DETERMINATION AND IMPROVEMENT OF BUILDING SPEED IN RAPID FREEZE PROTOTYPING

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ABSTRACT

Rapid freeze prototyping (RFP) is a solid freeform fabrication process that builds an ice part by rapidly freezing water in a layer by layer manner. One advantage of this process is the ability to build ice parts faster than other SFF processes. The factors that affect the speed of contour building and interior filling in RFP are identified. The influence of these factors is analyzed through heat transfer and material flow analyses. A model based on heat transfer analysis is proposed to determine the maximum achievable speed of contour building under stable conditions. Experiments are conducted to validate the performance of the proposed model for determination of building speed.

KEYWORDS

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

1. INTRODUCTION

Rapid Freeze Prototyping (RFP) is a novel solid freeform fabrication (SFF) process that uses water as the building material and makes three-dimensional ice parts by freezing water according to their CAD models layer by layer. This process is being developed by us to address many of the existing issues in the current SFF processes, such as high cost, poor surface finish, low building speed, etc. Details of this process can be found in Ref. [1-4]. The advantages of this process, including cleanness, lower cost, potential better surface finish and building accuracy, ease of stress compensation, and faster building speed, were discussed in [2-4]. Potential applications of this process include part design visualization and rapid tooling such as RTV silicone molding, investment casting, and sand casting[5-6]. The most promising application appears to be investment casting. In a patented investment casting process, called the Freeze Cast Process (FCP), ice patterns instead of traditional wax patterns were used to make metal parts. This process was developed to address problems and technical difficulties of traditional investment casting such as wax pattern expanding, ceramic shell cracking, etc.[5]. One major concern in the FCP process is ice pattern making. The traditional method of making ice patterns is by injecting water in a mold and making it frozen. Some main issues in this method include compensation of water expansion 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 short time, without the cost and other issues of mold making. This is especially valuable in case that a small amount of complex metal parts and thus ice patterns are needed.

RFP has the potential to increase the part building speed to a much higher level than most other SFF processes because of the following reasons:

1) Ice layer binding is achieved naturally through hydrogen bonds, thus the environmental

temperature can be very low without the need to ensure sufficient layer binding strength through improving environmental temperature as other thermal deposition processes.

2) Since water expands rather than shrinks when freezing, the expansion can be compensated by adjusting line spacing. As a result, there is much less stress caused by phase change as compared with other thermal deposition processes.
3) Water has a lower viscosity than molten wax and plastic. In conjunction with the above two features, RFP can use a faster interior filling mode by simply flushing water to the interior of a boundary (built with a regular scanning mode) to a predetermined height. The flushing mode is more efficient than the regular line-by-line filling mode.

However, to take advantages of the above, the process parameters must be controlled to avoid building process failures such as the water line stability problem. To do this, a good understanding about heat transfer in building a new layer and the flow of deposited material is essential. Through detailed thermal analysis and material flow analysis, parameters can be optimized to result in faster building speeds and to avoid failures in both contour building and interior filling in the meantime.

The paper is organized as follows: Section 2 provides detailed heat transfer analysis and discusses the influence of various process parameters; Section 3 analyzes the material flow behavior and stability problem; and Section 4 concludes this paper.

2. HEAT TRANSFER ANALYSIS

Figure 1 shows our current RFP experimental system. It includes: a) a three-dimensional positioning subsystem, b) a material extruding and ejecting subsystem, and c) a freezer. The whole experimental system is controlled by a personal computer, with the movements in the three axes and the nozzle ejecting frequency controlled by a PC-bus based stepping motor controller. The material extruding subsystem is also controlled by this motion controller. The material supplying subsystem feeds water to the ejecting nozzle from a reservoir by a pressure device at a pre-set constant pressure. The nozzle, which mainly consists of a miniature solenoid valve, a jet, and a heating cover, generates water droplets at a controlled frequency and size.

