AN EXPERIMENTAL AND ANALYTICAL STUDY OF ICE PART FABRICATION WITH RAPID FREEZE PROTOTYPING

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ABSTRACT
Rapid Freeze Prototyping (RFP) is a new solid freeform fabrication process that builds an ice part by rapidly freezing water layer by layer. In this paper, we will present our recent progress in the development of this novel process. An experimental system has been built for conducting the research. It consists of an XY-table and Z-stroke driven by micro-stepping motors and a water dispensing and deposition subsystem which incorporates a solenoid valve and a syringe pump placed inside a freezer. Simple heat transfer analysis is made to help select proper values of process parameters and predict part building failures. Example ice parts have been successfully built with this process. Key factors of this freeform fabrication process are identified.

KEYWORDS
Solid Freeform Fabrication, Layered Manufacturing, Rapid Freeze Prototyping, Ice Patterns

1. INTRODUCTION
The solid freeform fabrication processes which deposit material directly to build parts through thermal extrusion or drop-on-demand ejection play an important role today in the SFF research field and equipment market. These processes include Fused Deposition modeling (FDM), Shape Deposition Manufacturing (SDM), Multi-Jet Modeling (MJM), etc. Material diversity, relative cleanness, and cheap material and equipment cost are strengths that contribute to their success. For example, the building process usually only involves material melting /solidifying and thermal extrusion without substantial chemical reaction and laser processing. This means more applicable building materials and lower cost. Accordingly, these processes can more easily be used for developing desktop rapid prototyping systems. However, most of these processes also have drawbacks and could further benefit from improvements such as surface smoothness and build accuracy, reduction of building time and thermal stress for large solid parts, and adaptability of process parameters to part building quality. Due to various technical limitations of material flow control such as surface tension, nozzle dragging effect, start-stop response delay, etc., part building accuracy and surface smoothness of some of these processes cannot compete with laser based processes. On the other hand, the part building quality is sensitive to the change of process parameters because these processes are heat based and are sensitive to the amount of heat and the condition of heat consumption. Any change in process parameters, such as layer thickness and depositing speed, affect not only the total heat which needs to be consumed but also the condition of heat consumption [1-4].

The concept of Rapid Freeze Prototyping (RFP) process was recenlty developed by us to address the above issues. It is a novel SFF process that makes a part by selectively depositing and freezing the material (water or brine) layer by layer. Figure 1 [4] illustrates the process of Rapid Freeze Prototyping. In this process, the building environment is kept at a temperature below water's freezing point (-20°C in our experimental system). Water is extruded or ejected from the nozzle and deposited onto the previously solidified ice surface. The newly deposited water is cooled by the low temperature environment through convection and by the ice surface of the previous layer through conduction. As a result, the deposited material freezes rapidly and binds to the previous layer, forming a new layer of the part. The part is built with water (pure or with some agent) and the support, where necessary, is built with either brine or water of a different color. The nozzles and feeding pipes are kept at certain temperatures to pre-cool water close to its freezing point but remaining in the liquid state so that the material can flow freely. During the deposition process, the ratio of material flow rate in continuous method or liquid droplet frequency in drop-on-demand method versus the nozzle moving speed is set according to predetermined layer thickness and line width.

