Investigation of Part Accuracy and Surface Roughness in Rapid Freeze Prototyping Based Investment Casting

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ABSTRACT

The study as described in this paper is aimed at investigating the dimensional accuracy and surface finish of metal parts made by investment casting with ice patterns generated by rapid freeze prototyping. The process of investment casting with ice patterns is described and contrast with conventional investment casting with wax patterns is made. The selection of binder material for ceramic slurries and the need for an interface agent to separate the ice pattern from the ceramic slurry in the mold making process are discussed. The accuracy and surface finish of ice patterns and of the metal castings are presented and discussed. The parts used in this investigation include cylinders with vertical and slant walls and a turbine impeller.

Keywords: solid freeform fabrication; rapid freeze prototyping; ice patterns; investment casting

1. Introduction

Investment casting has been widely used in industry for years to produce castings of intricate shapes to close tolerance[1]. Wax is the most commonly employed material to make patterns. Natural or synthetic waxes and various additives are used to achieve minimum shrinkage and close reproducibility of pattern dimensions as well as strength for stability in handling and storage. However, there still exist some problems in using traditional wax patterns such as expansion of the wax pattern in the process of melting that might cause ceramic shell cracking. New approaches to improve the performance of investment casting process are constantly being sought.

A novel investment casting process, called the freeze cast process (FCP), was patented by Yodice in 1991[2]. In this process ice patterns instead of traditional wax patterns are used to make metal parts. Through ten years of research, Yodice and others have demonstrated the possibility and advantages of investment casting with ice patterns[3-6]. The advantages of FCP over the competing casting processes include low cost, high quality, fine surface finish, and no shell cracking problem. These strengths make FCP a significant alternative to the traditional investment casting for production of quality near-net shape castings at reasonable costs. The FCP process starts with a solid master pattern fabrication and the associated silicone mold making. The solid master pattern can be made either by conventional machining methods or by modern rapid prototyping techniques. Then ice patterns are made from silicone molds by injecting water in the mold and make it frozen. Because the ice patterns in the FCP process are made from silicone molds, some new problems are introduced such as multi-directional water expansion during freezing and air bubble generation. These problems can be solved by making ice patterns

with the Rapid Freeze Prototyping (RFP) process, an environmentally conscious rapid prototyping (RP) technique that was recently developed by us[7,8].
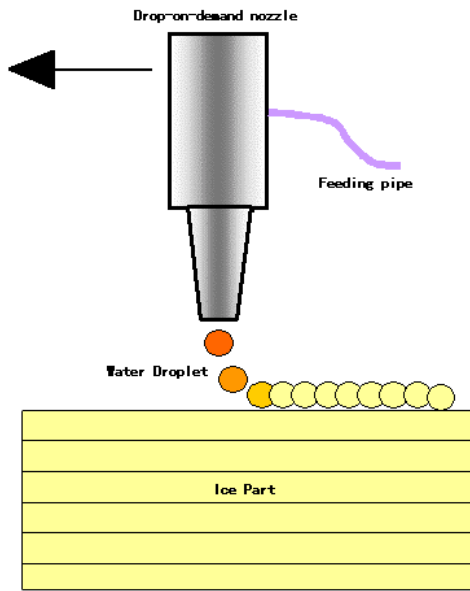

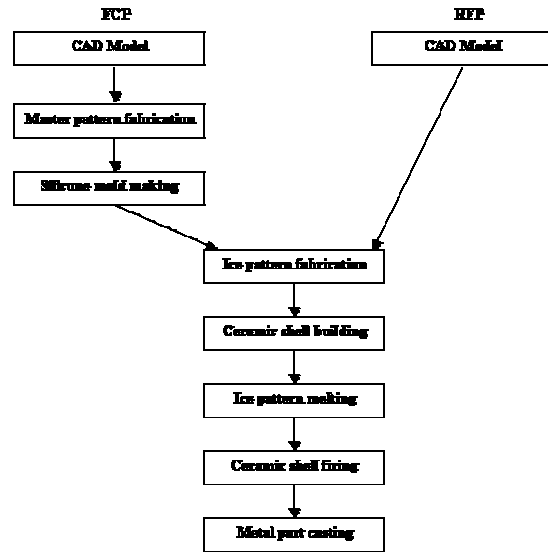Fig. 1. Principle of rapid freeze prototyping.   Fig. 2. Comparison of the operation steps between RFP and FCP.

