RAPID FREEZING PROTOTYPING WITH WATER

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ABSTRACT
Rapid Freezing Prototyping (RFP) with water is a novel solid freeform fabrication technique that can generate three-dimensional ice objects by depositing and rapidly freezing water layer by layer. The support where necessary is made of brine whose freezing point is lower than pure water. After building the part, the support can be removed by utilizing the melting temperature difference between brine and water. Preliminary experiments have shown that the ice patterns produced by this technique can be used for design visualization and silicone molding. This paper will present the concept and some experimental results of the RFP process as well as potential applications.

KEYWORDS
Solid Freeform Fabrication, Rapid Prototyping, Rapid Tooling, Layered Manufacturing, Rapid Freezing Prototyping, Ice Patterns

1. INTRODUCTION

Since the late 1980's, several Solid Freeform Fabrication (SFF) techniques have been investigated, and some commercially developed. These techniques allow freeform fabrication of complex-geometry parts directly from their CAD models [1]. By directly or indirectly employing SFF technologies in tool, die and mold fabrication, Rapid Tooling (RT) process is accomplished. These tools may serve the purpose of forming a prototype part in the end use material for design evaluation, or produce a product that only a small quantity need to be manufactured. The direct RT method consists of producing the tools with the SFF techniques and/or some post processing, such as Selective Laser Sintering with post processing technology of low melting point alloy infiltration. The indirect RT method involves secondary steps by integration of SFF and conventional shape duplication technologies. Successfully used indirect RT technologies include RTV (Room Temperature Vulcanization) molding, sand casting, investment casting, metal spraying, Keltool, and electroplating/electroforming based tooling. Currently, it is more widely used than direct RT [2-3].

With the additional shape duplication process in indirect RT, the mechanical properties of

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the prototypes made by SFF techniques are less critical. The materials of the prototypes are not necessarily ABS plastic, ceramic, or metal. However, the following properties are very critical:

- Accuracy: Generally speaking, accuracy for tooling needs to be higher than that for design visualization [4].
- Surface finish: The surface finish of the prototype determines the best achievable surface finish of the final tools. In many cases, the prototype needs to be polished after building in order to obtain better surface finish.
- Easy part removal: This property means less geometry limitation of tooling. If a part is not easy to remove, the mold has to be split into several sections to make. This results in more preparation time and some loss of tooling accuracy.
- Easy part joining: This is an additional desired property for complex geometry tooling. When a part is too complex or impractical to build due to strength or orientation reasons, it is desirable to build the part in several portions and then join them together.

Unfortunately, few SFF techniques satisfy all the above properties. For example, the Stereolithography Apparatus (SLA) can build parts with good accuracy and surface finish; however, the SLA part removal is not easy except for QuickCast parts. On the other hand, wax parts made by Fused Deposition Modeling (FDM) have good properties of easy removal and easy joining, and can be directly used for investment casting, however, the accuracy and surface finish need to be further improved as compared to SLA parts [5].

In terms of Rapid Prototyping or design visualization, techniques which are able to build colorized and transparent parts can provide more information about the design result and can give more clear and accurate evaluation. Almost all plastic depositing based SFF techniques can build colorized parts with colorized material, such as the FDM technique provided by Stratasys and the Model Maker provided by Sanders Prototypes. The parts made by most of the techniques including the FDM and Model Maker are not transparent. They are acceptable in most cases for design visualization. However, in some special cases, such as surgery plan preparation models and very complex one-part subassemblies, these models are not enough. The designer or the surgeon needs more interior information inside the model.

This paper presents the Rapid Freezing Prototyping (RFP) process that is being developed by us to address the above tooling and designing demands. By using water as the material and rapid freezing as the building method, RFP can build ice patterns with good accuracy and surface finish. Easy part removal and joining, colorized (different portions in different colors) and transparent parts are additional good properties for both tooling and design visualization. This paper is organized as follows. Section 2 introduces the principle of Rapid Freezing Prototyping. Section 3 discusses the main features of this novel process. Section 4 provides some preliminary application results, and section 5 concludes the paper.