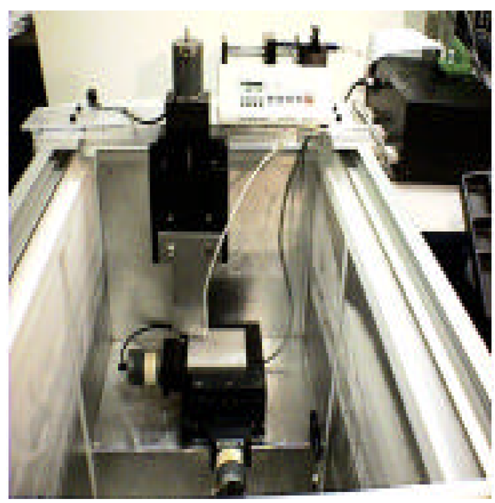
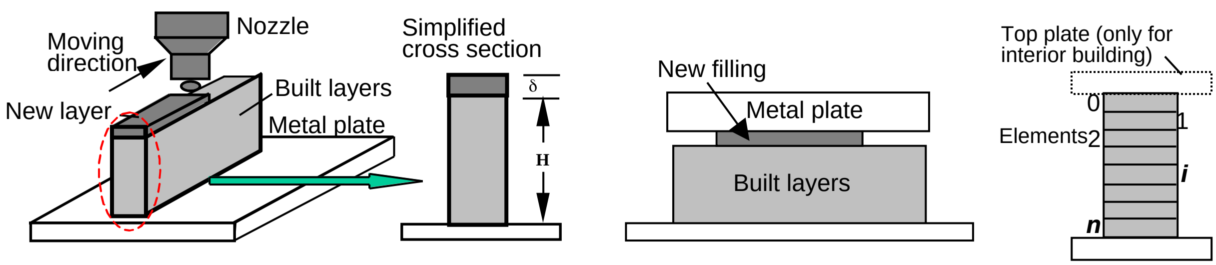


Figure 1. Rapid Freeze Prototyping Experimental System

The formation of a well shaped and uniformly deposited ice line is fundamental to the building of a three-dimensional ice part. There are two dominating factors in the ice line building process: material freezing and spreading on the building surface. Freezing is caused by the fast cooling of the built layers and the cold environment. It is a contributing factor to the improvement of ice line resolution. However, the spreading of the newly deposited water caused by surface interaction between the water and the top ice layer (associating with surface tension, capillary force, and viscous force) negatively affects ice line resolution. The balance between the positive factor and the negative factor determines the final ice line quality, i.e. line resolution and evenness. It is important to identify the parameters that have significant influence on the balance and to understand this influence in order to control the process and build successful ice parts. Theoretical analysis of the heat transfer between a newly deposited layer and the previously built layers can provide quantitative information about the freezing process.

To analyze heat transfer in both the newly deposited layer and the previously built layers, we need to treat boundary building and interior filling separately. Boundaries should be built with smaller layer thickness in order to get fine resolution, accuracy, and surface finish. Interiors can be built by flushing water every *N* layers (much thicker than one single layer) in order to improve the building speed. The newly deposited material for boundary building is mainly cooled down through conduction by the previously built layers, while convection is relatively insignificant. For interior filling, in order to improve cooling rate, a cold metal plate can be placed on top of the newly filled layer. So the newly filled interior layer is cooled down mainly through conduction by both the metal plate and the previously built layers, while convection is again relatively insignificant. To simplify the analysis, we will not consider the heat transfer along the nozzle moving direction (i.e. scanning direction) and the heat transfer through convection. Since the boundary is built up with only one line, the line has no neighboring lines and thus no heat transfer in XY plane. For interior filling, the temperature gradient in XY plane is also negligible. So for both boundary building and interior building, heat transfer occurs mainly in Z direction and thus it is a one-dimensional problem. The analysis models are given in Figure 2(a) and Figure 2(b).



(a) Boundary building model (b) Interior filling model (c) Finite elements

Figure 2. Finite element analysis models for both boundary and interior building

Finite element analysis is used to tackle this heat transfer problem. The model consisting of a multitude of previously built layers and a new layer is divided into small elements of three kinds (see Figure 2(c)): (A) interior elements (each with two neighboring elements), (B) surface element (on top of new layer), and (C) boundary elements (bottom and top elements touching the metal plate). The governing equations can be obtained as follows[7]:

(A) For an interior element P(*i*)   ($0<i<n$)

$$T_i^{\Delta\tau} = F_0(T_{i-1} + T_{i+1}) + (1-2F_0)T_i$$

$$where \quad F_0 = \frac{\lambda\Delta\tau}{\rho c(\Delta z^2)}$$

(B) For the surface element P(*0*) in boundary building without a metal plate on top

$$T_0^{\Delta\tau} = 2F_0T_1 + (1-2F_0)T_0$$

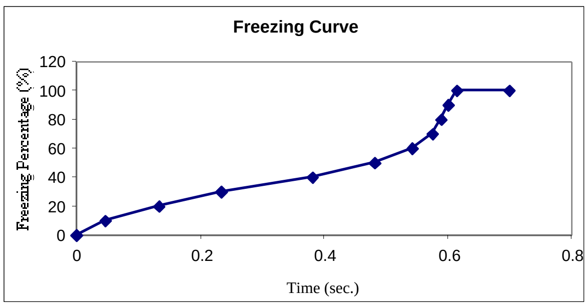
(C) For the boundary elements P(0) and P(*n*)

$$T_n^{\Delta\tau} = T_0^{\Delta\tau} \quad T_M$$

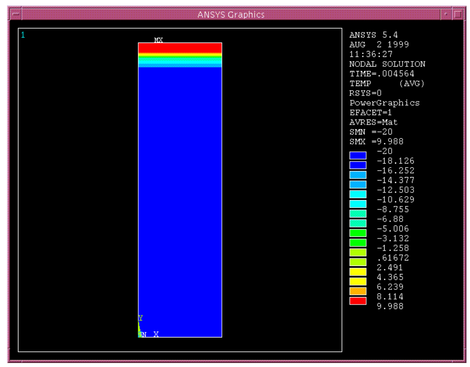
(with metal plate on top for interior building)

In the above equations, $T_i^{\Delta\tau}$, T_M, Δz, c, and λ represent the updated temperature after time $\Delta\tau$, metal plate temperature, element size in Z direction, specific heat, and conductivity of ice/water, respectively.

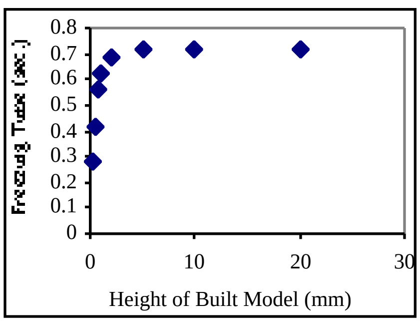
Figure 3 shows some heat transfer analysis results in boundary building. In this analysis, the time required to freeze the deposited material completely, called the freezing time and denoted by τ_F, is investigated. Before τ_F, at least part of the material is in liquid state and there are material flow and surface tension effects. After τ_F, heat transfer only lowers the new layer's temperature, with no surface tension effect, no phase change, and no significant volume change. Figure 3(a) shows the ice percentage change in the new layer as a function of time. The freezing time is the time (0.62 sec.) when the freezing percentage reaches 100%. Figure 3(b) shows the cross-sectional temperature distribution at the freezing time. Figure 3(c-f) shows the influence of total height of built layers, layer thickness, initial droplet temperature, and environmental temperature on the freezing time.



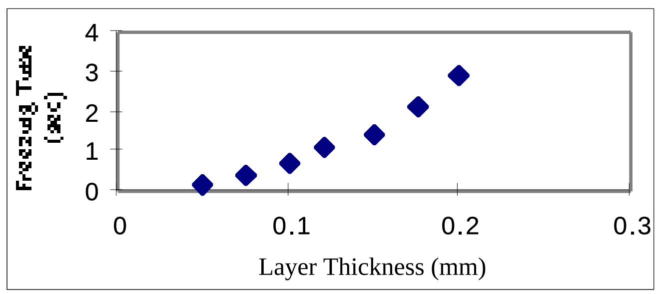
(a) Water freezing percentage



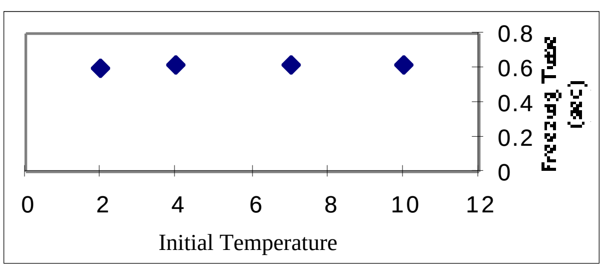
(b) Cross-sectional temperature distribution