Similar to other solid freeform fabrication (SFF) techniques, the RFP process can directly build a three-dimensional ice part based on a CAD model by selectively depositing and rapidly freezing water in a layer-by-layer manner. Figure 1 demonstrates the principle of Rapid Freeze Prototyping. The water is ejected drop by drop in a drop-on-demand mode. The build environment is kept at a temperature below water's freezing point. Pure water or colorized water is ejected from the nozzle and deposited onto the substrate or the previously solidified ice surface. Water droplets do not solidify immediately. Instead, they spread and unite together to become part of a continuous water line. Then the newly deposited water is cooled by the low temperature environment through convection and by the previously formed ice layer through conduction. As a result, the deposited material freezes rapidly and binds to the previous layer firmly through the hydrogen bond. After one layer is finished, the nozzle is elevated upwards a height of one layer thickness, waiting a predetermined period of time for complete solidification of the deposited water, and then depositing water again to build the next layer. This procedure continues until the designed ice part has been fabricated. The most important advantages of the RFP process include: cheaper and cleaner, potential to build accurate ice parts with excellent surface roughness, sufficient layer binding, no residue after part removal in the molding process, no shrinkage issue, and easiness of compensating material expansion. Detailed description and explanation about these can be found in previous papers[7,9]. With RFP it is possible to make ice patterns directly from CAD models in a short time, without the high cost and other issues of mold making. There is a strong synergy between the FCP and RFP. FCP is suitable for quantity production of metal parts by investment casting with ice patterns, while RFP provides a good way to make small to medium quantity ice patterns with better accuracy and more flexibility. Figure 2 illustrates the comparison of the operation steps between RFP and FCP.

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Unlike other RP technologies, the RFP process and its application in investment casting have their own unique characteristics. A lot of issues need to be addressed before applying the ice patterns in investment casting. It is apparent that the accuracy and surface finish of ice patterns from RFP are dominant factors that influence the ultimate quality of metal castings. It is essential to study the part accuracy and surface finish of ice patterns achievable by RFP. The effect of different processing parameters on the layer thickness and layer width has been studied and reported in a previous paper [8]. The ultimate goal of the present paper is aimed at studying the accuracy and surface finish of metal parts made by investment casting with ice patterns. Though FCP has demonstrated the success of using ice patterns to make metal parts by investment casting, there is little information available in the literature. The investment casting with ice patterns was studied as discussed in the present paper in order to understand the fundamentals of this technology and make them available in the public domain. The selection of the binder material for ceramic slurries and the need for an interface agent to separate the ice pattern from the ceramic shell in the mold making process are discussed. The process of investment casting with ice patterns is described and contrast with the conventional investment casting with wax patterns is made. The accuracy and surface finish of the metal parts from ice patterns are also presented. The parts used in this investigation include cylinders with vertical and slant walls and a turbine impeller.

Table 1   The composition of the Premium type Talladium TILITE Ceramic Alloy (weight%)

Nickel	Chromium	Molybdenum	Titanium	Intermetallic Beryllide
60-76	12-21	4-14	4-6	>1.8

Table 2   The processing parameters for making cylinders with vertical and slant walls

Speed (mm/s)	Frequency (Hz)	Distance* (mm)	Slant Angle (º)	Pressure (kPa)
36	160	3	0-55	27.44

