A STUDY ON EFFECTS OF PROCESS PARAMETERS IN RAPID FREEZE PROTOTYPING

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ABSTRACT

Rapid Freeze Prototyping (RFP) is a relatively new solid freeform fabrication process, which builds a three-dimensional part according to a CAD model by depositing and freezing water droplets layer by layer. A study on the effects of RFP process parameters including the nozzle scanning speed, droplet size, and droplet frequency in building ice parts with a single-nozzle work head is made. Presented in this paper are the results of this study which indicate that these process parameters determine the ice layer thickness and ice line width, which in turn determine the surface roughness and the waiting time required after depositing each layer of water (i.e. between successive layers) during the ice part building process.

1. Introduction

Rapid Freeze Prototyping is a method of solid freeform fabrication (SFF) that uses water freezing into ice as its medium. The setup consists of a pressurized water containment unit, an X-Y table to control the plate to obtain the correct part geometry, a Z-axis elevator to raise the nozzle for the successive layers, a circuit driven nozzle and a freezer. Figure 1 shows a schematic of the setup [1].

The nozzle is a precision micro-dispensing drop-on-demand nozzle which is opened cyclically by a function generator. The nozzle has water supplied to it via a Teflon tube. Once the water leaves the Teflon tube, it enters the nozzle where it encounters stainless steel, polyphenylene sulfide, polyetheretherketone, ethylene/propylene rubber, butyl, epoxy, and finally sapphire before it is released to the substrate below [4]. The materials the water comes into contact with are important because if the water sticks to these materials the flow rate will be decreased significantly due to adhesion. The materials that comprise the feed tube and nozzle are materials that the water will flow through with minimal adhesion [6].

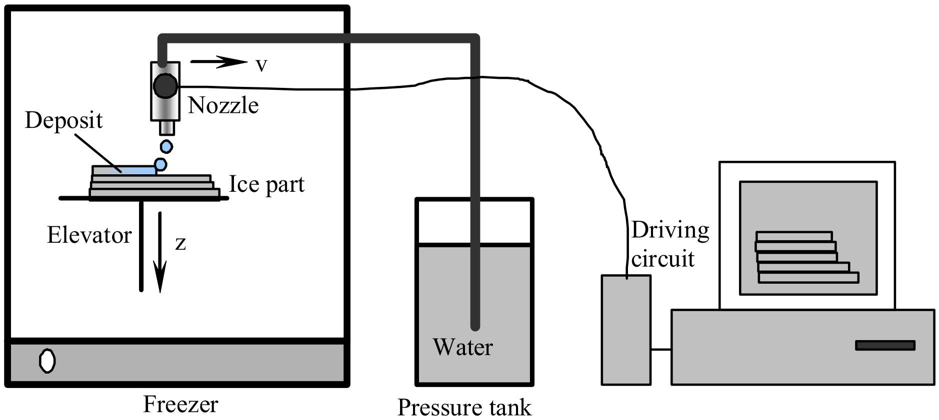

Figure 1. Principle of Rapid Freeze Prototyping

There are many advantages to using Rapid Freeze Prototyping over other SFF techniques, which include Stereolithography, Fused Deposition Modeling, Selective Laser Sintering, Laminated Object Manufacturing, Three Dimensional Printing, and Direct Materials Deposition. Other SFF techniques use various materials in their processes including UV curable resin, wax, ABS, metal/ceramic/polymer powders, and adhesive coated sheets [1]. Since RFP uses water as the working material, the working environment is much cleaner than the alternative SFF techniques. Water is also readily available and cheap to use. RFP also offers fast build time, less energy consumption, clean and easy detachment from the substrate and very good surface finish. A typical ice part fabricated by RFP is shown in Figure 2 [8].


Figure 2: An ice part built by RFP

The freezer used in the setup is a standard commercial freezer that is set to –20 °C. The nozzle can be operated in a range of 200 to 900 Hz. With a clean nozzle allowing water to flow through without constrictions, the frequency does not change the flow rate. This is further discussed in Section 4 of this paper. The nozzle has a heat source that prevents the water from freezing while it is waiting to be dispensed. This keeps the water at about 4°C before it is dispensed. The water is released from the nozzle at a height of 3-5 mm onto an aluminum plate, which is the substrate.

