Increase of Heat Transfer to Reduce Build Time in Rapid Freeze Prototyping

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ABSTRACT

Reduction of part build time in the Rapid Freeze Prototyping (RFP) process, which fabricates a 3D ice part layer-by-layer by depositing and freezing water droplets, has been achieved by increase of heat transfer. Three mechanisms have been experimentally investigated: 1) cooling the substrate, 2) use of forced convection, and 3) use of a chilling plate. Cooling the substrate is effective for parts of small heights but becomes ineffective with increase in part height. Forced convection produced desirable reduction in part build time but with the undesirable formation of frost on the built ice part. The use of chilling plate to increase heat conduction proved to be most effective. To ensure that the frozen ice from the deposited water can be easily removed from the chilling plate, various surface coats were investigated and the most effective surface coat was found to be a thin Teflon film. After incorporating the chilling plate we have successfully achieved 75% reduction in part build time.

1. INTRODUCTION

The Rapid Freeze Prototyping (RFP) process is a freeform fabrication process which builds a part by depositing water droplets and freezing them rapidly layer by layer [1-4]. The RFP apparatus, shown in Figure 1, consists of a substrate table capable of X-Y travel and a nozzle head capable of motion in the Z direction. The entire apparatus, including the moving axes, is housed in a freezer that provides a temperature controlled environment. The required part geometry is traced by controlling the movement of an X-Y table while fine water droplets are deposited through a nozzle in a workhead mounted on the Z axis. The water droplets freeze on contact with the substrate or the previously deposited layer, forming a 3D geometry according to a CAD model. Two nozzles are used, one for the deposition of water and another for support material. The support material (eutectic dextrose solution) is needed to help generate parts of complex geometry with features such as holes, overhangs, slant walls, etc. Many parts of various shapes have been built using the RFP process. Compared with other SFF processes, RFP is a low-cost and environmentally friendly process because it uses water as the build material and inexpensive equipment to build parts. Other benefits of this process include fine surface finish, low energy use, and ease of pattern removal for casting and molding applications.

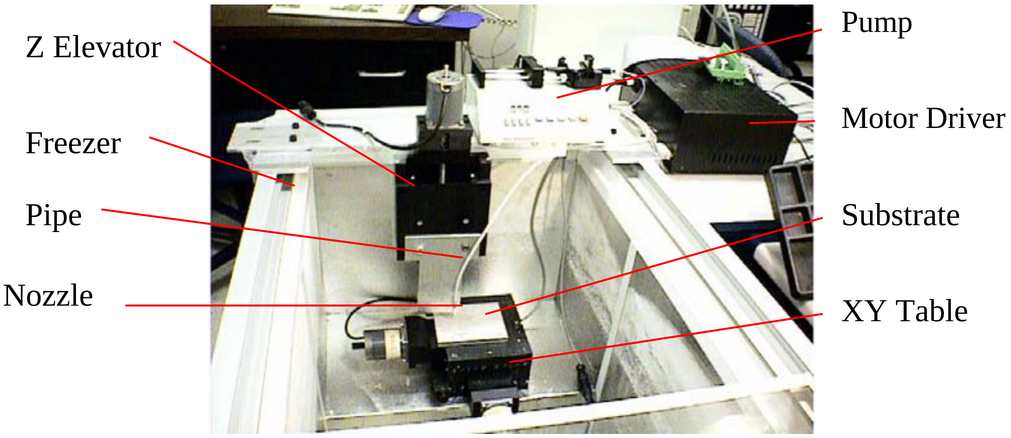


Figure 1. The Rapid Freeze Prototyping (RFP) apparatus

One potential application of the RFP process is using the fabricated ice parts as patterns for investment casting [5,6]. Wax patterns have traditionally been used in investment casting to make molds [7]; however, they have several disadvantages, the most significant of which is shell cracking during de-waxing. The cracking leads to difficulties in the manufacture of castings with thin cross-sections. Our overall research objective seeks to improve the capability of the RFP process so that it can be used to make thin-walled ice structures. Such improvement could facilitate new development of the shell mold process and enhance the means of producing small, intricate precision components.

This paper describes an attempt to lower the temperature near the part build surface during the water droplet deposition in the RFP process in order to increase heat transfer, reduce build time, and enable fabricating thin-walled ice structures. The increase in heat transfer was achieved by: (1) Conduction – This was done through two mechanisms: (a) lowering the substrate temperature with coolants and (b) using a chilling plate; (2) Convection – This was done by using a fan to create forced convection in the system. These various mechanism and their results on heat transfer are detailed in the present paper.