* Distance between the nozzle and the topmost built layer

2. Experimental apparatus

Before we proceed to present the experimental results, we like to introduce briefly the experimental apparatus used in this study. Figure 3 shows the experimental setup to fabricate the ice patterns. A personal computer controls the whole system, including three stepping motors of the XYZ moving axes and water flow rate. Besides the PC, the hardware of this experimental system consists of the other four subsystems: 1) water ejecting subsystem, 2) positioning subsystem, 3) electronic control device, and 4) freezer. The freezer is used to provide a low temperature environment, which is as low as -18°C in our experiment. The 3D positioning subsystem is placed inside the freezer. A metal plate is mounted on the XY table as the building substrate. The nozzle is mounted on an elevator which can move in the Z direction. The movement of the building substrate relative to the nozzle makes it possible to deposit material in the XY plane. The water ejecting subsystem consists of a constant pressure device, a water reservoir, a feeding pipe with temperature control capability, and a nozzle with a miniature solenoid valve. The constant pressure device and water reservoir are not shown in Figure 3. The pressure device provides a constant preset pressure according to the ejecting rate requirement. The temperature of the feeding pipe is controlled in a proper range, allowing the water in the pipe to be pre-cooled but still in the liquid state so that the water can flow freely. The miniature solenoid valve controls water flow on and off to generate water droplets. 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. In our study, the pulsed signal driving the valve is produced by an HP 3312A Function Generator. The output can be monitored by a Tektronix 2236 100MHz oscilloscope. The electronic control device of this system is used to amplify the pulsed signal and control the three stepping motors. Motors are driven to move in a linear resolution of up to 0.25μm by the motion control cards (AT 6400, provided by Compumotor).
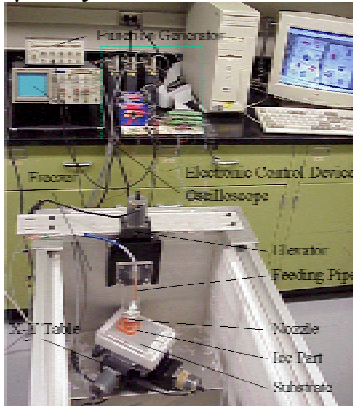

Fig. 3. Rapid freeze prototyping experimental setup.
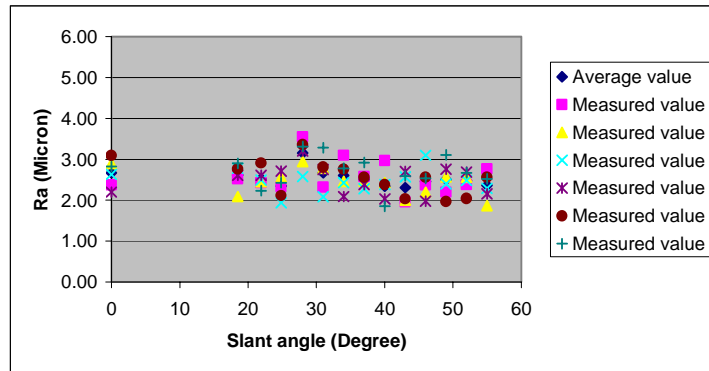

Fig. 4. Surface roughness of the cylinders with vertical and slant walls.

3. Surface roughness of fabricated ice patterns

The surface finish of the fabricated ice pattern significantly influences the surface roughness of the cast metal part. The surface finish of ice pattern was tested and the results are presented and discussed in this paper. The parts used in this investigation include cylinders with vertical and slant walls, and an impeller with turbine blades. Since the surface finish of an ice pattern is very hard to test, we use UV urethane to duplicate the surface of the ice pattern and then measure the surface finish of the duplicated urethane part.

Cylinders with vertical and slant walls were first made and their surface finish measured. We previously studied the effect of different processing parameters on the layer thickness and layer width, which significantly affect the accuracy and surface finish of ice patterns[8]. Based on the previous experimental results, the processing parameters listed in Table 2 were used to make cylinders with vertical and slant walls. Based on the experimental measurement, the average layer thickness is 0.173 mm when the cylinder wall is vertical. The measured surface roughness of cylindrical ice patterns is shown in Figure 4. The experimental results show that the surface finish is independent of the slant angle and the average surface roughness of the cylinders is 2.54 μm Ra. This is due to the unique characteristics of RFP which distinguish it from the other RP techniques. As described in our previous study [8], after being ejected onto the building surface, a water droplet undergoes deformation, spreading, and freezing. The shape change ends with complete freezing. The deformation and spreading of a droplet are affected by the droplet's initial speed and mass. The freezing process is mainly affected by the environment temperature. Deformation and spreading help make continuous ice lines and smooth surface. Water freezing and spreading on the building surface are two dominant factors. The balance of the two factors can result in a very smooth surface finish of ice part. The mass of the water line (formed by the ejected water droplets) in unit length contributes significantly to the balance mentioned above. The water pressure, diameter of the nozzle orifice, and scanning speed affect

the mass of water line in unit length. Among the parameters, water pressure and diameter of the nozzle orifice increase while the scanning speed decreases the mass of water line in unit length. By carefully choosing the processing parameters, the water can flow into the corners of steps between two layers resulting in a relative good surface finish. On the other hand, it is more difficult for the other RP techniques to avoid the stair-step effect, and either lengthy post-process finishing or modification of the build cycle has to be performed. For example, the use of meniscus films at the intersections of layers can be employed to reduce discontinuity of SLA part surface due to stair-step effect.

