Investment Casting with Ice Patterns Made by Rapid Freeze Prototyping

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ABSTRACT

One of the most promising applications of rapid freeze prototyping (RFP) is making metal parts by investment casting with the built ice parts. The integration of RFP and investment casting allows fast creation of complex net-shape metal parts directly from their CAD models. The advantages of doing so include no part geometric complexity limitation, no experience of parting line design and assembling needed, clean and low-cost of process operation, and good performance. In this paper, we will present our recent study on binder selection, slurry making, ceramic shell making, and the casting results of the metal parts.

KEYWORDS

Solid Freeform Fabrication, Rapid Prototyping, Rapid Tooling, Rapid Freeze Prototyping
Ice Patterns, Investment Casting

1. INTRODUCTION

Rapid Freeze Prototyping (RFP) is a solid freeform fabrication process that builds three-dimensional ice parts directly from the CAD models. To make a functional part (metal or plastic), some traditional shape duplication processes are needed, which is similar to some other SFF processes. Previous studies have demonstrated the feasibility of making plastic parts from ice patterns by Ultra-Violet (UV) light curable silicone molding, sand casting, and investment casting[1-4]. Investment casting appears to be the most promising application and there are some studies related to this application. In the late 1940s, the Mercast process used frozen mercury to make net-shape parts. The mercury pattern was first formed in a special aluminum mold and was then invested in alcohol/silica slurry, which eventually formed the mold cavity for casting. Mercast was a successful process that yielded excellent quality castings. But the molds were expensive and mercury is hazardous to health, eventually the process was forced into disuse. Dry ice was also used as frozen pattern in the cast processes developed later[4]. The industrial use of these processes provided valuable information on the low-temperature investment casting slurry for the potential application of rapid freeze prototyping. In 1991, an investment casting technology, which was patented in 1991 (US Patent # 5,072,770), has demonstrated the possibility and advantages of investment casting with ice patterns. The technology, called Freeze Cast Process (FCP), was developed by DURAMAX Co. It starts with the building of solid master and silicone mold. Then ice patterns are made with the mold and dipped into refrigerated ethyl silicate slurry and stuccoed. After repeating the dipping and drying processes, a ceramic shell is made and then it is put in room temperature and allow the ice pattern to melt, drain, and dry. The shell is obtained and needs to be heated before ready to pour molten metal. Figure 1 illustrates the operation steps of the process. FCP has several advantages over the competing casting processes, including low cost, high quality, fine surface finish, no shell cracking problem, easy process operation, and faster run cycle. One major concern in the FCP process is ice pattern making[4-6]. 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.

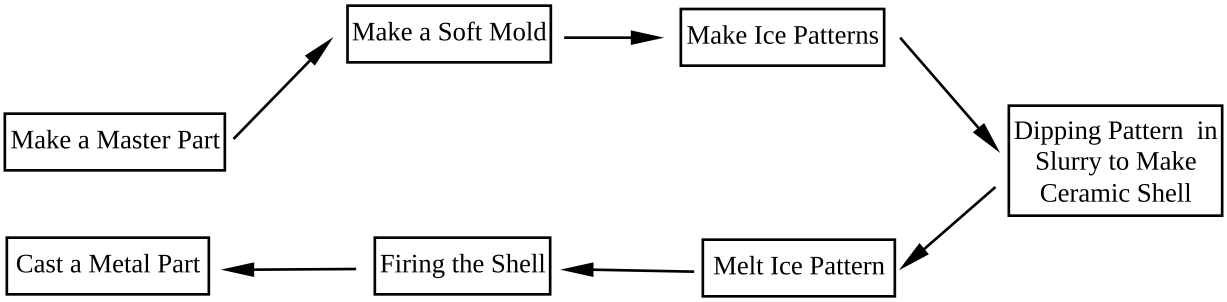


Figure 1. Freeze Cast Process Operation Steps

Though FCP has demonstrated the success of using ice patterns to make metal parts by investment casting, there is no detailed information reported yet. The following sections are based on our recent study, conducted mainly at Tsinghua University with close collaboration with University of Missouri – Rolla. The study was aimed to find the best slurry composition (including binder, catalyst, ceramic powder, and separating agent), operating process and condition, and required processing of ceramic shells.

2. MATERIAL FOR LOW TEMPERTURE INVESTMENT CASTING

The slurry used for investment casting with ice patterns (operating at a low temperature) should have different features from slurry used for regular investment casting. For example, the slurry for low-temperature investment casting should contain no water, not freeze at sub-zero temperatures, and has medium drying speed.