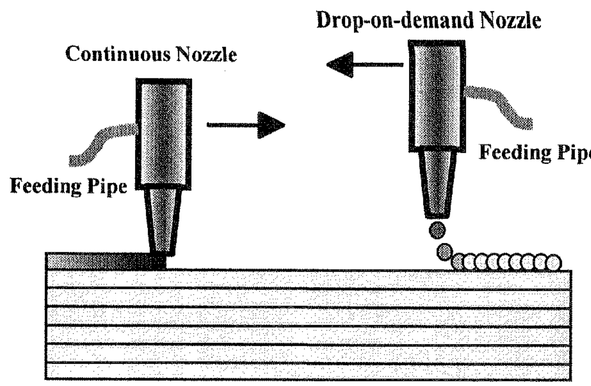


Figure 1. Principles of Rapid Freeze Prototyping

The advantages of this novel process, including cleanness, lower cost, potential better surface finish and building accuracy, and ease of stress compensation and potentially faster building speed, were discussed in [3-4]. The potential applications of this process include part design visualization and rapid tooling such as RTV silicone molding, investment casting and sand casting [3-5]. For example, in a patented investment casting process, called Freeze Cast Process (FCP), ice patterns are used to make metal parts instead of traditional wax patterns. This process was developed to obviate problems and technical difficulties of traditional investment casting method such as wax pattern expanding, ceramic shell cracking, highly skilled operation requirement, etc.[6-7]. However, one major concern in this process is ice pattern making. Traditional methods to make ice patterns is injecting water in a mould and making it frozen. Some main issues in this method include water expansion compensation during freezing, air bubble removal, ice pattern de-molding, and part complexity limitations. With RFP it is possible to make accurate ice patterns directly from CAD models in a very short time, without the cost of mold making and without the above issues . This is especially valuable in case that a small amount of complex ice patterns and metal parts is needed with an extreme time concern.

The paper presents our recent progress in the development of RFP. It is organized as follows. Section 2 introduces the experimental setup for conducting the RFP part building experiment. Section 3 presents the method and result of the heat transfer analysis for the RFP part building process. Section 4 demonstrates some results of three-dimensional ice part building. Section 5 concludes this paper.

2. EXPERIMENTAL SETUP

An experimental setup was developed to conduct the study of this process, as shown in Figure 2. The software of this system accepts an .STL file from Pro/Engineer or other CAD packages and slice the CAD file into a .CLI file which represents the contour information of each sliced layer. This software further generates NC codes according to the contour information of the sliced layer and the specific process parameters of RFP such as building speed and material ejection rate. Then the NC code is sent to a motion control card to control the building of ice parts. The hardware of this experimental system consists of three major parts: XY table and Z elevator, a material extrusion subsystem, and electronic control devices. The three-axis moving mechanism is driven by three stepping motors. The XY table is placed in a freezer at a low temperature of -20°C. The heat generated by stepping motors, however, increases the temperature of the table to about 0°C which may vary ±2°C depending on the working status of the motors. A metal plate is mounted on the XY table as the building substrate. This plate is isolated from the table so that its temperature is kept at a constant temperature of -20°C. The nozzle is mounted on the Z elevator and can move only in Z direction. However, the movement of the building substrate relative to the nozzle makes it possible to deposit material in the XY plane. After one layer is finished, the nozzle is elevated upwards a height of one layer thickness, waiting for the XY table to move and depositing material to build the next layer.

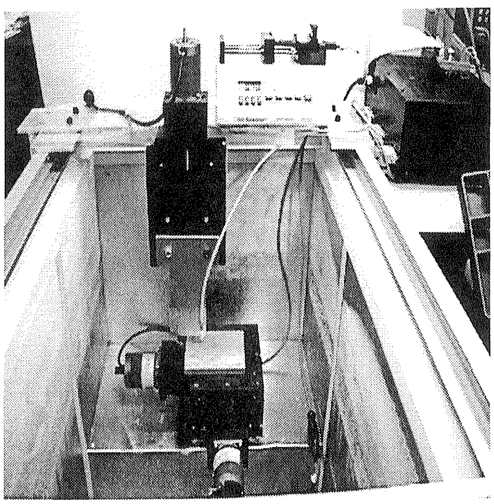


Figure 2. Rapid Freeze Prototyping Experimental Setup

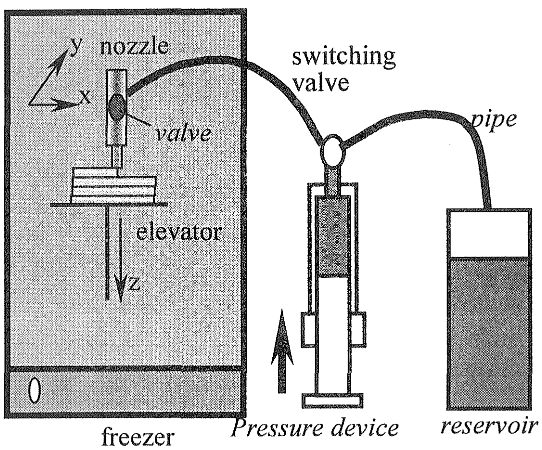


Figure 3. Material Extruding Subsystem

The material extrusion subsystem consists of a constant pressure device, a material reservoir, a feeding pipe with temperature control capability, and a miniature solenoid valve based nozzle, as shown in Figure 3. The pressure device provides a constant preset pressure according to the extrusion rate requirement. The feeding pipe is controlled at a proper temperature range, allowing the water in it to be pre-cooled but still in liquid state. The miniature solenoid valve controls material flow on and off in continuous method, and generates water droplets in drop-on-demand method. In the latter case, the response time of the valve determines the minimum achievable droplet size and the material flow resistance determines the minimum pressure required to generate droplets, both of which are vital to the success of making ice parts with drop-on-demand method.