The objective of this paper is to explore the variable parameters in RFP and show the relationships between these parameters and the effects they have on fabricating ice parts. The presentation of this paper is as follows. In Section 2 the process parameters are discussed and studied analytically. Section 3 discusses the surface roughness of ice parts and the minimum waiting time between successive layers and shows the relationship of the variable process parameters to these characteristics of ice parts. Section 4 presents the experimental results obtained in creating ice parts. Section 5 concludes the paper.

2. Analysis of Varying Process Parameters

The current RFP setup, which is shown in Figure 1, has two process parameters that can be varied. By changing one or both of these parameters, the layer thickness and line width will change. The changeable parameters are the water feed rate, f, and the scan speed, ν. The water feed rate is controlled by the water pressure, P, and the nozzle diameter, d. The water feed rate is measured in mm^3/s. The water pressure is varied and controlled by the height difference in the water source and nozzle. The scan speed is encoded into the program that controls the X-Y table. The scan speed is measured in mm/s.

To begin the study of the water feed rate, the droplets that are released from the nozzle are considered. The droplet size is dependent upon the diameter of the nozzle and the surface tension of the water. The following equation can be used to determine the amount of mass contained in a single droplet [2]:

$$m = \frac{\pi d \sigma F(d / V^{1/3})}{g} \tag{1}$$

where m is the mass of the droplet, σ is the surface tension of water, V is the volume of the droplet and $F(d/V^{1/3})$ is an empirical correlation function. We will assume that in this case the empirical correlation function has a value of 1, which means that there are no satellite drops formed and there is not any water left hanging at the tip of the nozzle [2]. Equation 1 can be used to check the number of droplets being released by the nozzle in each opening pulse. This is a concern for the higher frequency settings, since the nozzle could be open for such a short amount of time that not enough water could flow through to create a single drop, thus the water feed rate would be inconsistent and hard to predict.

The water feed rate can be found by considering an invisid flow, which is acceptable for this flow. Bernoulli's equation is used to determine the velocity of the water flowing as if the nozzle were kept opened continuously [3]. The water feed rate can be calculated by knowing the diameter of the nozzle, the duty cycle set for the nozzle through the function generator (which is the percentage of time the nozzle is actually open) and the height difference between the nozzle and the water containment unit as follows:

$$f = \frac{\pi}{4} d^2 N \sqrt{2g\Delta h} \tag{2}$$

where d is the nozzle opening diameter, N is the duty cycle of the function generator, g is the gravitational constant and Δh is the height difference between the nozzle and the water supply unit. The nozzle must be clear and free of contaminants to produce good results with a low error between the calculated and measured masses.

As soon as the water droplets come into contact with the substrate, they combine with each other to form a continuous water line before freezing. The length of this line is calculated by multiplying the scan speed, *v*, by the time, *t*, taken to create the section. The volume of this line is Avt, where A is the cross sectional area of the line. The volume of the line is also equal to the water feed rate, *f*, multiplied by time *t*. [1] Setting these two volume equations equal to each other gives the cross-sectional area of a water line:

$$A = f \ / v \tag{3}$$

Figure 3 shows a typical section of the ice wall after some layers have been deposited. From this figure, a relationship between the layer thickness and line width can be found. This relationship is:

$$\Delta z = w \cdot \sin(\alpha/2) \tag{4}$$

By combining equations (3), (4), and the relationship $A = w \cdot \Delta z$, the layer thickness and line width can be derived as:

$$\Delta z = \sqrt{\frac{f \cdot \sin(\alpha/2)}{v}} \tag{5}$$

$$w = \sqrt{\frac{f}{v \cdot \sin(\alpha/2)}} \tag{6}$$

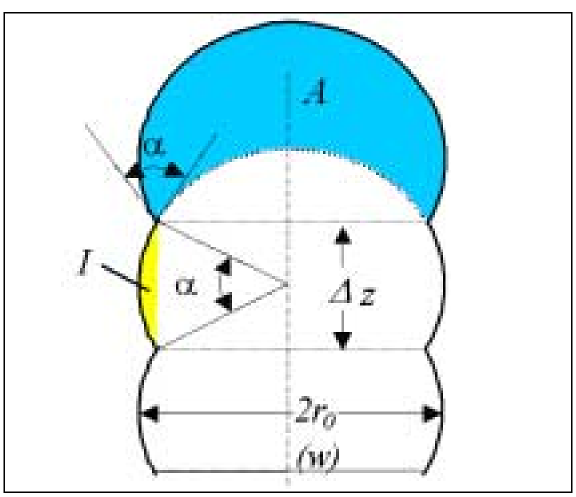

Figure 3: Cross section illustration of an ice line

where α is the water-ice contact angle, which has been determined to be 20° for water [1]. The water-ice contact angle α was determined by measuring the layer thickness and line width in various ice parts. Equations (5) and (6) were then used to find α. It is seen in equations (5) and (6) that the layer thickness and line width depend on the variable parameters, which are the water feed rate and the scan speed.