2.1 Binder

Binder is one of the major slurry materials. Water glass, ethyl silicate, and silica gel are the most often used binder materials for investment casting. However, in order to be suitable for low-temperature investment casting, the binder material should not freeze, not lose effectiveness, and have good fluidity at a sub-zero temperature. The ceramic shell made with water glass has low strength and low accuracy, thus it is not considered for our study. Silica gel is made with water glass and contains 40~50% water. It will freeze once it is put in low-temperature environment. So it is not possible to use silica gel as the binder for our study either. Only ethyl silicate satisfies the requirements and is used as the binder in our study[7].

Pure ethyl silicate can be used to produce a binder but it is more usual to employ a condensed or concentrated form containing about 30% to 40% silica by weight. In our experiment, the 40# ethyl silicate, which contains 40% silica by weight, is used. The ethyl silicate directly received from the vendor has no binding property. To be used as binder, the ethyl silicate must be chemically decomposed by reaction with water. The reaction produces alcohol and silica in an active state-the colloidal state which contains silica particles larger than a solution but smaller than a slurry[8]. By strictly controlling the amount of each composition, we can obtain a stable colloid which contains no free-state water. Since ethyl silicate is not soluble with water, the reaction only occurs on the contacting surfaces and is thus slow. Alcohol is soluble with both ethyl silicate and water. By adding alcohol, the reaction speed can be substantially increased. The composition is listed in Table 1. The adding of hydrochloric acid is to decrease the pH value and keep the colloid stable.

Table 1. Composition of the binder

Distilled water	40# ethyl silicate	Alcohol	Hydrochloric acid
12 ml	200 g	232 g	3.2 ml

2.2 Ceramic Powder

Fire-proof ceramic powder is another important factor for the success of shell making. Good powder can result in smooth surface finish, high accuracy, and good property of the castings. Factors that needs to be considered when choosing the powder material include the density, melting point, linear expansion coefficient, chemical composition, cost, etc. In practice, the fire proof powder material usually has several particle sizes with a certain mixing ratio. The ratio of fine/medium/coarse powder is critical for the shell quality. In order to obtain smooth ceramic shell surface, a certain amount of fine grade powder is needed. Table 2 gives the mixing ratio of our ceramic powder.

Table 2. Mixing ratio of the clay based alumino-silicates powder

270 mesh	200 mesh	70/100 mesh	30/60 mesh
30%	30%	35%	5%

During the heating and firing treatment of the ceramic shell afterwards, alcohol and water will evaporate, resulting in volumetric shrinkage, tiny holes, and tiny cracking. The more percentage of the alcohol and water, the more serious the shrinkage and defects. So increasing the powder percentage in the slurry (i.e. reducing water and alcohol percentage) will help reduce the shrinkage and defects caused during heating and firing treatment. In our study, we try to increase the powder percentage as long as the fluidity can satisfy the casting requirement. The percentage we use is (Powder : Binder) 300g : 100 ml.

2.3 Catalyst

Catalyst is required to make the binder for low-temperature investment casting. Without catalyst, the gelling of the slurry directly mixed with powder can take days or longer. The gelling time depends on temperature, binder composition, and pH value. Among these three factors, pH value is the most important one. Existing studies indicate that the slurry is the most stable when pH = 2.0, thus the gelling time is the longest. When pH = 5.0~6.0, the slurry is the most unstable and the gelling is the fastest. When pH < 1.0, the slurry is also unstable.

Adding catalyst can change the pH value of the slurry from its stable value to its unstable value, thus improving the gelling speed and productivity. The adding amount of catalyst determines the gelling speed. Practical shell making operation needs moderate gelling speed. A too fast gelling speed usually results in worse slurry fluidity, causing it difficulty to fill the whole cavity.

The catalyst can be either acid (to change pH value towards 1.0) or alkaline (to change pH value towards 6.0). The popular acid catalyst includes H_2SO_4, HCl, H_3PO_4. The alkaline catalyst includes NaOH, $Ca(OH)_2$, MgO, CaO, $Mg(OH)_2$, Na_2CO_3 and various organic materials. In our study, we use alkaline catalyst.