The electronic control device (Figure 4) of this system is used to control the three stepping motors of the XYZ moving axes and to control the material flow rate, which is proportional to the resultant linear moving speed of the XY table. Motors are driven to move with a linear resolution of up to 0.25μm. The motion control card (AT 6400, provided by Compumotor company) can output a pulsed signal with a pulse width of 0.3 μs to the fourth axis at a frequency proportional to the resultant moving speed of XY table. The speed proportion factor is treated as a process parameter before NC code generation and is configured by software. The output signal is sent to a circuit which widens the pulse to 0.2ms, making it compatible with the response of the valve. In this circuit, the frequency of the signal determines the droplet frequency and the pulse width determines the droplet size. Since the pulse width is constant, the pulse frequency (i.e. number of droplets per second) is proportional to the material flow rate. Accordingly, the material flow rate is proportional to the resultant moving speed of the XY table. The proportion factor can be changed by either varying the speed proportion factor or by adjusting the pulse width.

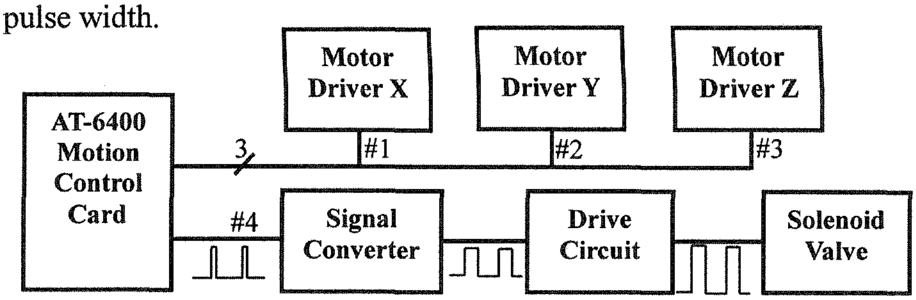


Figure 4. Schematics of the electronic control device

3. ANALYTICAL STUDY OF ICE LAYER BUILDING

Before starting to build ice parts, analysis with the ANSYS software package is conducted to help understand the water freezing process when depositing a new layer of water on a previously built ice layer. The analytical result will be used to guide the process parameter settings, such as layer thickness, drawing speed, and waiting time between two successive layer. In this study, only the heat conduction in Z direction (or between layers) and convection with the environment is considered while the heat transfer in the direction of nozzle movement and that between neighboring lines are neglected. This simplification is reasonable because the nozzle drawing (resulting from XY table movement) speed is much faster than heat transfer rate in the nozzle movement direction. On the other hand, we concern contour building more than interior filling. For contour building, there is no neighboring lines perpendicular to the drawing direction. The built contour is exposed entirely to the environment and consumes heat mostly through conduction between layers in Z direction and through convection to the air. This is a two-dimensional, non-linear transient heat transfer problem and can be analyzed by ANSYS [8]. The simplified calculation model is shown in Figure 5. The height of the model, *H,* is proportional to the number of layers built. It is varied from 0.5 mm to 20 mm while the newly deposited layer thickness δ is kept at 0.1 mm to see the influence of height on new layer freezing time. In another analysis, the height is kept at 5 mm constant while the newly deposited layer thickness is varied from 0.05 mm to 0.20 mm to see the influence of layer thickness on new layer freezing time. In both cases, according to the condition of the experimental system, we assume that the previously built layers has an initial temperature of −20°C, the newly deposited layer of water has an initial temperature of 10°C, and the building metal substrate and the environment have a constant temperature of -20°C. The time *T* required for the newly deposited water to freeze completely is investigated with this assumption.

