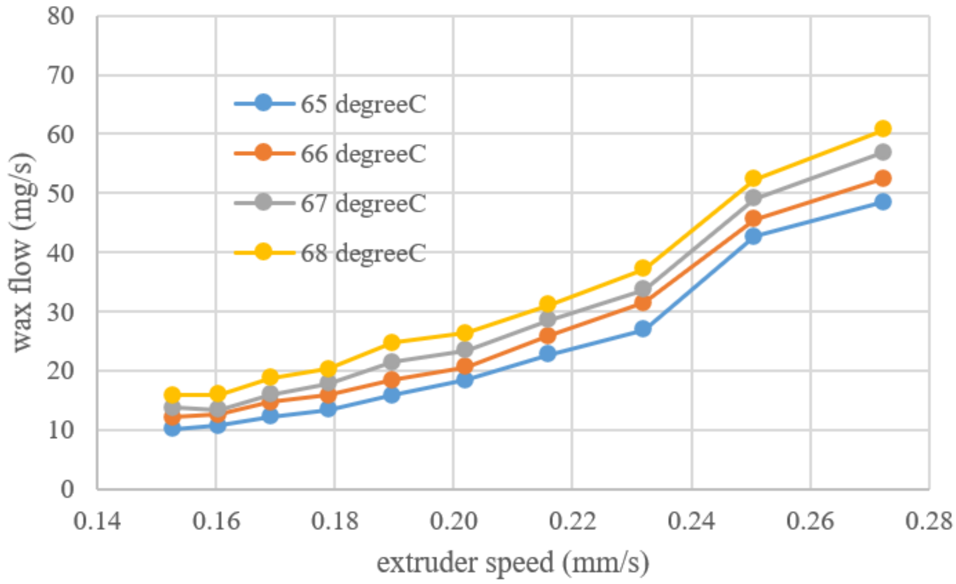


Figure 7 The relationship of extrusion speed and injection-grade wax flow at various temperature from 65 to 68°C

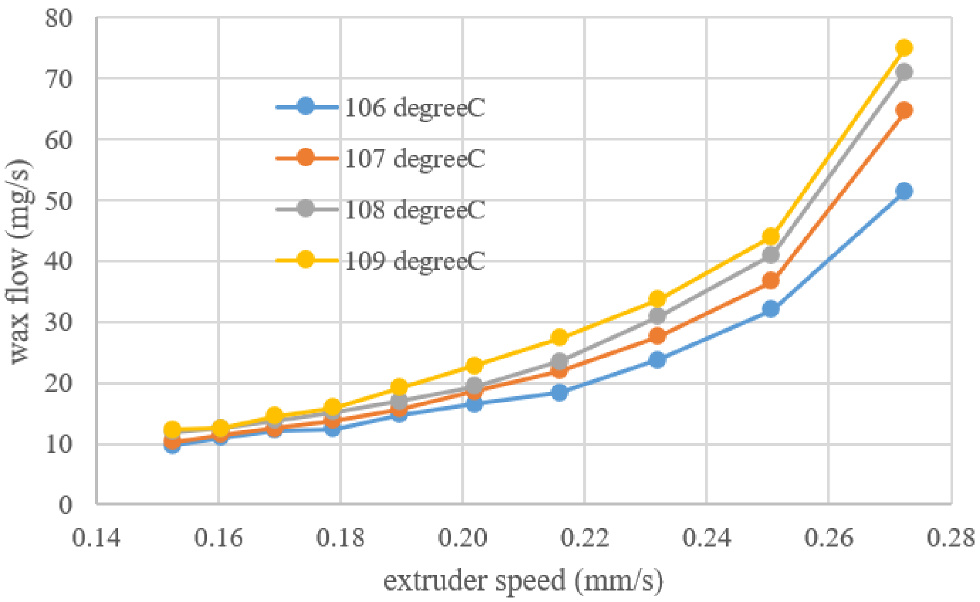


Figure 8 The relationship of extrusion speed and carving and milling-grade wax flow at various temperature from 106 to 109°C

3.2 Simple shape experiment results

The cuboid and cylinder models as illustrated in Figure 4 were experimental printed from the modified 3D-wax printer. For the injection-grade wax, the extrusion temperature was set at 66 and 67°C while it was set at 107 and 108°C for the carving and milling-grade wax. Tables 2 and 3 show the 3D-printing parts' results obtained from all experiments. The number in brackets are the percentage differences comparing to the computer model dimensions. Please note that the results were averaged from 3 samples. The data in both Table 2 and Table 3 were used to represent the trend of shape size.