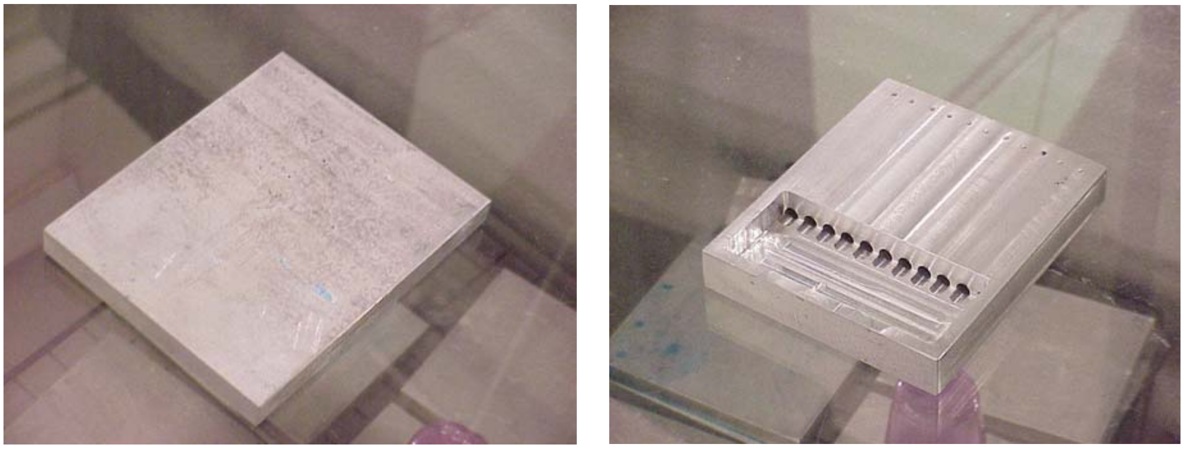
2. COOLING SUBSTRATE

The first mechanism we investigated to increase heat transfer was modifying the substrate to reduce its temperature by incorporating coolant passages. This modification, compounded with the use of liquid nitrogen, permitted cooling of the substrate to the extremely low temperature of -140^{o}C. The reduction in the substrate temperature resulted in a significant reduction in the water solidification time, thus permitting the production of a thinner part in a shorter build time.

The rate of heat conduction is proportional to the difference between the temperatures of the two media involved in the heat conduction [8]. Liquid nitrogen, which boils at $-196^{o}C$, acts as a perfect heat sink when it comes in contact with the aluminum substrate at the freezer temperature of $-20^{o}C$, permitting rapid heat transfer to occur from the substrate to the liquid nitrogen. The substrate base plate modification increased the surface area of contact between the liquid nitrogen and the aluminum plate.

The pocket on the side of the substrate base plate acts as a reservoir for the manual input of liquid nitrogen. The liquid nitrogen flows into coolant passages drilled into the plate through the reservoir and cools the substrate from the inside. The heat transferred to the liquid nitrogen by the base plate changes the phase of the nitrogen from liquid to its more stable gaseous form, which vents through the miniature coolant passages built into the top of the base plate, thus enabling very low temperatures and very high rates of cooling. Figure 2(a) & (b) show the original substrate and the modified substrate, respectively.

To measure the temperature achieved by the two substrates, nine holes were drilled into the substrates just under the substrate surface. Through these holes, thermocouples were inserted at nine different points on each of the two substrate surfaces. Figures 3 and 4 plot the measured temperatures for the original and modified substrates, respectively. Because the temperatures measured by the nine thermocouples are very similar, only the temperatures obtained from two thermocouples are shown in these figures. With the original substrate, the thermocouples indicate a downward temperature trend (Figure 3), which is expected because of the use of liquid nitrogen. Even with considerable liquid nitrogen the lowest temperature achieved was only $-40^{o}C$, after which the temperature leveled out and remained constant. However, with less than half the liquid nitrogen used in the original substrate, the temperature in the modified substrate dropped to $-140^{o}C$ before leveling out.



(a) (b)

Figure 2. The original substrate (left) and the modified substrate (right)

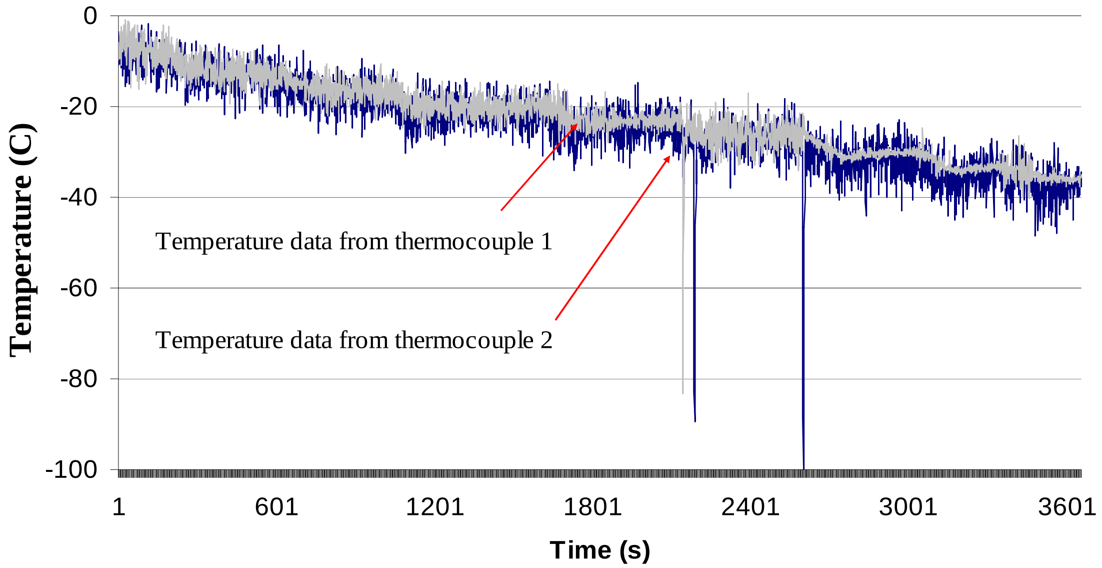


Figure 3. Temperature during part build (with the original substrate)