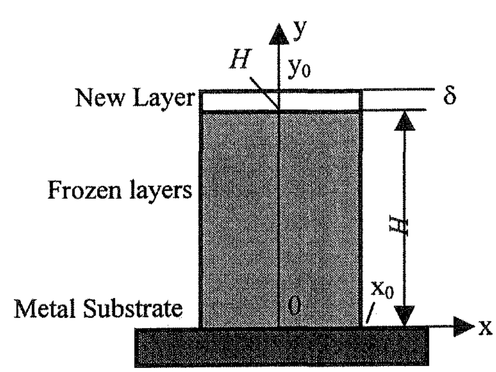


Figure 5. Heat transfer calculation model for Rapid Freeze Prototyping process

The above initial condition can be expressed by

$$T = 10°C \qquad \text{for } H \le y \le y_0$$

$$T = -20°C \qquad \text{for } 0 \le y < H$$

The boundary condition can be expressed by

$$T = -20°C \quad \text{(including the substrate and air environment)}$$

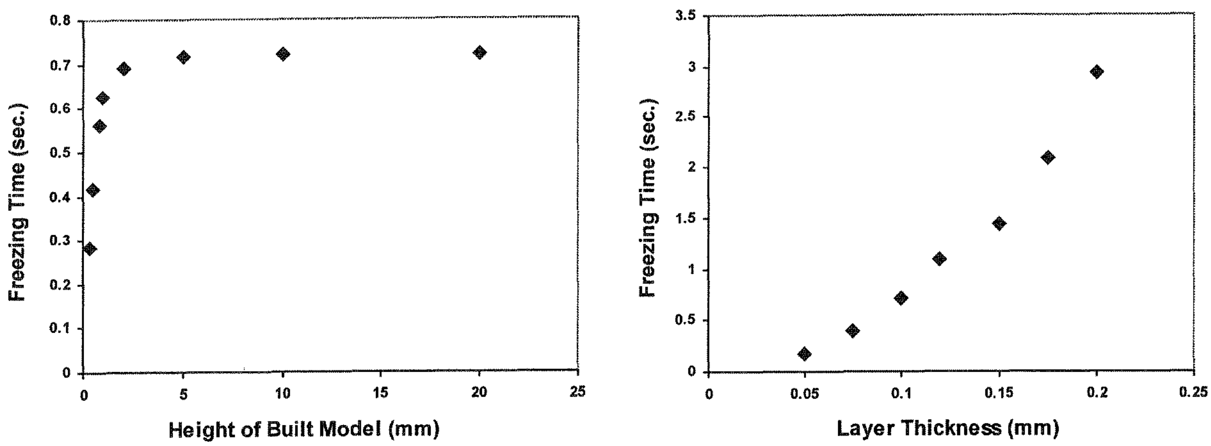


Figure 6. Influence of built model height and newly deposited layer thickness on freezing time

Figure 6 shows the result. From this figure, we observe that:

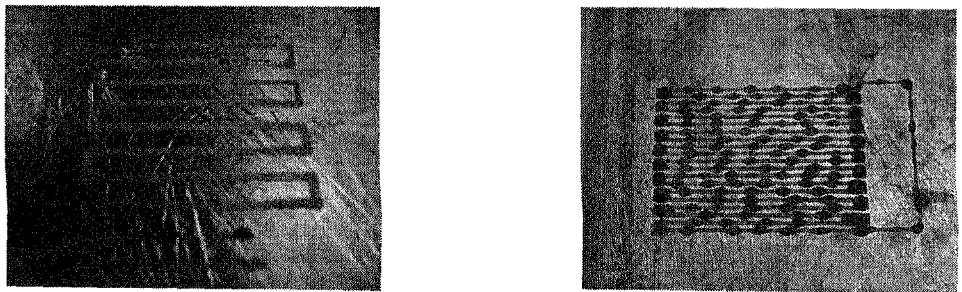
1) As height H becomes larger, a longer time T is needed to freeze the newly deposited layer. However, when H is over 2 mm, this influence becomes negligible. This means that the additional material in Z direction over 2 mm does not significantly decrease the cooling speed.

2) As layer thickness δ becomes larger, a longer time T is needed for the water to freeze. So reducing building layer thickness can effectively shorten the freezing time, which means better freezing process control and thus better building resolution.