Table 2 Injection-grade wax, 3D-printing-part-measuring dimensions at two extrusion temperatures and various layer height settings

Cuboid model

Temperature (°C)	Layer height (mm)	Width (mm)	Height (mm)	Thickness (mm)
66	0.2	21.92 ± 0.46 (+9.58%)	21.57 ± 0.38 (+7.83%)	4.40 ± 0.15 (+10.00%)
	0.3	21.83 ± 0.21 (+9.17%)	21.65 ± 0.33 (+8.23%)	4.40 ± 0.00 (+10.00%)
	0.4	21.38 ± 0.16 (+6.92%)	21.52 ± 0.26 (+7.58%)	4.22 ± 0.18 (+5.42%)
67	0.2	21.93 ± 0.25 (+9.67%)	21.87 ± 0.46 (+9.33%)	4.33 ± 0.21 (+8.33%)
	0.3	21.50 ± 0.36 (+7.50%)	21.63 ± 0.31 (+8.17%)	4.47 ± 0.15 (+11.67%)
	0.4	20.88 ± 0.19 (+4.42%)	21.27 ± 0.65 (+6.66%)	4.30 ± 0.00 (+7.50%)

Cylinder model

Temperature (°C)	Layer height (mm)	Diameter (mm)	Thickness (mm)
66	0.2	21.02 ± 0.50 (+5.08%)	4.28 ± 0.08 (+7.01%)
	0.3	20.67 ± 0.27 (+3.33%)	4.37 ± 0.06 (+9.17%)
	0.4	20.50 ± 0.23 (+2.50%)	4.23 ± 0.15 (+5.83%)
67	0.2	20.92 ± 0.54 (+4.58%)	4.30 ± 0.00 (+7.50%)
	0.3	20.43 ± 0.22 (+2.17%)	4.40 ± 0.00 (+10.00%)
	0.4	20.18 ± 0.13 (+0.92%)	4.20 ± 0.10 (+5.00%)

When 3d-printing injection-grade wax, only at the slow injection speed of 0.15 mm/s together with the printing speed of 130-150 mm/s could achieve the 3D-wax shapes since the higher injection speed caused wax overflow. The average dimensions of all results, as shown in Table 2, were larger than the original 3D computer model. It could be noticed during the experiment that the wax was quite runny and instead of forming a nice and round layer during injection, it then formed the flat one. Furthermore, at lower layer height, the size of samples was also larger. This was because the printer head was moving up only at a small step at the lower layer height setting leaving smaller space between layers. During that, the volume of the extrude material was too large for the space. Thus, the wax was forced to spread outwards. Dimensional error of cuboid was more than that of cylinder since the movement of the nozzle was not continuous. When making cuboid the nozzle must have travelled linearly and stop briefly to change its direction for each side of a square, while making cylinder, the nozzle direction only followed circular perimeter. In 3D-printing, material overflow generally occurs at the suddenly change of nozzle speed. The problem has been solved using filament pull back feature in modern FDM 3D-printer but it is not practical in extrusion-type nozzle like this system. From those results, it was suggested that the nearest shape could be made by setting the extrusion temperature of 67°C and 0.4-mm layer height. These were possibly decent settings for more sophisticated part printing.

Table 3 Carving and milling-grade wax, 3D-printing-part-measuring dimensions at two extrusion temperatures and various layer height settings.

Cuboid model

Temperature (°C)	Layer height (mm)	Width (mm)	Height (mm)	Thickness (mm)
108	0.6	20.93 ± 0.76 (+4.67%)	20.90 ± 0.44 (+4.50%)	3.87 ± 0.12 (-3.33%)
	0.8	21.00 ± 0.46 (+5.00%)	20.93 ± 0.45 (+4.67%)	3.98 ± 0.38 (-0.42%)
	1.0	21.10 ± 0.75 (+5.50%)	20.97 ± 1.00 (+4.83%)	3.80 ± 0.20 (-5.00%)
109	0.6	20.90 ± 0.35 (+5.50%)	21.03 ± 0.35 (+5.17%)	3.87 ± 0.12 (-3.33%)
	0.8	20.43 ± 0.59 (+2.17%)	20.60 ± 0.72 (+3.00%)	4.00 ± 0.00 (+0.00%)
	1.0	20.50 ± 0.36 (+2.50%)	20.43 ± 0.38 (+2.17%)	3.93 ± 0.12 (-1.67%)