Table 3. The processing parameters for making an impeller with turbine blades.

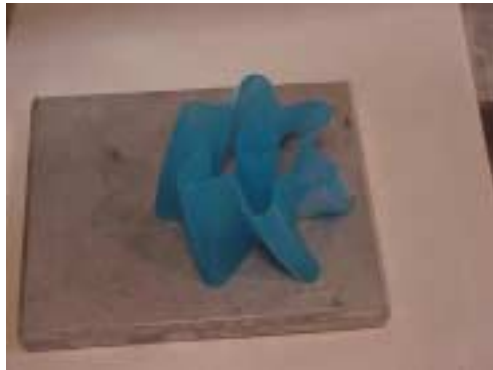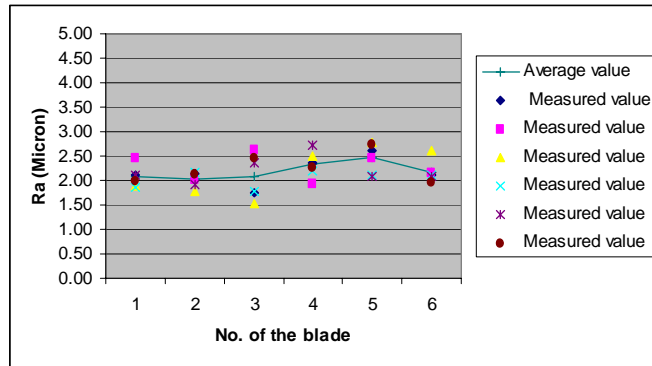| Speed (mm/s)	Frequency (Hz)	Distance (mm)	Pressure (kPa)
60	400	10	30

Fig. 5. Ice pattern of a turbine impeller

Fig. 6. Surface roughness for each of the six blades of an impeller.

Table 4. Dimensional comparison between the measured values and the nominal values (Φ 7.62mm x 8.128 mm).

No.	Measured OD (mm)	OD deviation (mm)	Measured height (mm)	Height Deviation (mm)
1	7.518	-0.102	8.233	0.105
2	7.544	-0.076	8.084	-0.044
3	7.658	0.038	8.487	0.359
4	7.634	0.014	8.013	-0.115
5	7.601	-0.019	7.912	-0.216
6	7.633	0.013	7.971	-0.157
7	7.633	0.013	8.451	0.323
8	7.645	0.025	8.458	0.330
9	7.626	0.006	8.426	0.298
10	7.629	0.009	8.509	0.381
11	7.629	0.009	8.352	0.224
12	7.638	0.018	8.261	0.133
Average	7.616	0.028	8.263	0.224

Besides the cylinders with vertical and slant walls, an ice pattern for a turbine impeller was also built to show the capability of RFP in fabricating intricate ice patterns with good surface finish. The impeller has six turbine blades and the cross section of the bottom end is greater than that of the top end. Each blade surface is actually a slant curve surface and an offset between two successive layers is needed in the RFP process. The processing parameters are

listed in Table 3. Figure 5 shows the picture of the ice pattern for the turbine impeller. The height of the impeller is 43.55 mm. The outside (circumference) diameter of the big end is 81 mm and that of the small end is 64 mm. It took 6.5 hours to fabricate the part. The layer thickness is 0.145 mm on average. It can be seen that no stair-step effect is found on the slant curve surface because of the good fluidity of water and the balance between spreading and freezing. The measured surface finish for each of the six blades is shown in Figure 6. The average surface roughness of the six blades is 2.20 µm Ra.

Table 5. Measured and nominal lengths of the major and minor axes.

Slant angle (°)	Length of major Axis (mm)			Length of minor Axis (mm)		
	Nominal	Measured	Deviation	Nominal	Measured	Deviation
0	7.62	7.616	-0.004	7.620	7.616	-0.004
19	7.62	7.620	0.000	7.226	7.463	0.237
22	7.62	7.612	-0.008	7.069	7.404	0.336
25	7.62	7.648	0.028	6.914	7.239	0.325
28	7.62	7.671	0.051	6.728	7.163	0.435
31	7.62	7.696	0.076	6.532	7.010	0.479
34	7.62	7.684	0.063	6.317	6.896	0.579
37	7.62	7.696	0.076	6.086	6.782	0.696
40	7.62	7.722	0.102	5.837	6.579	0.741
43	7.62	7.747	0.127	5.573	6.452	0.879
46	7.62	7.752	0.132	5.293	5.987	0.693
Average	7.62	7.678	0.061	6.472	6.963	0.491