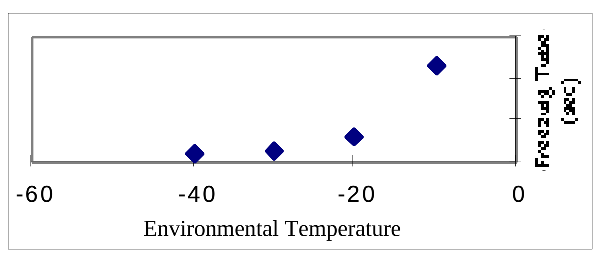
(c) Freezing time vs. building height



(d) Freezing time vs. layer thickness



(e) Freezing time vs. initial droplet temperature (°C)

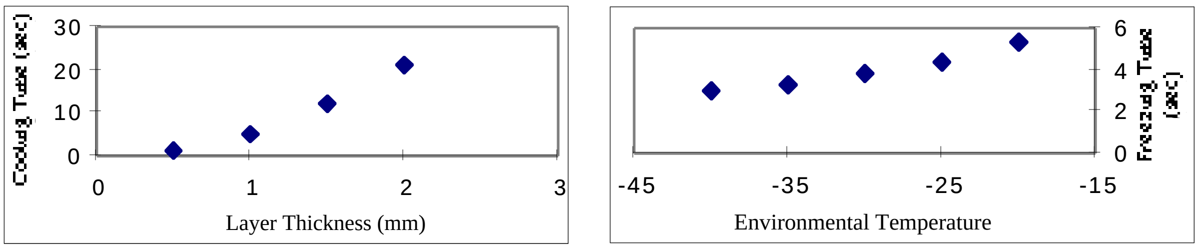


(f) Freezing time vs. environmental temperature (°C)

Figure 3. Analysis results for boundary building

We can see that layer thickness and environmental temperature are more significant in affecting the freezing time, while initial droplet temperature has limited influence. This can be explained by the fact that water releases much more heat during freezing than during temperature drop from the initial droplet temperature to water's freezing point. The height of built layers only significantly affects the freezing time before it reaches about 2 mm. After that, its influence becomes negligible. This is good for process control because we do not have to adjust other process parameters with built height once it reaches 2 mm. The information obtained from the heat transfer analysis provides quantitative understanding of the temperature and phase change in depositing the new layer. It can help optimize process parameters and solve the stability problem discussed in the next section.

Figure 4 shows the analysis result for interior filling. In this analysis, the time needed to cool down the new filling layer is investigated. This time, called the cooling time, is defined as the time required to cool down the new layer's temperature to within 20% of the initial temperature difference with the metal plate's temperature. For example, if the initial droplet temperature is 5°C and the metal plate's temperature is –20°C, then the cooling time is the time that lowers the new layer's highest temperature to –15°C. The reason that we use Cooling Time instead of Freezing Time for interior filling is that we must cool down the newly filled layer in order to start the next layer. It can be seen form Figure 4 that a smaller filling thickness or a lower metal plate temperature results in a shorter cooling time. However, considering the time required to move the metal plate over the filling layer, smaller layer thickness means more operations and thus not necessarily reduces the total filling time. The optimal filling thickness needs to be calculated with the consideration of both cooling time and metal plate operation time.



(a) Cooling time vs. layer thickness (at -20°C) (b) Cooling time vs. environmental temperature (°C)

Figure 4. Analysis results for interior building

3. MATERIAL FLOW ANALYSIS

After a droplet is ejected onto the building surface, it will deform, spread, and freeze. The shape change ends with complete freezing. Deformation and spreading help to make continuous ice lines, however, overspreading will cause failure of shape control and ice line building. The shape deformation and material flow in the plane perpendicular to the scanning direction (nozzle moving direction) is analyzed in Ref. [8]. The material flow along the scanning direction is discussed in this section.

In our experiments of ice line and part building, we have observed the stability problem as shown in Figure 5. The left one generated a good ice line with even line width, while the right one lost control of line building (lots of water blobs were formed). This is a typical stability problem. The reason for this phenomenon is the complex interaction of water surface tension, capillary force, gravity, and water viscosity[9]. During the process that an evenly distributed water line changes to a spherical blob, the energies associated with this process are (refer to Figure 6):

$$E_{\sigma-L} = E_{\sigma-R} + E_{\mu} + E_s + E_g \qquad E_s = k_s L, \quad E_{\mu} = k_{\mu} f(\bar{u}) L$$

$$E_{\sigma-L} = k_{\sigma} L, \quad E_{\sigma-R} = k'_{\sigma} L^{\frac{2}{3}}, \quad E_g = k_g L^{\frac{1}{3}}$$

$$Therefore: \quad f(\bar{u}) = \frac{1}{k_\mu}\left[k_\sigma - k_s - k'_\sigma L^{-\frac{1}{3}} - k_g L^{-\frac{2}{3}}\right]$$