4. ICE PART BUILDING EXPERIMENTS

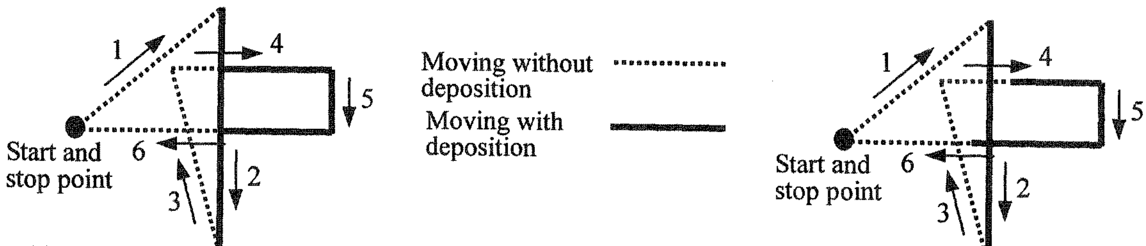
In the experiments described below, only drop-on-demand method is given because it can provide better control on material flow with our current experimental system. Continuous extrusion method will be investigated after an upgrade of the experimental system to include a valve on-off control device and a new nozzle design. Ice part building experiments were conducted in the following steps:

1) Building ice lines. This step is to provide optimal building parameter values such as building substrate temperature, drawing speed (i.e. XY table movement speed), layer thickness, droplet frequency and size. From the experiments, we can see the influence of these parameters on ice line building quality. We have observed that insufficient substrate temperature can cause uneven line width as shown in Figure 7. Proper ratio of droplet frequency versus drawing speed have been obtained from these experiments. Another goal of ice line building experiments is to help find out the relationship between the drawing speed and the material deposition delay error. There exists a time delay between on-off of the control signal and open-close of the valve. There exists another time delay between open-close of the valve and start-stop deposition of the materials because there is a distance between the nozzle and the building surface. The two delays will result in material deposition errors in the drawing direction. Figure 8 shows an experiment that is done to measure the deposition error and to help optimize the most suitable drawing speed and valve distance.



(a) Fine ice lines (b) Poor ice lines

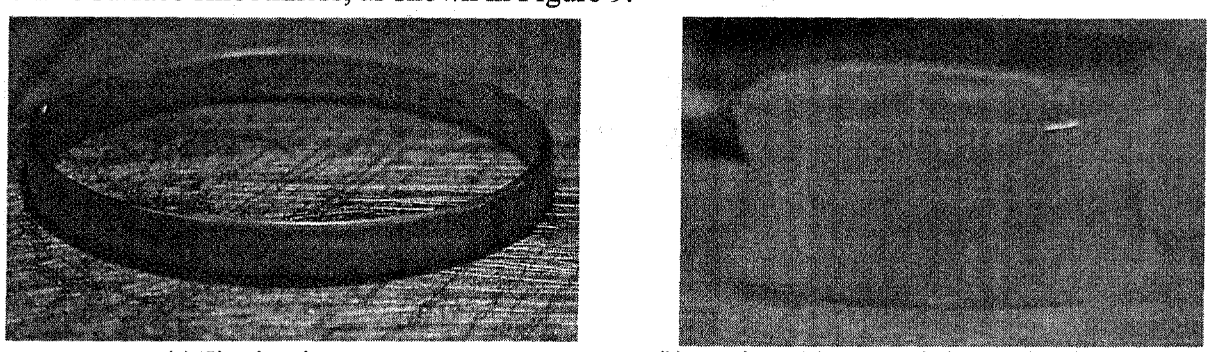
Figure 7. Ice lines built



(a) Programmed deposition route (b) Actual deposition result

Figure 8. Drawing route to measure valve start-stop errors

2) Building ice rings. The purpose of this experiment is to find out a suitable waiting time between two layers for successive part building, in addition to the practical knowledge obtained from ice line building. From the heat transfer analysis above, it is found that the complete freezing time for a new layer is around 0.7 second when the model height is over 2 mm. However, for successive part building, in order to prevent heat accumulation with layer building, the previous built layer should have been cooled down to almost the environment temperature before starting to build the next layer. The analysis shows that the time to cool down the previous layer could be tens of seconds depending on many heat consumption factors. A group of experiments with different waiting time is taken to figure out the suitable waiting time value. Samples with insufficient waiting time show unevenness of ring height and wall thickness. On the other hand, samples with sufficient waiting time have an even ring height and wall thickness, and fine surface smoothness, as shown in Figure 9.