2. PRINCIPLE OF RAPID FREEZING PROTOTYPING

2.1 Concept of the Technique

RFP is a novel SFF process that makes a part by selectively depositing and freezing the material (water or brine) layer by layer [6]. As shown in Figure 1, water is pumped from a reservoir to the nozzle by a peristaltic pump and then deposited onto the previous solidified ice surface or the substrate. The newly deposited material is cooled by both the low temperature environment and the ice surface. As a result the deposited water freezes rapidly and sticks to the previous layer, forming a new layer of the part. Where necessary, brine is used instead of water to build the support. The nozzle and the transmission pipe are heated and kept at a temperature just above the freezing point of water so that the material may flow smoothly. During the building process, the ratio of the in-nozzle material flow rate to the XY scanning speed is very critical. A too large ratio may cause failure to control its out-nozzle flow along the ice surface. On the other hand, a too small ratio may cause discontinuity of the freezing strands (See Figure 2). The ratio of material flow rate to the XY scanning speed can be kept at the best value by controlling the rotating speed of the peristaltic pump.

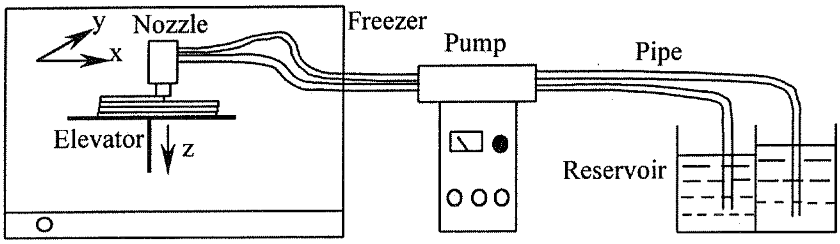


Figure 1. Principle of Rapid Freezing Prototyping

(a) Ratio too large (b) Normal ratio (c) Ratio too small

Figure 2. The schematic drawing of strands for different levels of the ratio of material flow rate to XY scanning speed

When the part with support is finished, the next step is to remove the support structure. As shown in Figure 3, there is some special solvent in the tank for removing the support. The solvent is kept at a temperature beyond the melting point of brine ice but under that of the pure ice so that only the support gets melted. The solvent used here must have two basic properties: not soluble with water and a large density difference from water. The first property is to ensure that the brine melt from support is not dissolved in the solvent and has no unexpected influence on the boundary of the ice part. The second property is to let the brine be separated easily from the part and support, either rising up or sinking down easily in the solvent. The blender is applied to accelerate the support removal procedure.

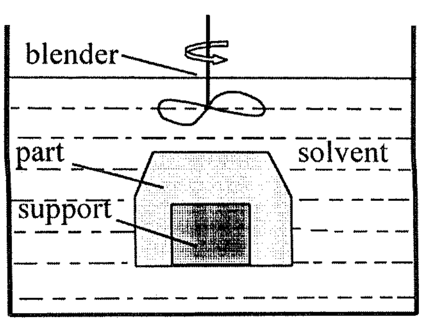


Figure 3. Support removal of Rapid Freezing Prototyping parts

2.2 The Current Experimental System

An experimental system is being designed and built for the research and development of the Rapid Freezing Prototyping process. A goal is to be capable of automatically building ice parts from the data provided by CAD software. The main components of the system are (Figure 1):

1) Material extruding subsystem
2) Material deposition nozzle
3) XYZ three-dimensional positioning subsystem
4) Support removal subsystem
5) Freezing chamber

The material extrusion subsystem pumps repetitively a desired amount of water from the reservoir into the nozzle and then deposits it onto the building surface. This function is achieved by utilizing a peristaltic pump, which uses rollers to squeeze the liquid through a flexible plastic tube. One end of the tube is inserted into the container of the building material, and the other end attached to the nozzle. The advantages of extruding water by a peristaltic pump include: (a) accurate metering of the liquid volume; (b) simplified maintenance due to the fact that there is no contact between the pump mechanism and the liquid; and (c) the pump has multiple channels which can be used for extrusion of building material and support material. The extruding speed of the pump is controlled by the pulses generated by the motion controller.

The material depositing nozzle in this experimental machine will have multiple tips which are designed for depositing building material, support material, and fast material depositing to improve build speed. The tip selection is accomplished by activating a certain electromagnet; see Figure 4. In order to prevent the material in the nozzle and the pipe from overcooling to freeze, some heating components are employed to keep them at a certain temperature, typically around 5°C.