4. Accuracy of fabricated ice patterns

To investigate the dimensional accuracy of the fabricated ice pattern, a cylindrical part was chosen in this study. The cylinder's outer diameter is 7.62mm and the height is 8.128mm. Different combinations of processing parameters can lead to different values of layer thickness and layer width. The processing parameters listed in Table 2 were employed here again to build the cylinders with vertical walls. To check the variations of the dimensions, a total of twelve vertical cylinders were made. Table 4 lists the measured values of the cylinder outer diameter and height. From Table 4, it can be seen that the measured cylinder outer diameters are very close to the nominal value, i.e. 7.62mm. The dimensional variation of the outer diameter is 0.028 mm on average. The dimensional variation for the height of the cylinder is a little greater. The height variation between the measured and nominal values is 0.224 mm on average, with the maximum and minimum variations of 0.381 mm and –0.044mm respectively. The larger relative error of the cylinder height is due to the uneven distribution of water in the spreading process. To eliminate this problem, a new design of the RFP machine is being investigated, which will have a cutter to remove ice to keep the layer thickness more even.

Cylinders with slant walls were also made using the processing parameters listed in Table 2. The slant angle is between 0°and 46°. From Figure 7, it can be seen that the cross section perpendicular to the slant cylinder axis is an ellipse instead of a circle. Theoretically, the length of the major axis has no relationship with the slant angle. So the length of the major axis is independent of the slant angle with the value of 7.62 mm. The length of the minor axis decreases with the increase of slant angle. The nominal lengths of the minor axis with different slant angles

are listed in Table 5. Figure 7 also shows that there is no offset between two successive layers on lines 1 and 2 and the slant angles on lines 3 and 4 are the same as slant angle of the cylinder. As discussed in our previous study[8], the layer thickness decreases and the layer width increases with the increase of the slant angle. Consequently, the deviation of the length of the minor axis should increase with the increase of the slant angle. The experimental results shown in Table 5 agree with this trend. On the other hand, the deviation of the length of the major axis should not change and keep the value around 7.62mm no matter what the slant angle is. The experimental results display a slight increase of the length of the major axis with the increase of the slant angle. This is because the uneven distribution of water on the vicinity facilitates the spreading processing resulting in a wider layer width in this area. In general, water can flow along two directions: along the printing direction and perpendicular to the printing direction. As discussed above, the slant angle at the two apexes of the major axis is different from that of the minor axis. Therefore, the slant angle causes the uneven layer thickness and layer width even within one single layer. The height at the two apexes of the major axis is always greater than minor axis. Accordingly, the wall thickness at the two apexes of the major axis is smaller than minor axis. Thus the uneven distribution of water facilitates spreading process of water from higher place to lower place and make the narrower wall thickness a little bit wider. The deviation of the length of the major axis is within 1.8%. But the slant angle results in a significant deviation of length of minor axis. This can be avoided by adjusting the scanning speed. A larger scanning speed should be used to make a slant cylinder with a larger slant angle.
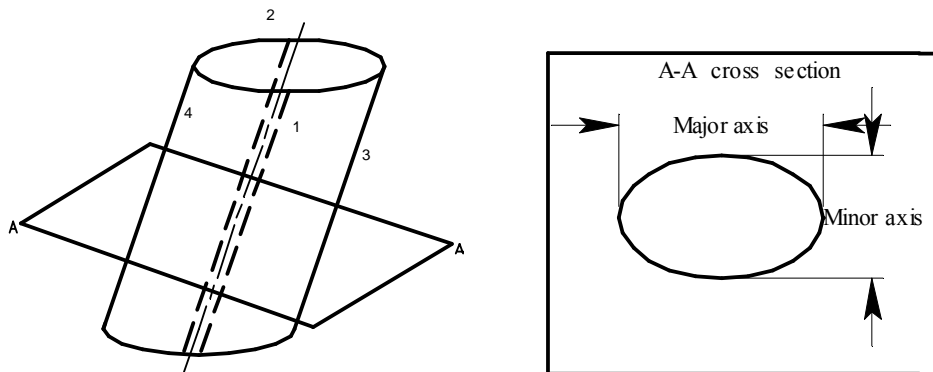

Fig .7. Profile of the cross section A-A perpendicular to the cylinder axis.