Cylinder model

Temperature (°C)	Layer height (mm)	Diameter (mm)	Thickness (mm)
108	0.6	21.21 ± 0.61 (+6.04%)	3.93 ± 0.32 (-1.67%)
	0.8	20.82 ± 0.66 (+4.08%)	3.93 ± 0.12 (-1.67%)
	1.0	20.33 ± 0.85 (+1.67%)	3.48 ± 0.10 (-12.92%)
109	0.6	21.17 ± 0.29 (+5.83%)	4.10 ± 0.17 (+2.50%)
	0.8	20.72 ± 0.79 (+3.58%)	4.10 ± 0.10 (+2.50%)
	1.0	20.38 ± 0.84 (+1.88%)	3.77 ± 0.06 (-5.83%)

Similar to the previous experiments, 3D-printings of the carving and milling-grade wax were conducted at two different temperatures and three different layer height settings. The layer heights of 0.6, 0.8 and 1.0 mm with line pattern, 100% infill were tested. The results are shown in Table 3. Again, the number in brackets are the percentage differences comparing to the computer model dimensions.

Because this material was more difficult to inject and the larger nozzle was used, the higher extrusion speed of 0.27 mm/s and the slower printing speed of 40 mm/s were set to accommodate the material flow. The results in Table 3 show even larger shape but with smaller thickness than the original 3D computer model. With larger injection nozzle and hence, larger wax line volume, the similar size problem that had occurred with the injection-grade wax could also be noticed here. With more material flowing of each layer, the material was still liquid and more spread outwards. More flat layers were formed causing larger size objects. At lower layer height setting, thickness of the wax parts was increased since the printer injected more layers and more material but due to that, the parts were also larger. From the experiment, it was still unclear which extrusion temperature or layer height settings were suitable for 3D-printing of more sophisticated part since the injection conditions and the equipment design were not optimum for this material. To improve, the extrusion nozzle unit must be redesigned. However, it was decided that the lower extrusion temperature of 108°C and 1.0-mm layer height were selected for the next preliminary tests since some heat would accumulate on layers during printing a larger 3D-object and affect the layer solidification.

3.3 Preliminary 3D-model printing results

Figures 9 and 10 show the 3D-printing Buddha statues that were printed from the modified 3D-wax printing machine using injection-grade wax and carving and milling-grade wax, respectively. It can be noticed from both figures that the overall shapes of the printing results are similar to the original 3D-computer design but with less detail and unsmooth surface finish. Since it was unable to control the material injection flow to match the nozzle movement, there was some excessive material on the statue surface of both cases. Especially, in the case of injection-grade wax, where the excessive material got hardened at the nozzle tip during printing causing some more lumps of material on the surface. The same problem was reported in the previous work of Wang et al., who tried to 3D-print fish Surimi gel using plunger type nozzle [16]. It was reported that the application of a small nozzle diameter led to relatively poor models due to inconsistent extrusion.

Printing the Buddha statue from the carving and milling-grade wax was faster than the injection-grade wax due to its larger nozzle diameter however, less detail and more clear printing layer were noticed. As expected, the printing speed and material flow were not perfectly synchronised, particularly at a small area where the nozzle was turning and changing direction in which excessive material could be noticed clearly on the surface. To print carving and milling-grade wax, supports adding was necessary since the material layer was heavier than the injection-grade wax. This resulted in more work required to get rid of the supports after finish printing.

Figure 9 The 3D-buddha image model made of injection-grade wax

Figure 10 The 3D-buddha image model made of carving and milling-grade wax

4. Conclusions

From this preliminary study, 2 unmodified types of wax were experimented using in house design extrusion unit. The study results suggested that printed part dimension and accuracy related to material properties and extrusion control. Plunger type extrusion is possible for making 3D-wax model however more understanding on material properties together with better extrusion unit design are necessary to achieve the printing object resolution and accuracy. Thoroughly analysis of wax solid-liquid phase and viscosity are also benefit for the new design. Printing temperature, extrusion speed, printing speed, layer height and nozzle diameter are the parameters that are needed to be considered to make suitable flow of semisolid line for printing. Also, apart that, another way to help achieving wax 3D-printing is to chemically improve the wax properties in order to ease flowing or maintain its viscosity at a wider range of extrusion temperatures.

5. Acknowledgements

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