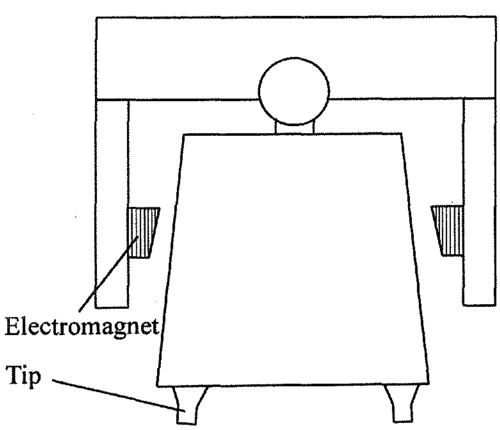


Figure 4. Multiple-tip nozzle

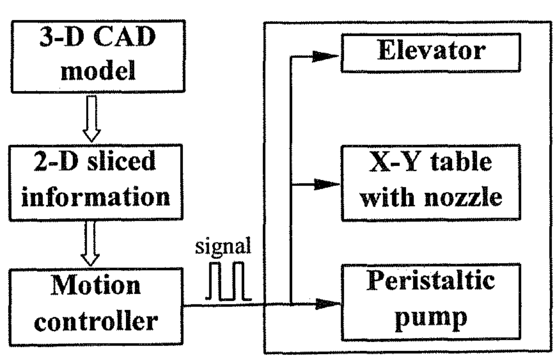


Figure 5. Control system structure of RFP experimental machine

The whole system will be controlled by a personal computer (Pentium-200MHz). The three-axis movement and the peristaltic pump are controlled by a PC-Bus based 4-axis stepping motor controller (OEM AT 6400, by Compumotor Co.). The software to be developed generates the Numerical Control (NC) codes according to the sliced contour information of the CAD model. The stepping motor controller uses the NC codes to control the motion of the elevator in Z direction and the nozzle in X and Y directions. The peristaltic pump is also controlled by this motion controller. The schematic of controlling is shown in Figure 5.

The support removal subsystem introduced above is shown in Figure 3. The accurate temperature control of the solvent is essential to the success of support removal.

The building mechanism, including the nozzle, the elevator, and part of the XY positioning table, is placed in a temperature controlled freezing chamber. The temperature is controlled by a computer-interfaced controller. The typical chamber temperature is controlled at -20°C. Generally speaking, lower temperature allows faster building of ice parts.

2.3 Building Strategy

Contours and interior fillings of each layer of the ice part are built with different aperture tips. In order to build the ice parts with good accuracy and surface finish, the contours are built by depositing material with a smaller aperture tip, typically 0.3 mm in diameter. However, the interior fillings are built by depositing with a larger aperture tip to improve the building speed; see Figure 6. The properties which make this building strategy possible include almost no heat accumulation, natural binding of layers, and excellent fluidity.

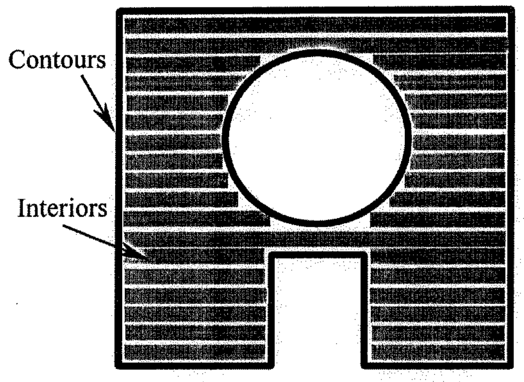


Figure 6. Cross section of an ice pattern

3. MAIN FEATURES OF RAPID FREEZING PROTOTYPING

By using water as the building material, RFP distinguishes itself from the current SFF techniques in the following main features.

(1) RFP is a cheaper and cleaner prototype building technique. The building process and the building material have no negative impact on the operator and the environment. The process has no harmful UV light and does not produce smell, smoke, noise, or garbage.

(2) RFP has the potential to build accurate ice parts with excellent surface finish although substantial research will be needed to achieve fine part accuracy.