2.4 Separating Agent

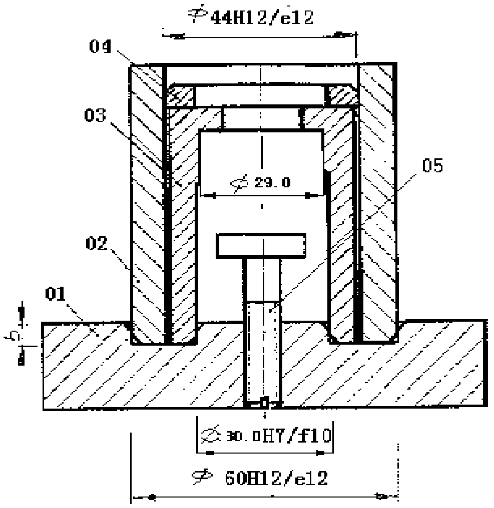
Separating agent is needed for investment casting with ice patterns. The reason is that the slurry contains alcohol and water. The alcohol and water will interact with the ice pattern surface. The decomposition process releases heat which causes more decomposition. As a result, the ice pattern surface will be seriously damaged. The separating agent material must satisfy the following requirements:

- Not soluble with water or alcohol.
- Not reacts with water or alcohol.
- Not freeze at sub-zero temperatures.
- Have good coating property on ice surface at low temperatures.
- Non-toxic and no pollution.

In our experiment, we use the mixture of silicate oil and kerosene (1:1 ratio). Before coating the ice patterns, the separating agent is cooled to the ice pattern temperature.

3. INVESTMENT CASTING EXPERIMENTS

Since the following study is focused on the process of investment casting with ice patterns, the ice patterns can be built either by rapid freeze prototyping or by traditional molding method. In order to evaluate the casting accuracy, the ice pattern should be simple and easy to measure. In this study, we use a cylindrical ice pattern made by traditional molding method. The ice pattern is made with a steel mold with a diameter of 30 mm, as shown in Figure 2. Separating agent is coated on the outer and interior cylinders before injecting water to help remove the ice pattern after freezing.



01-base 02-outer cylinder 03-interior cylinder
04-sealing ring 05-fixing axle

Figure 2. Steel mold for making cylindrical ice patterns

3.1 Ceramic Shell Making

The steps to make a ceramic shell with an ice pattern are as follows:

- Prepare binder with composition listed in Table 1 and mix ceramic powder material with mixing ratio given in Table 2.

- Measure 20 ml binder, 60 g powder mixture, and 3 ml catalyst. Put them separately in a low-temperature environment of –5°C and allow them to cool down.
- Make cylindrical ice pattern with steel mold shown in Figure 2 and measure the diameter of the obtained ice pattern.
- Cover the ice pattern with the outer cylinder (part 02 in Figure 2) and coat the interior surface of the outer cylinder with separating agent.
- Mix binder with powder and then add the catalyst.
- When the slurry is about to gel, inject the slurry into the outer cylinder and keep vibrating to let the air in the slurry out.
- After the slurry has completely set, take the mold out and put in room-temperature environment to melt the ice pattern and drain the water.
- Take the ceramic shell out of the outer cylinder and measure the interior diameter of the shell cavity and observe the surface quality.

The shell making experiments have shown that the shell dimensions keep changing with time at room temperature, as given in Table 3.

Table 3. Ceramic shell diameter (mm) vs. time at room temperature

Samples	Original size (after demolding)	24 hours	48 hours	72 hours
1	29.82	29.62	29.56	29.54
2	29.78	29.66	29.62	29.60
3	29.76	29.60	29.56	29.52
4	29.76	29.62	29.58	29.54

It can be seen from Table 3 that the shells all have the largest diameters originally and then the sizes become smaller and smaller at room temperature. The sizes change most significantly during the first 24 hours. The sizes vary 0.12 ~ 0.20 mm during the first 24 hours, 0.04 ~ 0.06 mm during the second 24 hours, and 0.02 ~ 0.04 mm during the third 24 hours. The shrinkage is caused by the evaporation of the residual water and alcohol in the shell. To make the shell dimension get stable quickly, we select to fire the shell after removing from the mold. Table 4 gives the shell diameter variation with time at room temperature. Comparing Table 4 with Table 3, we can see that after firing treatment, the shell dimension becomes more stable. The variation in 48 hours is negligible.