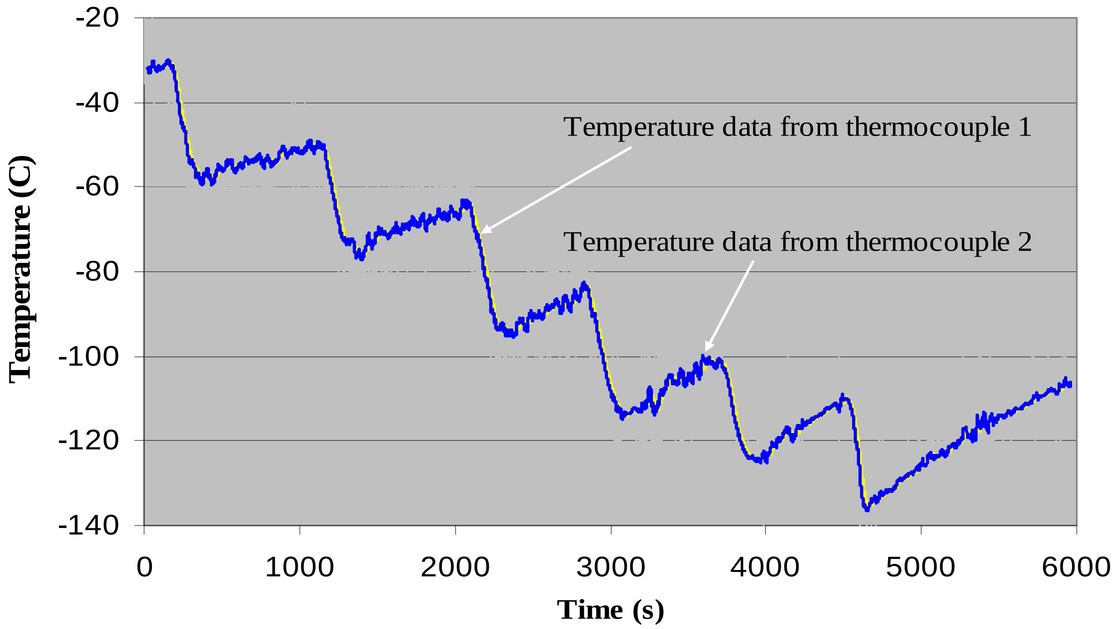


Figure 4. Temperature during part build (with the modified substrate)

Simulations performed in Fluent [9] to predict the time required to freeze a layer of water showed a substantial reduction in the water droplet freezing time with decrease in the substrate temperature. The total heat loss, the liquid fraction, and the temperature decrease in the deposited water as functions of time were also simulated in Fluent to identify the water freezing time and the wait time between layers. The results obtained in Table 1 are for the first layer of water deposited on the substrate at various substrate temperatures. These results indicate that with an ambient temperature of -140^{o}C, the wait time between layers can be shortened to about 5 seconds.

These simulation results were used to guide experiments in which test parts were built with reduced wait time between layers. From Table 1 we conclude that the lower the substrate temperature, the shorter the time to freeze and the shorter the wait time between layers. The wait time was taken as the duration for the difference between the temperature of the deposited water and the temperature of the ambient to reduce to 1% of the difference between the initial water droplet temperature and the ambient temperature. With the new substrate design, our experimental results showed that we could reduce the wait time between layers to about 15 seconds. With the original substrate, the shortest possible wait time was 40 seconds. The new substrate therefore permitted a reduction of over 60% in wait time between layers.

Table 1. Simulation results (from Fluent) of time to freeze the first layer of water above the substrate and wait time at various ambient temperatures

Temperature (^{o}C)	Time to Freeze (s)	Wait time (s)
-140	0.8	5.0
-120	0.9	5.5
-100	1.1	6.4
-80	1.0	7.0
-60	1.5	8.0
-40	2.5	10.5
-20	4.7	13.7
-10	9.6	20.2

3. FORCED CONVECTION

When a layer of water is deposited on the aluminum substrate it is subjected to heat conduction through the substrate on one side and heat convection on its top surface. The high thermal conductivity of aluminum leads to effective heat transfer from the water layer at the very beginning of the ice part fabrication process. As the part height increases, heat dissipation slows rapidly due to the low thermal conductivity of ice. A series of simulations were run in Fluent; the simulation results on the time taken for a deposited water layer to freeze at the ambient temperature of -35^{o}C are summarized in Table 2. Clearly a layer of water deposited on an aluminum substrate transfers its heat much faster than a layer of water deposited on ice because ice has a much lower heat transfer coefficient than aluminum.