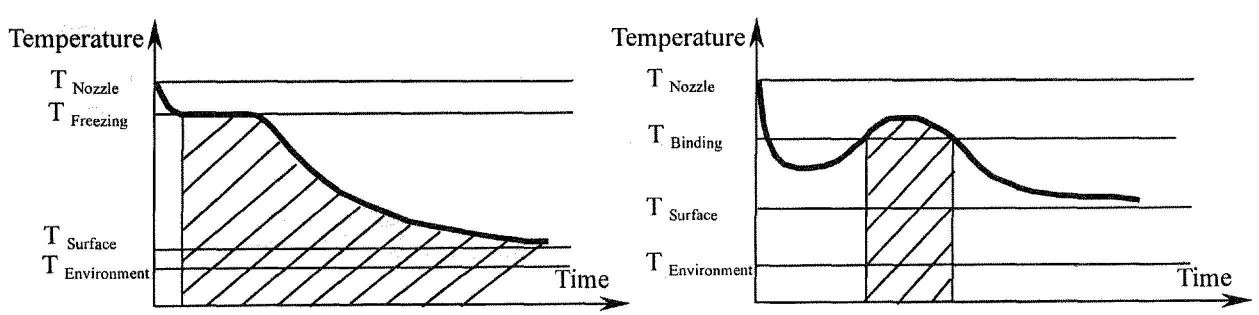
(3) The ice part made by RFP is easy to remove from a mold simply by warming it up and making the mold dry. There is no residue problem. The ice parts are also easy to join due to its self-welding property. A very complex part can be separated into several portions to make and then join them together.

(4) RFP does not have the problem of heat accumulation. Water is a kind of crystalloid material and the binding of adjacent layers is accomplished by the hydrogen bond. So the in-nozzle material can be kept in liquid state by keeping its temperature just a little bit above the freezing point. The heat generated during freezing of the deposited material can be easily absorbed by the building surface and the surrounding cold air, thus resulting in no heat accumulation. In other heat related SFF processes, such as FDM, the material is not crystalloid. In order to obtain good fluidity and enough binding strength between adjacent layers, the in-nozzle material must be heated to a fairly high temperature. The environment can not easily absorb the provided heat in time. As a result, the heat will accumulate and affect the accuracy and surface finish of the parts.

(5) RFP has a much longer binding time than FDM. The temperature of the very thin layer material near the building surface is believed to be most important for the binding property. The schematic temperature change curves of the critical portion of material for RFP and FDM are shown in Figure 7. In RFP, water is a kind of crystalloid material and thus the curve has a flat section which means the material is freezing. The binding between adjacent layers is achieved by hydrogen bond. After freezing, additional cooling by the environment and built part still contributes to better binding. However, in FDM, the curve has no flat section. The binding between adjacent layers is achieved by thermal joining. So only the effective period during which the temperature is higher than the binding point contributes to the binding. This effective period is determined by the nozzle temperature, the environment temperature, and the building speed. Due to limitations of the three factors, the effective period is also limited.

(6) During the freezing in RFP, the material expands and causes compress stresses in the part. The expansion of the material can be mostly compensated by properly selecting of the interior fill spacing. However, for other depositing SFF techniques, when solidifying, the material shrinks and causes tensile stresses in the part. The shrinkage is much more difficult to compensate due to the material additive building style of SFF. The tensile stress may cause notable distortion, and even cracks or delamination between adjacent layers.

(7) It is very easy to build colorized parts with RFP process. Different portions of a part can be built with the same material of different colors.



(a) Typical cooling curve in RFP (b) Typical cooling curve in FDM

Figure 7. Comparison of typical cooling curves of deposited material in RFP and FDM

4. APPLICATIONS OF ICE PATTERNS

All applications of ice patterns are faced with the problem of low operating temperature. This indeed makes application more difficult. However, in some cases, this problem can be solved or the advantages of RFP are dominant factors. The following describes some of the proper advantageous RFP applications.

4.1 Visualization

RFP can easily build colorized and transparent ice parts. This feature is very important in some cases. For example, a model of diseased organ can help the surgeon to prepare the operation better. By utilizing RFP, a colorized ice model can be made with the CT scanning information, different portions in different colors. This colorized ice model can help the surgeon to get more information and better understanding about a disease focus. The transparent feature of the ice model makes it possible to see the internal structure of the ice model of the diseased organ.

4.2 Rapid Tooling

RTV silicone rubber molding is one of the most popular Rapid Tooling technologies. Our preliminary experiment shows that silicone molding with ice patterns at low temperatures is feasible. A major disadvantage is that it takes longer time for the silicone (2-composite mixture) to cure (at -10°C). However, easy pattern removal is a great advantage of RFP in case the part is very complex and the accuracy is very critical. In this case, after the silicone mold cures, the ice pattern can be removed from the silicone mold by melting instead of physical removal, and thus an accurate complex plastic part can be duplicated very rapidly. The procedure is as shown in Figure 8 and some pictures are given in Figure 9.