5. Material for low-temperature investment casting

Though FCP has demonstrated the success of using ice patterns to make metal parts by investment casting, no detailed information can be found in the inventor's patent or papers[3,4]. A research group in Tsinghua University, China, has also made some efforts on making metal parts with ice patterns[6], but the surface finish of metal parts shown in their paper is not very impressive[10]. Some materials used for investment casting with ice patterns should have different features from those used for regular investment casting. Our study is aimed at finding satisfactory materials for binder, ceramic powder, catalyst, and interface layer and consequently make metal parts with better surface finish and higher accuracy. The choice of the materials for binder and interface agent will be discussed next.

5.1 Ceramic materials

It is well known that the slurry is made of the mixture of the binder and ceramic materials. Therefore, ceramic materials play an important role in successful mold (shell) making.

In general, ceramic materials are used in a very wide range of combinations and include silica sand, alumino-silicates, alumina, and zirconium silicate. Suitable choice of the ceramic materials can lead to smooth surface finish, high accuracy, and good property of the metal castings. The following factors need to be considered when choosing the ceramic materials: specific gravity, linear expansion coefficient, chemical composition, cost, and application. For example, a ceramic material usually has several particle sizes with a certain mixing ratio for shell making. The ratio of fine/medium/coarse powder is critical for shell quality. For applications such as making dental restorations, only fine investments should be used to make the molds. Because of our interest in studying the dental crowns using ice patterns, the M47-200ICC alumino-silicates (Ransom & Randolph, USA) was chosen. Its grain size is 200 mesh.

5.2 Binder

Binder is another major slurry material. It is mixed with ceramic material to make the slurry. For low-temperature investment casting, the binder solution should not freeze and should have good fluidity at a sub-zero temperature, and the corresponding mold or shell made must have good surface finish, high accuracy and high strength. These are the criteria used in choosing binder materials in our application. In general, there are three kinds of binder materials that can be chosen: water glass, silica gel, and ethyl silicate. Only ethyl silicate satisfies all the above requirements and was used in our study. Ethyl silicate can be either water based or alcohol based. Obviously, alcohol based ethyl silicate should be employed. Pure ethyl silicate can be used to produce a foundry binder but it is more usual to employ a condensed or concentrated form containing certain amount of silica, say 40% by weight. Ethyl silicate 'as received' has no binding properties, but must be chemically decomposed by reacting with water, i.e., hydrolyzed[1]. The reaction produces alcohol and silica in an active state. Since ethyl silicate is not soluble with water, the reaction only occurs on the interface and thus is slow. Alcohol is soluble with both ethyl silicate and water. By adding alcohol, the reaction speed can be substantially enhanced. The binder #18 (Ransom & Randolph, USA) is chosen for this study. It is a kind of alcohol-based prehydrolyzed ethyl silicate binder and contains 18% silica by weight. It is compatible with most of the refractory systems presently used in the ceramic shell process and thus very suitable for use in the production of ceramic shells and ceramic molds. The freezing point of binder #18 is below -56°C, so there is no problem in a sub-zero environment.

5.3 Catalyst

A catalyst is required to shorten the gelling time of the slurry (mixture of binder and ceramic material) for low-temperature investment casting. Otherwise, it will take days or even longer for the slurry to gel. In general, the gelling time mainly depends on temperature, binder composition, and pH value. The effect of pH value is more significant than the effect of the other two factors. As mentioned before, the slurry is most stable when pH value is equal to 2, thus the gelling time is the longest where pH=2. On the other hand, the slurry is most unstable and the corresponding gelling time is the shortest when the pH value is between 5.0 and 6.0. When pH value is less than 1.0, the slurry is also unstable. The aim of adding a catalyst is to change the pH value of the slurry from the range where the slurry is stable to the range where the slurry is unstable. Based on the arguments above, it can be seen that the catalyst can be either acid (to change pH value towards 1.0) or alkaline (to change pH value towards 6.0). The results in ref.[6] showed that triethanolamine has a good performance when used as a catalyst. Therefore, the mixture of triethanolamine and alcohol (1:1 volume ratio) was employed in this study.

5.4 Interface agent

It is well known that water (ice) and alcohol are soluble with each other, thus alcohol contained in the slurry will interact with the ice pattern surface. The decomposition process releases heat which causes more decomposition. As a result, the surface of the ice pattern may be seriously damaged. Therefore, an interface agent is necessary for investment casting with ice patterns, in order to prevent the ice pattern surface from being dissolved.