As the height of the wall increases, there is greater tendency for the newly deposited water layer to transfer its heat to the ambient air through convection. Therefore, forced convection through fan blowing was tested as a means to increase heat transfer. A real-time data acquisition system was used to measure the temperature in the RFP apparatus using two thermocouples, one placed at 10 mm from the part build surface (thermocouple 1) and the other at 1 meter from the part fabrication region (thermocouple 2), as shown in Figure 5.

Table 2. Simulation result of time to freeze for a water layer deposited at various heights

Height	Time to Freeze (s)
0 mm (on substrate surface)	2.8
1 mm	5.8
2.5 mm	8.4
5 mm	10.1
10 mm	12
12.5 mm	14.4
15 mm	17.1
17.5 mm	20.6

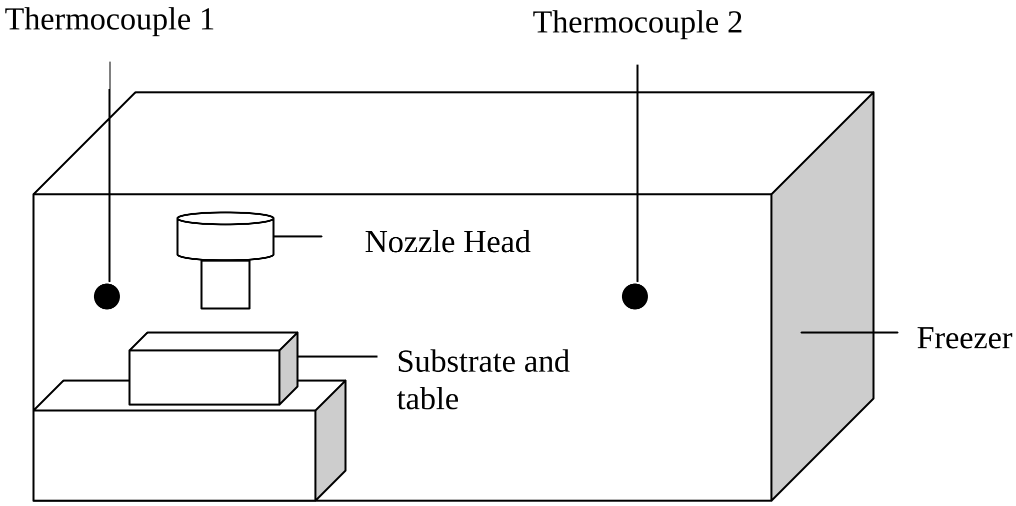


Figure 5. Thermocouples placement

The measured temperatures are shown in Figures 6 and 7. From Figure 6 we can see that the heat transfer is concentrated in the neighborhood of the deposited water. This is evidenced from the fact that thermocouple 2 exhibited nearly constant temperature throughout the build cycle. Liquid nitrogen was used to reduce the temperature around the part. The effect of pouring liquid nitrogen is indicated by the sharp downward spikes in Figures 6 and 7.

When a similar investigation was conducted with the introduction of forced convection by using a fan to blow air cooled by liquid nitrogen into the build area, the cooling of the part was found to be much faster than without forced convection. Parts were built successfully with a wait time of 20 seconds in this case, whereas without forced convection a wait time of 40 seconds was necessary. This reduction in wait time led to a 50% reduction in part build time. Although this cooling method provided considerable advantages, however, it also presented the problem of frosting. Frost appeared on the surface of the ice part as shown in Figure 8 when forced convection was used. Therefore, despite the reduction in wait time, this method did not appear to be a viable option for reducing the build time of ice parts.