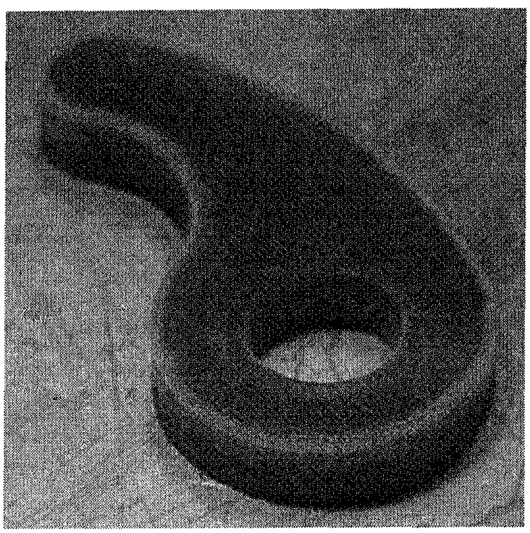
(a) Fine ice ring (b) Ice ring with uneven height and wall thickness

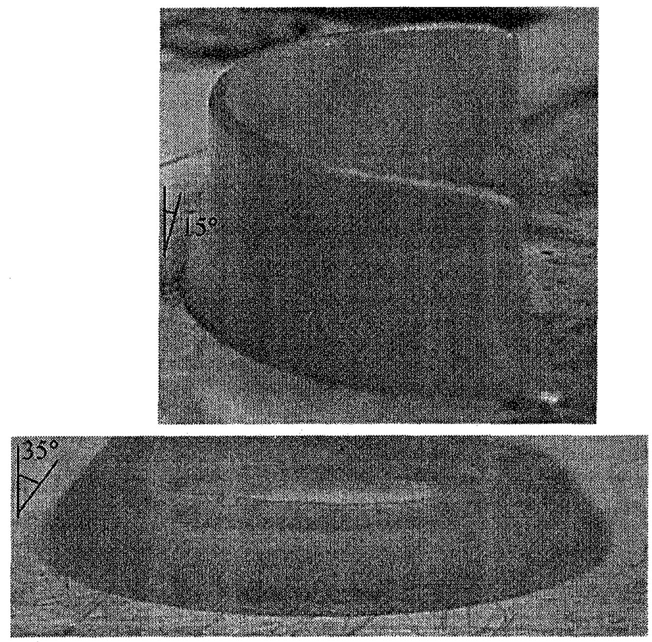
Figure 9. The effect of waiting time on ice ring building

Table I. Three-dimensional ice part parameters

Layer Thickness	Drawing Speed	Extrusion Pressure	Ejecting Frequency	Pulse Width	Environment Temperature	Nozzle Temperature
0.12 mm	40 mm/sec.	$1.5\times10^5 N/m^2$	400 Hz	0.2 msec.	-20°C	10°C

3) Building three-dimensional ice parts. Table 1 lists the optimal parameter values that were obtained from the above experiments and were used for three-dimensional ice part building. Figure 10 shows an ice link-rod and two ice conoids. The conoids are built to see the the maximum angle that can be achieved without support. In our experiments, a conoid of 35° angle was successfully made, as shown in Figure 10. The surface smoothness for both the conoids and the link-rod is very good as compared to parts made by other deposition based SFF processes without machining.





(a) Ice link-rod (b) Ice conoids of two different angles

Figure 10. Built three-dimensional ice parts

From the above experiments, we have observed that allowing enough cooling time before building the next layer and having high heat transfer rate are extremely important for the successful building of ice lines, rings, and three-dimensional parts. Insufficient cooling rate or cooling time can cause part building failure. This is because if the newly deposited water is kept in liquid state for some time, the surface tension will cause the water unevenly distributed, forming some water sweats on the building surface as shown in Figure 7(b). This surface tension effect can be restrained if the cooling rate is fast enough.

6. CONCLUSION

An experimental system has been developed to conduct the study of rapid freeze prototyping. The experiments conducted on this system have demonstrated the feasibility of making three dimensional ice parts by depositing and rapidly freezing water. The heat transfer analysis helps understand the freezing process and provides useful information to the selection of building parameters. Cooling rate, which depends on the environment temperature and cooling time between two successive layers, is a parameter critical to the success of part building.

Future work will focus on improving building resolution and part accuracy, and on process parameter optimization. Software will be developed to make complex three-dimensional ice parts with supports. Applications of ice parts will be another important issue in this research.

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