3. Surface Roughness and Build Time

The layer thickness is very important in any layered fabrication because of the impact it has on surface roughness. In layered fabrication a "stair-stepping" effect could become a problem because it increases the surface roughness of the part. In RFP layer thickness can be reduced by reducing the water feed rate or increasing the scan speed, but the build time is also increased [1]. The build time is discussed later in this section of the paper. The surface roughness of ice parts built by RFP can be predicted as follows:
The definition of surface roughness, R, is:

$$R = I / \Delta z = (0.5\alpha r_o^2 - 0.5\, r_o^2 \sin\alpha)/\Delta z \tag{7}$$

where I, Δz, α and r_o are defined in Figure 3. α is measured in radians for surface roughness calculations. Using Figure 3 and equation (5), it can be seen that

$$r_o = \frac{w}{2} = \sqrt{\frac{.5f}{v\sin(\alpha/2)}} \tag{8}$$

So, by substituting equations (5) and (8) into (7), the surface roughness is obtained as:

$$R = k\sqrt{f/v} \tag{9}$$

where

$$k = \frac{(\alpha - \sin\alpha)}{8\sin^{3/2}(\alpha/2)} \tag{10}$$

Thus, equation (9) shows that the surface finish is dependent upon the variable process parameters of RFP.

The build time for an ice part strongly depends on the minimum wait time between successive layers. The minimum wait time is the time to allow after a layer has been deposited before depositing the next layers to ensure the previous layer is solidified. Sui and Leu showed that the minimum waiting time between successive layers is [1]:

$$t_{\min} = \frac{E \cdot \Delta z}{\lambda \cdot \Delta T \sqrt{m}} \sqrt{1 + \frac{\lambda \Delta T}{E\phi}} \tag{11}$$

where E is the enthalpy, Δz is the layer thickness, λ is the thermal conductivity, ΔT is the temperature difference between the water and the freezing temperature, $m = 2h/\lambda w$, h is the heat transfer coefficient, w is the layer width, and ψ is the thermal diffusivity. The enthalpy can be calculated as $E = \rho(L + c\Delta T)$, where ρ is the water density, L is the latent heat of fusion, c is the specific heat of water and ΔT is the temperature difference between the water temperature and the freezing temperature [1]. This shows that the minimum wait time between layers and the build time can be changed by varying the process parameters which affect the layer thickness and line width.

4. Experimental Results

The water feed rate was measured and compared to the predicted value obtained by using equation (2). The diameter of the nozzle, d, was 0.003 in (0.0762 mm), the duty cycle was set to 50%, and the height difference, Δh, was 3158 mm. Using these values, the water feed rate was predicted to be 17.95 mm^3/s. The measured water feed rate, taken from an average using 5 different nozzle frequencies, was 18.76 mm^3/s. This is an error of 4.3%. In order to achieve a good comparison between the predicted water feed rate and measured water feed rate, a clean, unclogged nozzle must be used. It has been seen that as the nozzle starts to get clogged, the mass flow rate increases as the nozzle frequency increases. This is due to a long throw bladder contained in the nozzle that will force more water out through the constriction when there are a higher number of openings per second due to the higher frequency [4]. So, it is very important to use a clean, unclogged nozzle to produce the most accurate ice parts.

Equation (1) was used to determine if the nozzle was opened for a long enough period for each pulse to produce at least one droplet. The height difference was again set at 3158 mm, but the duty cycle of the function generator was decreased to 20% (which is the lowest feasible duty cycle for the equipment in use). The diameter of the nozzle was the same as before, which is 0.0762 mm, the surface tension of water is 7.34E-2 N/m, and a value of 1 was used for the empirical correlation function. The number of droplets produced at this water pressure was at least one drop per pulse in the nozzle frequency range of 200 to 900 Hz. Figure 4 shows the predicted number of droplets per nozzle pulse.