Based on the experimental results shown in refs.[6,10], the mixture of silicate oil and kerosene (1:1 ratio) was firstly tried in our study as the interface agent. The effect was not very obvious because of the fluidity of the interface agent. It would be better if an agent can form a solid thin layer on the surface of the ice pattern. The interface agent will not freeze just below 0°C thus can easily be coated on the ice pattern surface. With further decrease of temperature, the agent can solidify to form a thin layer to protect the ice pattern. The solubility of the agent material in water and alcohol and its melting point need to be considered. The cohesion parameters describe the extent of cohesion within condensed materials and of "adhesion" between condensed phases. So it can be used to express the solubility of the agent material in water and alcohol. The larger the difference of the cohesion parameters (total and various components) between two materials, the worse the solubility of them in each other. Detailed information about the cohesion parameters can be found in ref.[11]. The total cohesion parameter, δ_t, and its three components: dispersion, δ_d, polar, δ_p, and hydrogen-bonding, δ_h, were considered in this study. By comparing the cohesion parameters of various materials, an interface agent material was identified and used in this study. Table 6 lists the cohesion parameters of this agent as well as water and alcohol. The agent material's melting point is between –4°C and –5°C, so it is very suitable for our application. The material can still keep liquid state below 0°C facilitating the coating process. When the temperature further decreases, the material can solidify and form a solid thin interface layer on the ice pattern surface.

Table 6. Cohesion parameters of the interface agent material, water and alcohol.

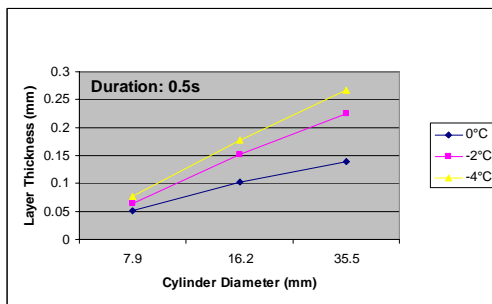| Materials	Cohesion parameters			
	δ_d	δ_p	δ_h	δ_t
Interface agent	16.4	0	0	16.4
Water	12.2	22.8	40.4	48
Alcohol	12.6	11.2	20	26.1

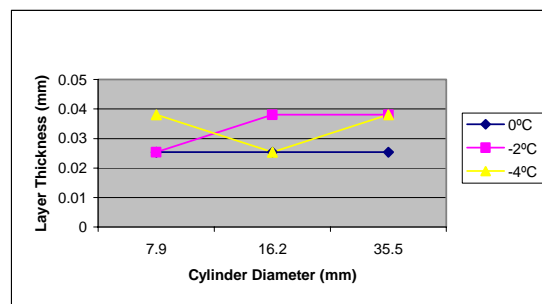Fig. 8. Thickness of the interface layer by immersing.

Fig. 9. Thickness of interface layer by spraying.

In general, there are two ways to coat the interface agent material on the ice pattern surface: immersing the ice pattern into the liquid and spraying the liquid material on the ice pattern surface. The thickness of the protective layer were tested based on these two methods. First, three solid ice columns with different diameters were immersed into the agent material

under different temperatures. The thickness of the protective layer can be calculated by comparing the original diameter and the diameter of the coated solid column. Figure 8 shows the thickness of the protective layer under different situations. It can be seen that the thickness increases with the increase of the volume of the ice pattern. This is because a bigger ice pattern has greater capability to cool the agent material around it so more agent material can reach its melting point. The thickness of the interface layer increases with the decrease of the temperature of the agent material. The lower the temperature of the agent material, the easier the solidification. In the latter case, an ice pattern was coated by spraying the agent material on its surface. Figure 9 shows the measured thickness of the interface layer. It can be found that the thickness is not affected by the aforementioned two factors anymore. Moreover, the thickness is less than that in previous case. The smallest thickness of the interface layer that can be achieved was 0.025mm. By comparing the two methods, we can see the first method is easier to coat the ice surface and the second method can achieve a smaller and more uniform thickness.

Fig. 10. Metal castings from ice patterns
(Material: Talladium TILITE ceramic alloys).

Fig. 11. Metal casting for a turbine impeller
(Material: 63Sn-37Pb solder).