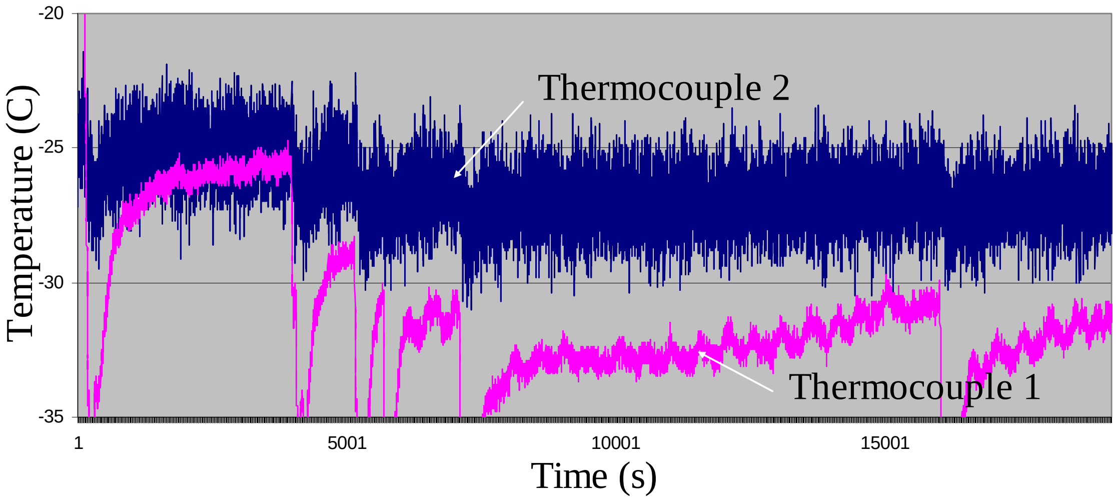


Figure 6. Temperature vs. time for part building without forced convection

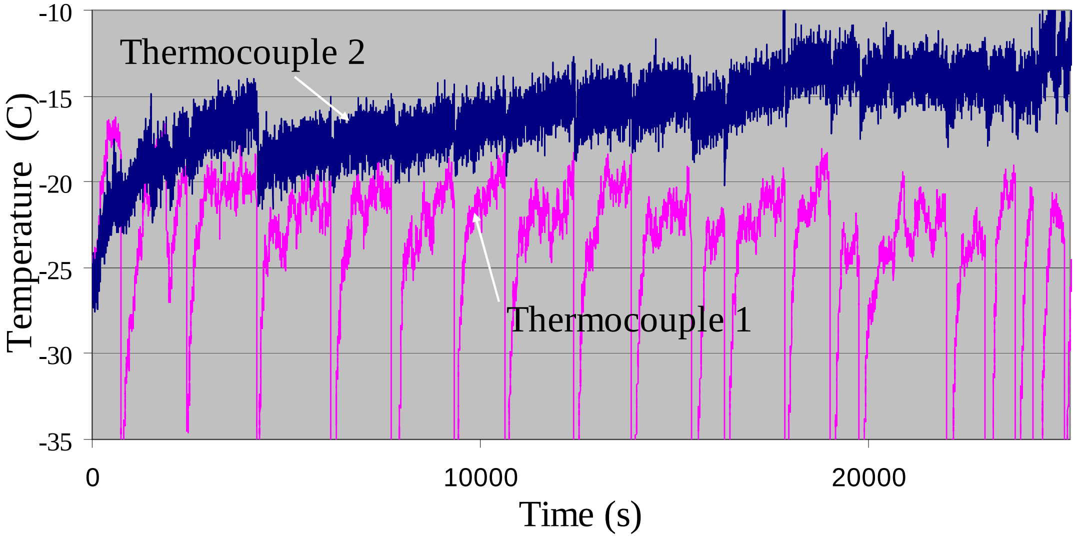


Figure 8. Temperature vs. time for part building with forced convection

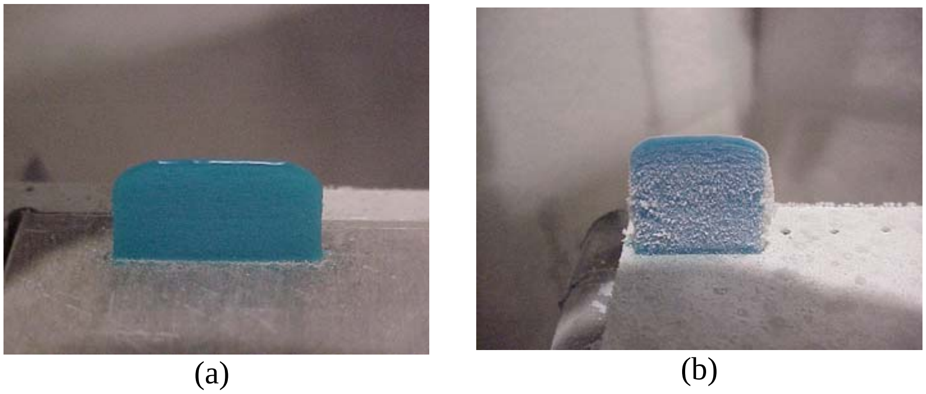

(a) (b)

Figure 8. An ice wall built (a) without forced convection and (b) with forced convection

4. CHILLING PLATE

The use of a pre-cooled plate to more effectively freeze deposited water was next investigated. The idea is to lower a chilling plate mounted on the z-axis after the deposition of each water layer to remove heart from the water and rapidly freeze it into ice. Figure 9 shows a CAD model and the actual chilling plate used. Besides cooling, the chilling plate provided a flat surface that could be used to flatten the newly deposited layer of water. Since conduction is a more effective mode of heat transfer than convection, it was conjectured that this plate could reduce the build time significantly. Preliminary experiments attempting to freeze a layer of water between the ice substrate and the chilling plate, however, indicated a tendency for the water to freeze onto the chilling plate. The ice part broke during its separation from the chilling plate. Therefore, identification of an interface film that would prevent the water from freezing onto the chilling plate became critical to the success of this technique.