In the above, $E_{\sigma-L}, E_{\sigma-R}, E_\mu, E_S, E_g$ are the surface energy of the water line, surface energy of the water sphere, energy due to water viscosity, energy due to capillary force, and energy due to gravity, respectively. $k_\sigma, k_{\sigma'}, k_g, k_s, k_\mu$ are the associated coefficients. These equations relate these various energies to the water line length L. For example, the energy consumed due to gravity is proportional to the sphere radius, and is thus proportional to the cubic root of the sphere volume or the water line length (since the water line width and line height are fixed).

The above equations are based on the following assumptions:

- *L >> R, and thus the line width change during the blob formation is negligible.*
- *The initial and final shapes of water deposit are an ideal even line and a half sphere.*
- *During the shape changing, there is no temperature, phase, or material property change.*
- $f(\bar{u})$ *is a monotonous increasing function about the average shape changing speed* $\bar{u}$

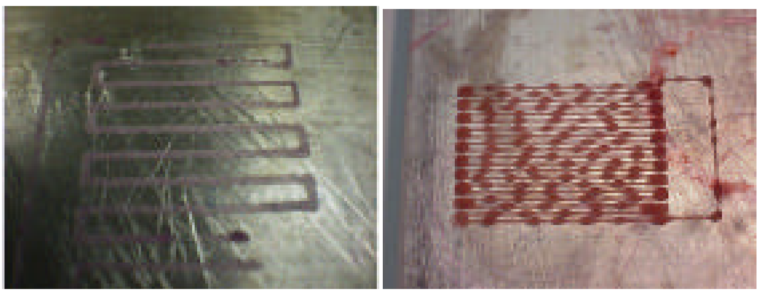


Figure 5. Built ice lines (left: fine line; right: unstable line)

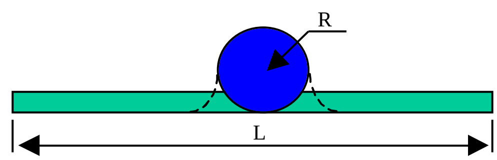
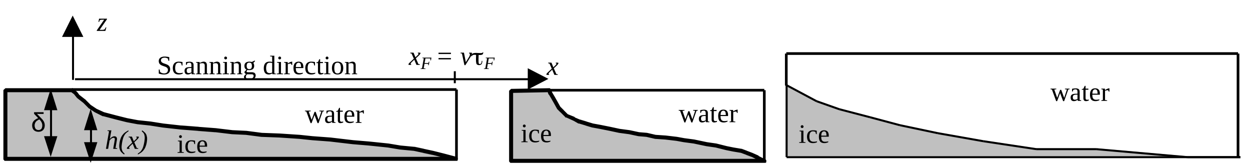


Figure 6. Shape change analysis model

If $E_{\sigma-L} > E_{\sigma-R} + E_\mu + E_S + E_g$, then $f(\bar{u})$ and $\bar{u}$ will be positive, which means the shape will change at a certain average speed $\bar{u}$. Otherwise, the shape will stay stable or semi-stable. A greater $\bar{u}$ means faster shape change, and the water line is more unstable. It can be seen that when the water line length L increases, the corresponding increases of the five energies are not the same. Some energies increase proportionally and others increase relatively slowly. As a result, both $f(\bar{u})$ and $\bar{u}$ increase and the water line becomes more unstable. This has been confirmed by our experimental observations.

In rapid freeze prototyping, since water freezes after deposition, the line profile is changing with time. Accordingly, the percentage of water after deposition is a function of time and thus is a function of distance from the nozzle along the scanning direction. Figure 7 shows the water-ice boundary profile for a newly deposited layer along the scanning direction and the influence of layer thickness and environmental temperature on the boundary profile. Smaller layer thickness (Figure 7(a)) and lower environmental temperature (Figure 7(b)) result in a smaller amount of water in the deposited water line.