6. Investment casting experiment

The cylinders built before for investigating the dimensional accuracy were used as the ice patterns in the investment casting study. Again, we only concern the outer diameter and height of the cylinder, which are 7.62mm and 8.128mm, respectively. The original dimensions of the ice patterns are listed in Table 4. The measured outer diameter, height, and surface roughness of metal castings from the ice patterns are listed in Table 7. Figure 10 shows some metal castings from ice patterns. There are two main reasons that cause the dimensional errors. One of the main reasons is the interface layer. Since the ice patterns were used and they were coated with the interface agent, the diameter and height of the ice patterns become larger. This can only be slightly compensated by the metal shrinkage. The other main reason that causes the dimension error is the mold inaccuracy because the ceramic mold changed during the firing stage. Further studies need to be performed to investigate the effects of various factors on mold inaccuracy. These factors include: 1) ceramic powder, binder, and catalyst materials; 2) ratio between powder, binder, and catalyst; 3) firing treatment.

For comparison, twelve metal cylinders are also made using wax patterns. The wax patterns were fabricated by a Model Maker 6Pro machine (Solidscape, USA). The super fine configuration parameters were employed for the Model Maker in this study. The slice thickness and wall thickness were 0.0127mm and 0.2032mm, respectively. The measured results are listed in Table 8. It can be seen that the metal castings from wax patterns have better casting accuracy while the metal castings from ice patterns have better surface finish. It should be noted that the

experimental results shown in this paper are only our results in progress, as further research is being performed to improve the casting accuracy and surface roughness.

A metal casting for a turbine impeller is also made as shown in Figure 11. As our centrifugal casting machine is not suitable for making a casting of this size, we had to manually pour the molten metal into the cavity. The 63Sn-37Pb solder was used to cast the part because of its low melting point. The procedure of making this part is the same as the process described above except that we had to melt the solder using a heater and then pour the molten alloy manually. It can be seen from Figure 11 that the casting has a good surface finish.

Table 7. Measured outer diameter, height, and surface roughness of the metal castings made from ice patterns.

No.	Measured OD (mm)	OD Deviation (mm)	Measured height (mm)	Height Deviation (mm)	Ra (μm)
1	7.633	0.013	8.100	-0.028	3.55
2	7.565	-0.055	8.091	-0.037	4.77
3	7.763	0.143	8.673	0.544	4.92
4	7.695	0.075	7.817	-0.312	3.81
5	7.835	0.215	7.929	-0.199	4.90
6	7.805	0.185	8.145	0.017	3.51
7	7.783	0.163	8.355	0.227	3.44
8	7.795	0.175	8.575	0.447	3.72
9	7.713	0.093	8.440	0.312	4.50
10	7.795	0.175	8.388	0.259	4.16
11	7.683	0.063	8.249	0.121	4.03
12	7.645	0.025	8.310	0.182	5.00
Average	7.726	0.115	8.256	0.224	4.19

Table 8. Measured outer diameter, height, and surface roughness of the metal castings made from wax patterns.

No.	Measured OD (mm)	OD deviation (mm)	Measured height (mm)	Height deviation (mm)	Ra (μm)
1	7.66	0.04	8.00	-0.13	5.25
2	7.70	0.08	8.00	-0.13	4.77
3	7.66	0.04	8.02	-0.11	4.44
4	7.58	-0.04	8.05	-0.08	5.99
5	7.65	0.03	8.02	-0.11	5.37
6	7.64	0.02	8.11	-0.02	5.25
7	7.67	0.05	8.07	-0.06	6.50
8	7.67	0.05	8.07	-0.06	5.81
9	7.66	0.04	7.93	-0.20	4.37
10	7.59	-0.03	8.02	-0.11	6.65
11	7.70	0.08	8.04	-0.09	6.21
12	7.64	0.02	8.02	-0.11	6.36
Average	7.65	0.04	8.03	0.10	5.58

7. Conclusions

The accuracy and surface finish of ice patterns made by RFP were presented in this paper. The reason why RFP can achieve a good surface finish was discussed. The investment casting with ice pattern has different characteristics from conventional investment casting with wax patterns. The materials required for low-temperature investment casting were discussed and identified, and the procedure of investment casting with ice pattern was described. The accuracy and surface finish of the metal castings obtained from our lab experiments were measured and compared with conventional investment casting. Metal castings from wax patterns have better accuracy while the metal castings from ice patterns have better surface finish. The main reasons causing the dimensional errors were also discussed. Future research will include investigations on how to further improve the part accuracy and surface finish of ice patterns and the cast metal parts.

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