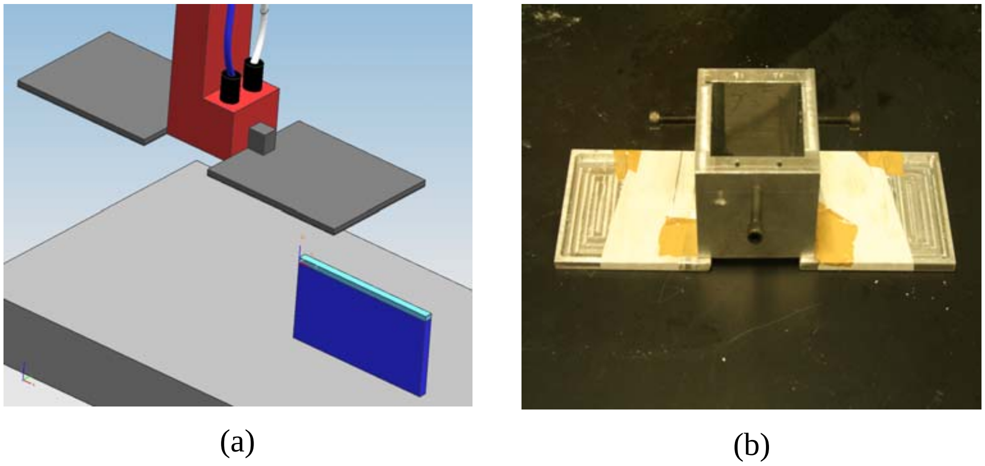
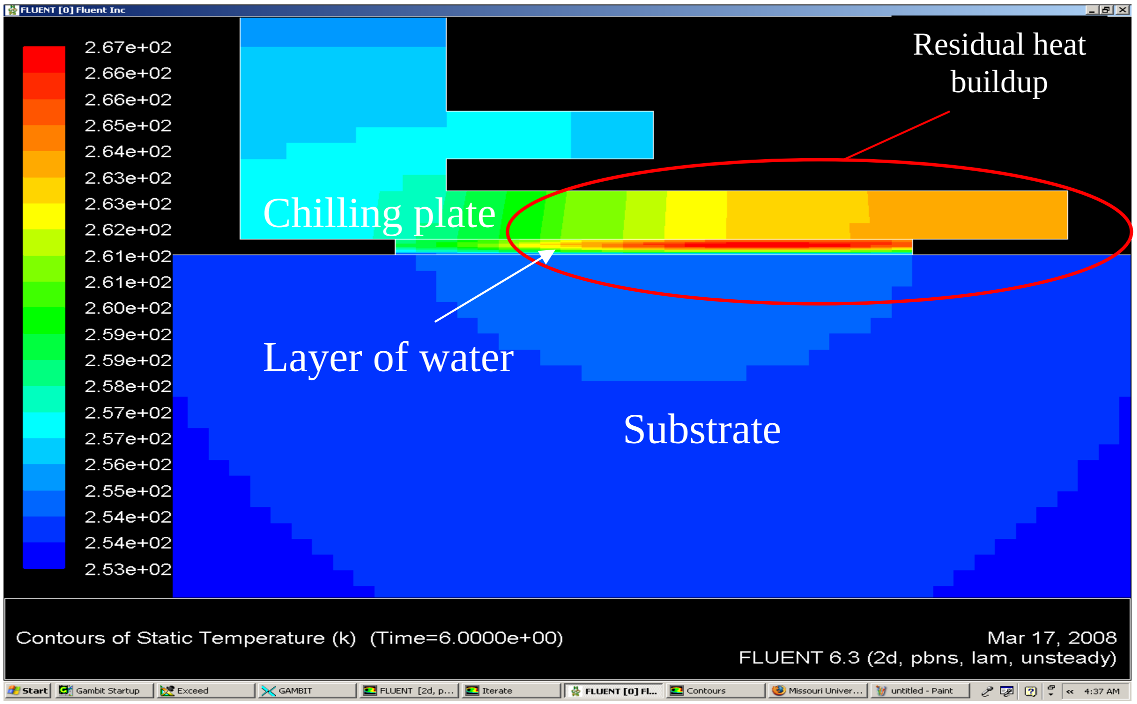

(a) (b)

Figure 9. The chilling plate investigated: (a) the CAD model and (b) the actual plate

Fluent was used to simulate the temperature and the liquid fraction in the chilling plate concept. The preliminary design of the chilling plate was a 3”×3” square with 0.2” in thickness. The temperature of the chilling plate increased from -20°C (253 K) to -8°C (265 K) after 6 seconds. The result is shown in Figure 10. Fluent simulation predicted that continuous use of the chilling plate for a period of over 50 seconds would result in residual heat buildup which will render the chilling plate ineffective. In an effort to prevent this heat buildup, instead of using a solid plate, the chilling plate was fabricated with coolant passages similar to the substrate plate. Figure 11 shows the chilling plate along with the aluminum substrate plate.