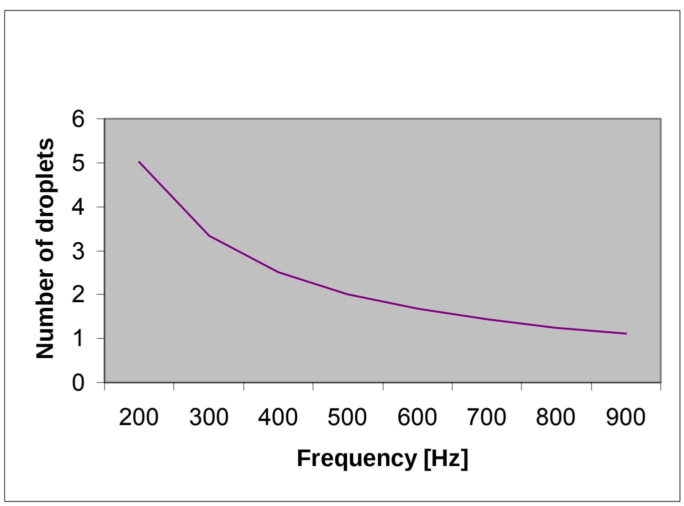

Figure 4: Predicted number of droplets released at 20% duty cycle

Ice parts were produced with varying water feed rates and the layer thickness was measured. The scan speed was kept at 50 mm/s. The layer thickness agreed well with the calculated values using equation (5), with the maximum error of 16.3% being at the highest flow rate and the lowest error of 1.8%. Figure 5 shows the comparison between the predicted layer thickness and the measured layer thickness at various water feed rates:

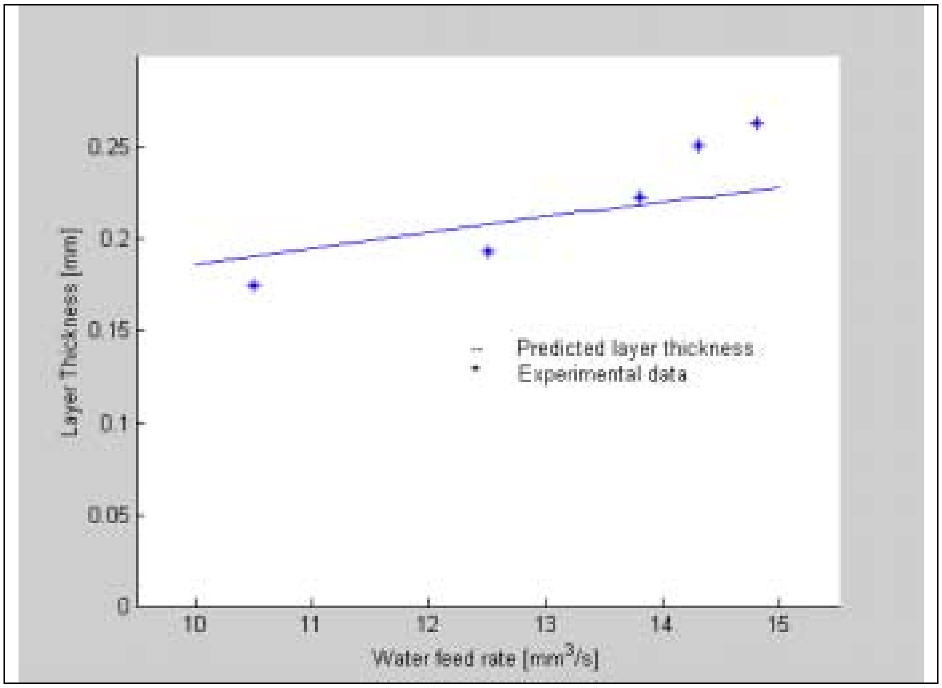

Figure 5: Comparison of predicted to measured layer thickness

5. Conclusion

The variable parameters in RFP, i.e. the water feed rate and the scan speed, can be altered to achieve the desired layer thickness, line width, surface roughness and minimum wait time (thus the build time) for ice parts. The variable parameters are very important to consider when fabricating ice parts, since they contribute to so many characteristics of ice parts. The water feed rate is controlled by the water pressure and nozzle diameter. The scan speed is encoded into the program used to operate the X-Y table. Besides considering the variable process parameters, it is also important to use a clean, unclogged nozzle in the RFP process in order to create the desired measurements for an ice part.

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