Table 4. Ceramic shell diameter (mm) vs. time at room temperature with firing treatment

Samples	Original size (after demolding)	Firing 30 min. and cooled down naturally	48 hours
1	29.50	29.52	29.52
2	29.70	29.76	29.76
3	29.74	29.78	29.80

3.2 Investment Casting Experimental Results

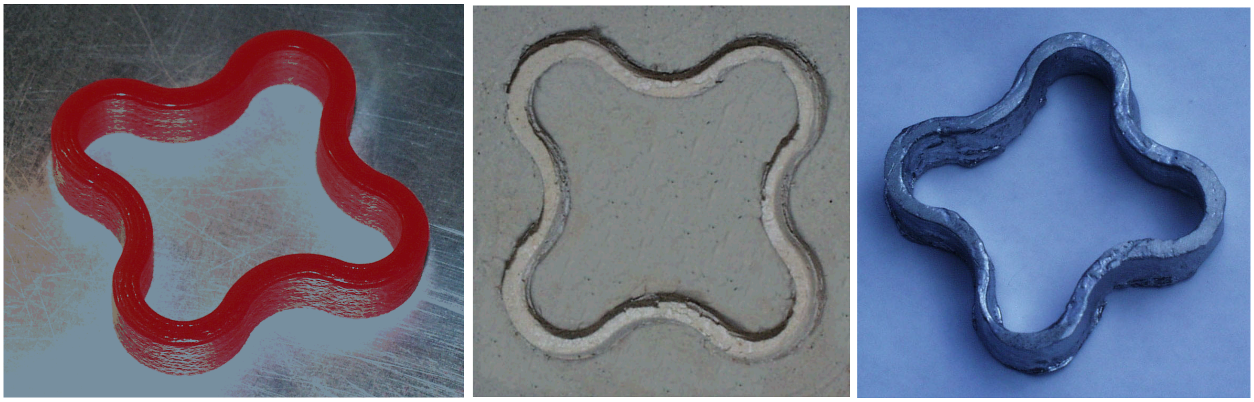
The ceramic shell obtained above still needs to be fired at a higher temperature for a longer time because the firing treatment mentioned above is only for the purpose of keeping shell dimensions stable and the firing treatment is short (only 30 min.) and mostly occurs on the surface region. To make the shell ready for casting, we fire the shell at 600°C for 2 hours and keep the temperature at 200°C when casting. There are three reasons for firing the green shell before casting[8]: A) to remove residual pattern material and solvents remaining in the ceramic shell, B) to sinter the structure of the ceramic, and C) to present the shell for casting at a predetermined and consistent temperature to reduce the temperature difference between molten metal and shell.

After firing, the shells are used for casting. In this study, we used casting aluminum ZL 103 as the cast material. Casting temperature is set at 638°C. The obtained metal part (cylinder) is measure and compared with the initial ice pattern and ceramic shell. Table 5 lists the results of 7 test samples. The dimensional variation due to firing (600°C for 2 hours) is 0.026% in average. The dimensional variation between ceramic shells and cast metal parts is 2.26% in average. And the dimensional variation between original ice patterns and cast metal parts is 2.84% in average, with maximum and minimum variation of 4.01% and 2.14% respectively.

Table 5. Dimensional comparison of investment casting with ice patterns

Samples	Shell Diameter before firing (mm)	Shell Diameter after firing (mm)	Cast Part Diameter (mm)	Relative error compared with ceramic shell	Relative error compared with ice pattern
1	29.82	29.80	29.22	2.21%	2.40%
2	29.86	29.86	29.30	1.88%	2.14%
3	29.68	29.66	28.74	3.10%	4.01%
4	29.56	29.60	28.80	2.70%	3.81%
5	29.84	29.80	29.26	1.81%	2.27%
6	29.82	29.80	29.22	1.95%	2.40%
7	29.70	29.72	29.08	2.15%	2.87%

Investment casting with ice patterns made by rapid freeze prototyping is the same as the process described above. Figure 3 shows the ice pattern made by rapid freeze prototyping, the obtained ceramic shell, and the cast metal part.



(a) Ice pattern made by RFP (b) Ceramic shell (c) Cast metal part

Figure 3. Investment casting with ice patterns made by RFP

4. CONCLUSION

Investment casting with ice patterns has some different requirements from regular investment casting (with wax pattern) both in the material and the operating process. It requires the binder not to freeze at sub-zero temperatures and not to react with ice. Making ceramic shell from ice patterns needs low temperature to avoid ice pattern melting. The study has demonstrated the feasibility of making metal parts by investment casting with ice parts made by rapid freeze prototyping. Binder materials satisfying the special requirement has been developed.

Further study will be focused on developing better binder material that can result in better ceramic shell accuracy and dimensional stability.

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