Contours of Static Temperature (k) (Time=6.0000e+00)

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FLUENT 6.3 (2d, pbns, lam, unsteady)

Figure 10. Temperature at time of 6 seconds after an aluminum chilling plate is in contact with deposited water

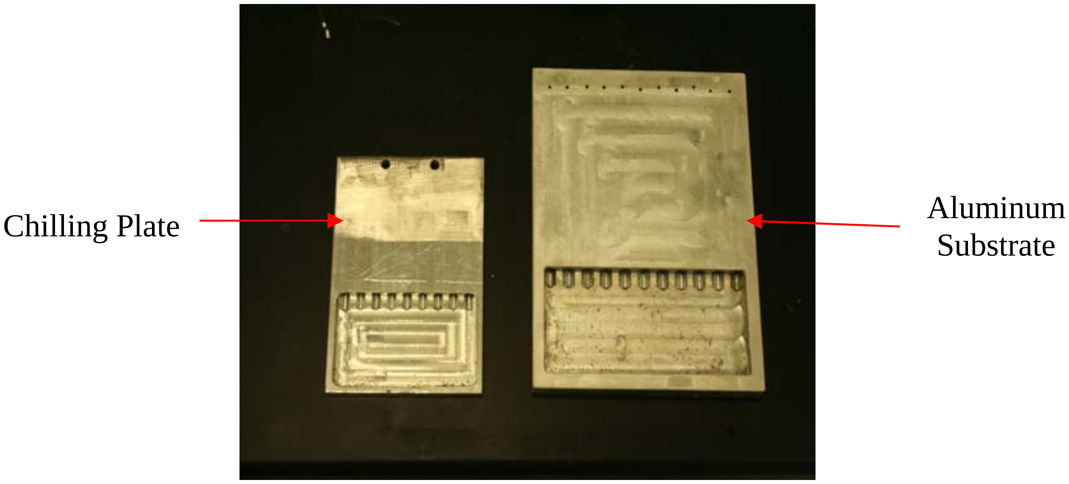

Figure 11. The chilling plate and aluminum substrate

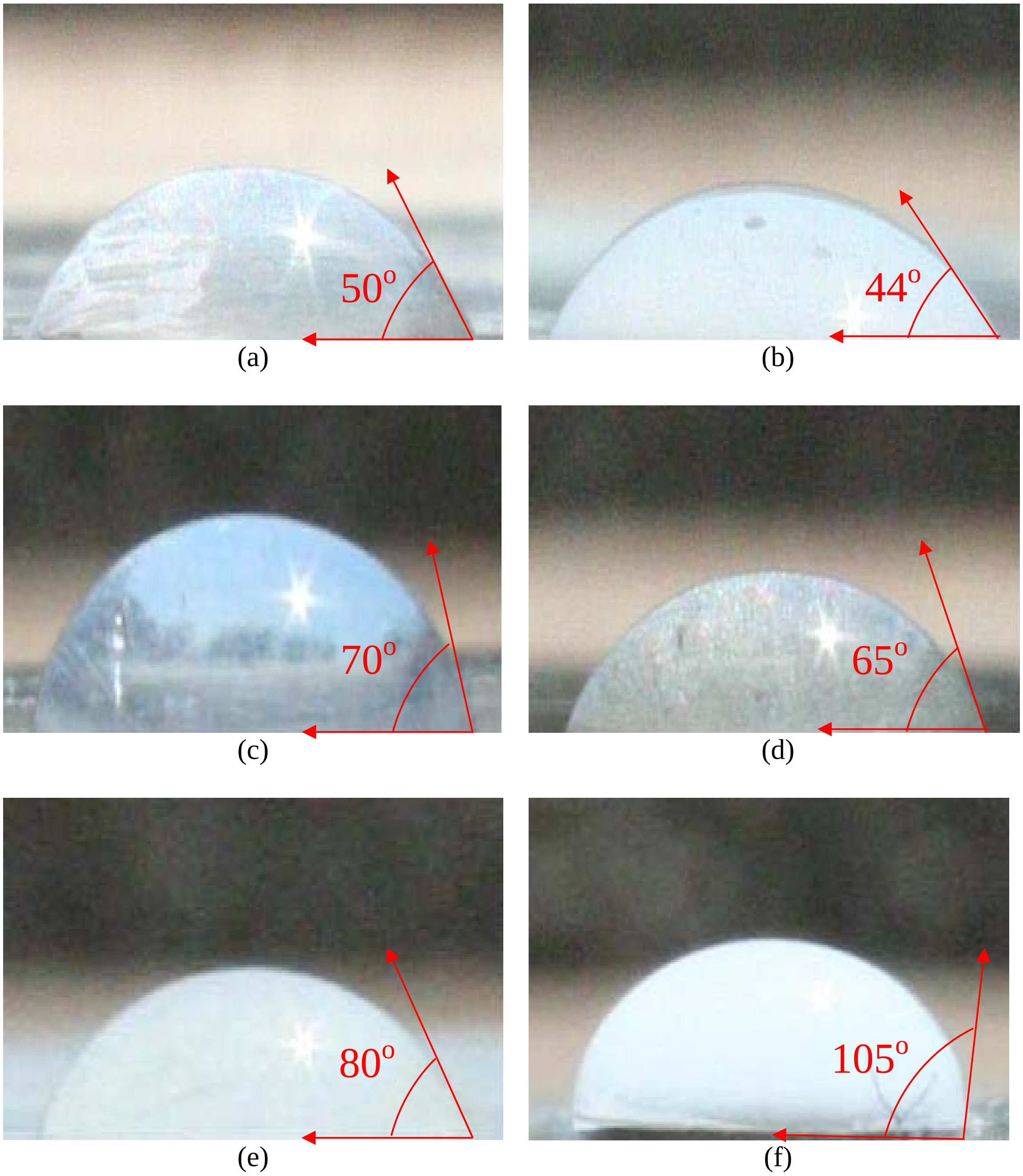

Figure 12. Enhanced images of a water droplet on various surfaces: (a) no surface coat (polished face), (b) paint coated aluminum sheet, (c) mylar, (d) cellophane tape, (e) latex and (f) Teflon