Another approach which uses UV curable silicone to replace the 2-composite silicone is being taken. In this approach, the material only reacts to UV radiation. The temperature is no longer an important factor for curing speed. Another advantage of this approach is that the curing speed is much faster than traditional silicone curing systems [7].

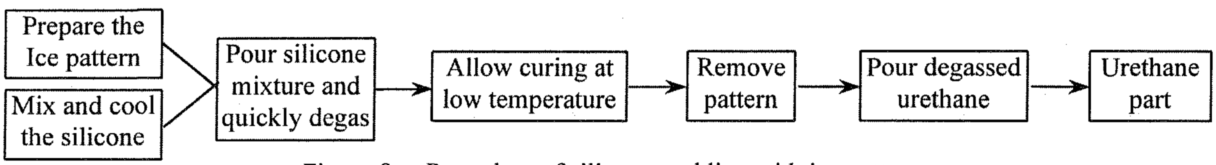
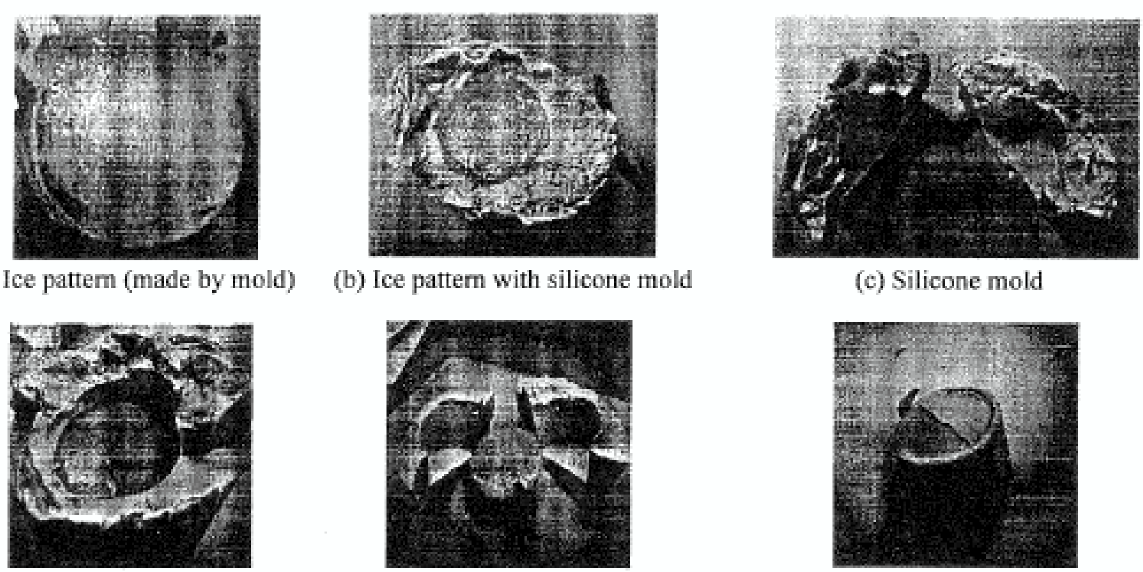


Figure 8. Procedure of silicone molding with ice patterns



(a) Ice pattern (made by mold) (b) Ice pattern with silicone mold (c) Silicone mold

(d) Pour urethane (e) Demolding (f) Urethane part

Figure 9. Silicone molding with ice patterns

5. CONCLUSION

Rapid Freezing Prototyping is a novel solid freeform fabrication process which has some advantages and disadvantages. The major disadvantage is that it needs low temperature operating environment. However, its advantages including good surface finish, potentially good accuracy, clean and cheap material, easy pattern removal and joining, easy expansion compensation, and fast building speed makes it a good choice in some application areas. Our preliminary experiment shows that low temperature silicone molding with ice patterns is feasible. Urethane parts have been made with the silicone mold made with ice patterns.

Experiments on tooling application such as UV curable silicone molding and metal casting (including sand casting and investment casting) are needed to validate the application potentials of ice patterns. The building process, including build strategy, process control, and parameter tuning, needs to be developed and physically verified.

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