(a) δ = *0.1 mm, T = -20°C* *Water volume* $V(x_F) = 1.47\ mm^3$

(b) δ = *0.1 mm, T = -30°C* $V(x_F) = 0.53\ mm^3$

(c) δ = *0.15 mm, T = -20°C* $V(x_F) = 6.4\ mm^3$

Figure 7. Influence of layer thickness and environmental temperature on boundary profile and water volume

Therefor, with consideration of water-ice profile change (using volume instead of using length), as an analogy to the stability of a pure water line, the deposited water becomes more unstable when the amount of water becomes larger. Since the deposited water will eventually freeze, this translates to a larger height variation in the built part for a greater amount of water. The amount of water can be computed using the following equation:

$$V(x_F) = w\int_0^{x_F}[\delta - h(x)]dx = vw\int_0^{\tau_F}\left[(\delta - h(v\tau)\right]d\tau = V(v\tau_F) \quad (1)$$

where v, w, δ, τ_F, x_F, and $h(x)$ are scanning speed, line width, layer thickness, freezing time, scanning distance at freezing time, and water percentage function, respectively. The function $h(x)$ can be obtained by transforming the relationship of freezing percentage vs. time (as shown in Figure 3(a)) to freezing percentage vs. scanning distance ($x = v\tau$).

To build an ice part, we need to control the height variation within an acceptable limit. To achieve the variation control, according to the above conclusion, we need to restrict the amount of water ($V(x_F)$) in the deposited line within a limit. So for any given environmental temperature (i.e. given $h(x)$), there exists a maximum alloable scanning speed. A scanning speed larger than this speed limit will proportionally cause the amount of water ($V(x_F)$) in the deposited line exceeding the limit (based on Equation (1)), and thus causing the variation over the acceptable limit.

In order to quantitatively determine the maximum allowable scanning speed to obtain acceptable part height variation for any given environmental temperature, we need to experimentally determine a maximum scanning speed for one environmetnal temperature. The speed value will be used to compute the maximum allowed water amount $V(x_F)$. Once $V(x_F)$ is obtained, we can use equation (1) and the freezing percentage function obtained from heat transfer analysis to calculate the maximum scanning speed for other various environmental temperatures.

As an example, we consider building a cylinder with a diameter of 50 mm and a height of 100 layers. The acceptable part height variation is 2%. The maximum scanning speed for the environmental temperature of –20°C is experimentally determined to be 75 mm/sec., and the computed $V(x_F)$ equals to 1.47 mm^3. The maximum scanning speeds at other environmental temperatures are computed as shown in Figure 8, which also provides the experimentally measured maximum scanning speed at various environmental temperatures. It can be seen that the predictions agree well with the experimentally measured results. Thus the value of the fundamental understanding and analysis as described is allowing us to theoretically determine the maximum allowable scanning speeds at various environmental temperatuers by measuring the maximum scanning speed at only one temperature.

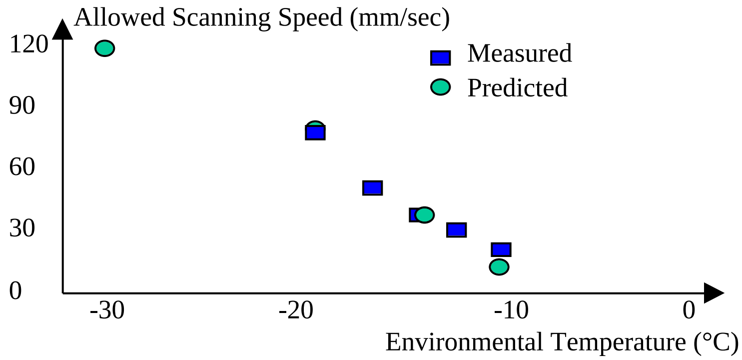


Figure 8. Predicted allowable scanning speed vs. experimentally measured allowable scanning speed

5. CONCLUSION

The heat transfer analysis together with material flow analysis helps to understand the freezing process and provides useful information to the selection of building parameters for build time reduction in rapid freeze prototyping. The analysis of ice line building stability provides an analytical method to predict maximum allowable scanning speed for any given environmental temperature with only one experimentally measured result, and this method is verified experimentally.

Further analyses and observations (especially microscopic material flow and freezing) are needed in the future to provide better understandings about rapid freeze prototyping, and to improve building speed as well as building accuracy and surface finish.

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