A major problem with the chilling plate approach was finding a surface coat that could prevent water from adhering to the chilling plate. The water repulsive properties of several materials were tested. These materials included paint coated aluminum sheet, mylar, cellophane tape, latex, and Teflon. The best material was chosen by examining the contact angle between a water droplet and the surface of each material. The larger the contact angle, the greater is water's tendency to repel that surface. Contact angles were measured using high-resolution digital photography. With ImageJ software [10], the contact angle between a water droplet and each surface coat was measured. The results are shown in Figure 12 and given in Table 3. It is clear that the largest contact angle occurs when the water droplet is deposited on the Teflon surface, of which the contact angle measured was 105^o. This value of the contact angle is confirmed by measurements done by other researchers [11]. Therefore, Teflon was identified as the best surface coat.

Table 3. Contact angles of water droplets with various coat materials.

Coat material	Contact angle of water droplet (degrees)
No coat (polished face)	50
Paint coated aluminum sheet	44
Mylar (Transparencies)	70
Cellophane tape	65
Latex	80
Teflon	105

The chilling plate coated with a Teflon film of thickness 0.1 mm was then used to produce ice parts with a reduced wait time between layers. With the chilling plate, parts were built successfully with wait time of 10 seconds between layers. This is consistent with the wait time predicted by Fluent and it translates to 75 percent reduction in part build time. The significant reduction in wait time is a great advantage of this method of heat transfer, which can produce better ice parts than using forced convection because of no frost formation.

5. CONCLUSION

The research result presented has shown that by increase of heat transfer, much shorter wait times between build layers are possible than what could be achieved previously in the Rapid Freeze Prototyping process. This greatly reduces ice part build time and also ensures that thin-walled ice structures could be built. Three techniques were investigated to increase heat transfer and reduce build time in RFP fabrication of ice parts. Modifications made to the substrate by the use of coolant passages filled with liquid nitrogen to decrease the substrate temperature were successful in bringing about a significant reduction in part build time for the initial layers of water deposited on the aluminum substrate. However, the effect of lowering the substrate temperature on reduction of wait time between layers decreased with increase in part height. Forced convection implemented with the use of a fan to circulate cold air produced desirable reduction of build time but with undesirable formation of frost. Very significant reduction in part build time was achieved using a chilling plate to increase the rate of cooling of deposited water by conduction. Contact angle measurement was used to identify the ideal surface coat, which was found to be a thin Teflon film. Fluent simulations predicted that the use of a chilling plate coated with a 0.1 mm Teflon film would bring about 75% reduction in part build time, which was confirmed with experiments.

6. ACKNOWLEDGMENT

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BIBLIOGRAPHY

1. Zhang, W., Leu, M. C., Ji, Z., and Yan, Y., 1999, "Rapid Freezing Prototyping with Water," Journal of Materials and Design, Vol. 20, pp. 139-145.
2. Leu, M. C., Liu, Q., and Bryant, F. D., 2003, "Study of Part Geometric Features and Support Materials in Rapid Freeze Prototyping," Annals of CIRP, Vol. 52, No. 1, pp. 185 – 188.
3. Sui, G., and Leu, M. C., 2003, "Investigation of Layer Thickness and Surface Roughness in Rapid Freeze Prototyping," Journal of Manufacturing Science and Engineering, Vol. 125, No. 3, pp. 556-563.
4. Liu, Q., and Leu, M. C, 2007, "Finite Element Analysis of Solidification in Rapid Freeze Prototyping," ASME Journal of Manufacturing Science and Engineering, Vol. 129, No. 4, pp. 810-820.
5. Yodice, A., 1999, "Freeze process cuts casting costs," Advanced Materials and Processes, Vol. 155, No. 4, pp. 35-36.
6. Liu, Q., and Leu, M. C., 2006, "Investigation of Interface Agent for Investment Casting with Ice Patterns," Q. Liu and M. C. Leu, ASME Journal of Manufacturing Science and Engineering, Vol. 128, No. 2, pp. 554-562.
7. Beeley, P. R., and Smart, R. F., 1995, *Investment Casting*, 1st Edition, The University Press, Cambridge, U.K.
8. Ozisik, M. N, 1993, *Heat Conduction*, John Wiley and Sons, Inc.
9. Fluent Inc., 2003, Fluent Online Users Guide, last referred on 10th October 20, 2007(http://bubble.me.udel.edu/wang/teaching/MEx81/fluent-help/html/ug/main_pre.htm).
10. ImageJ, Users documentation, last referred on 10th September, 2008 (http://rsbweb.nih.gov/ij/docs/index.html).
11. Teflon contact angle reference, last referred on 20th September, 2008 (http://www.lib.umich.edu/dentlib/Dental_tables/Contangle.html).