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Study on Investment Casting Directly with Rapid Prototype ABS Patterns

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Abstract - This paper presents studies for ABS RP pattern directly used in investment casting. Ceramic mold shell preparation procedures including CAD pattern designing; RP pattern formation; pattern surface finish and sealing; de-waxing and burnout are discussed. Geometrical effects such as bulk solid and thin wall are studied. For the process to be successful the preparation should start as early as CAD design stage. For bulk solid geometries, "Shell" function in CAD and "Sparse web" options are proved very effective and should be applied in combination; while for thin-wall patterns, Hot-Water De-Wax before burnout proved to be very effective.

Key words - Quick casting; Rapid Prototype (RP); Plastics; ABS

I. INTRODUCTION

Rapid prototyping (RP) techniques applied in investment casting could reduce dramatically the lead-time and cost. It also gives the companies the freedom to issue new products rapidly without significant increase total development time and cost. The ideal RP pattern for investment casting is no doubt wax, such as Thermojet MJM wax and FDM ICW06 wax. However based on Whovers' 2008-RP-Report in Fig. 1, more than 70% of RP units produce parts that are made of thermo plastic or thermo-set [1], simply because at present the RP units purchased by companies are used for multi-functions not only for demonstration and sampling, but also for fit and run pieces.

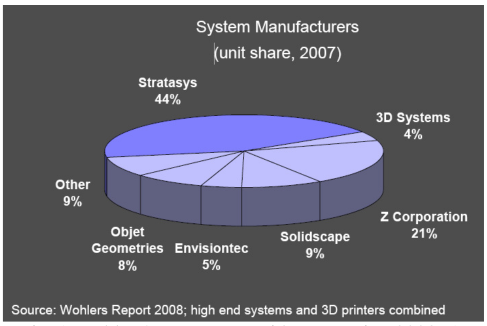

Fig. 1 Wohlers' report on Rapid Prototyping 2008 [1]

The major advantages of RP plastic/resin parts for direct investment casting are [2]:

1) It eliminates the need for tooling. Injection molds for wax patterns range from $3,000 to $30,000, and building the tools can take four to six weeks. With this technology, the tooling cost is eliminated and the lead-time for a cast part is slashed to just 10 days on average. This yields a savings of $30,000 and two to four weeks for a typical project, which makes investment casting viable for prototype quantities. The time and cost savings are true no matter how complex the part's design.
2) Since RP is an additive fabrication technology, there is no impact on the investment or delivery schedule as the pattern becomes more complex.
3) Additional time savings also occur in casting design, since RP patterns can be produced without adding draft angles to the CAD data.
4) A final consideration is the durability of the pattern. Patterns made from foundry wax and other additive fabrication technologies are easily damaged. And, transportation and routine handling can result in broken patterns. The strength and toughness of plastic/resin materials virtually eliminate pattern damage and the delays it can cause. The materials are also resistant to warping from heat and humidity.

Although CF (CastForm™ polystyrene) material used with LS (Laser Sintering) process is a fast and cost effective alternative, it is difficult and risky to clean a CF part from the loose powder [3]. Therefore other than wax or its hybrid counterpart such as CF material, there have been several RP techniques available for fabrication of investment casting patterns such as: ABS for FDM process [2], QuickCast™ photopolymer used in SLA (Stereo-lithography) [4] and PrimeCast 100 polymer for SLS [5]. Unlike wax patterns, special measures against shell cracking are necessary during the burnout process, because the coefficient of thermal expansion of the plastic/resin is almost one order of magnitude larger than that of investment ceramic materials. [6].

During plastic/resin pattern burnout process, cracking occurs when the stress induced on the ceramic shell is greater than the modulus of rupture (MOR) of the shell material. Although efforts have been made to understand the mechanism and to prevent shell crack due to thermal expansion, the theoretical background has not been completely clear, may be because of the technological difficulties. For example, the two dimensional heat-transfer during the thermal expansion of the pattern and ceramic shell was considered steady-state instead of transient [6]. Additionally, the temperature uniformity in the webbed pattern and the ceramic shell was assumed. However practically it is difficult to keep the temperature uniform during the continuous heating of the specimens. Thus, the temperature was increased by one step at a time and kept long enough to reach the desired uniform temperature in their study [7]. Most recently, transient analysis of heat transfer coupled with structure mechanics with nonlinear material models is conducted [8].

The objective of this paper is to understand more on this process through experiments and numerical simulation, making the process more stable, more repeatable and even establish a standard for the process.

II. EXPERIMENT STUDIES

Based on conventional investment casting practice, literatures of relative development and most importantly from the authors' multiple trail and error tests, the procedure was established as the following:

a) Design: The test samples are geometrically designed with the Solid-Works package and built using the FDM (Fused Deposition Manufacturing) RP process with ABS material from Stratasys. Special attention was paid for the inner solid and will be discussed latter in this section.
b) Finishing and sealing: The patterns were carefully polished with fine sand paper to assure good quality, and evenly sprayed with acrylic paint to avoid unwelcome penetration of slurry into the pattern material.
c) Ceramic Shell building: Then the patterns were fastened onto the wax gating and feeding base and coated with ceramic shell. For primary coat: 325 mesh Silica, 325 mesh Zorcon powders with ludox SM (binder), and for Backup coat: 120 mesh Silica with ludox SM (binder). The ceramic coating was built through successive stages of dipping and stuccoing. Between each coat, the shell was hanged in air conditioned room (about 24°C) for about 4 hours to dry. This procedure is repeated until the required shell thickness was obtained.
d) De-waxing: On completion of the shell building process, the expendable wax base has to be removed. For conventional procedure, the de-wax procedure is going on at about 180°C and 300psi in a steam autoclave. However, hot water de-waxing is introduced in this study to avoid shell crack. The details will be discussed later in this section.
e) Pattern material burnout and ceramic shell strengthening: Since ABS (Acrylonitrile Butadiene Styrene) is flammable when it is exposed to high temperatures. With oxygen，95% ABS material will burnout at temperatures between 300-400°C, while the rest will burnout. With inert gas, 87% burnout at 450°C, 2% burnout at 575°C and the rest will burnout totally at 1000°C, basically without any trace. Therefore, the traditional flash-furnace (at about 1100°C) could be used for two purposes: strengthen the ceramic shell as well as burn out the plastic pattern.
f) Pattern material residual/ash washout: After the burnout process, an ultrasonic water bath was used to washout possible residual/ash, to assure cast surface quality.
g) Casting: Finally the shell was heated again in the furnace. Then the red-hot ceramic shell was taken out and molten metal (stainless steel in this study) was pored into the cavity to form metal parts.

Two typical geometry characteristics were investigated to understand the process: Bulk solid and thin wall. Most of the experimental work was done in the actual foundry environment.

A. Bulk solid Geometries

Fig. 2 presents the application of solid ABS RP patterns used directly for investment casting, following above mentioned procedure. Dimensions of both pieces are in the envelopes of 15x40x50mm. After casting, key dimensions were measured and compared between the plastic RP patterns and the final metal pieces, the dimension tolerance is all within 1%.

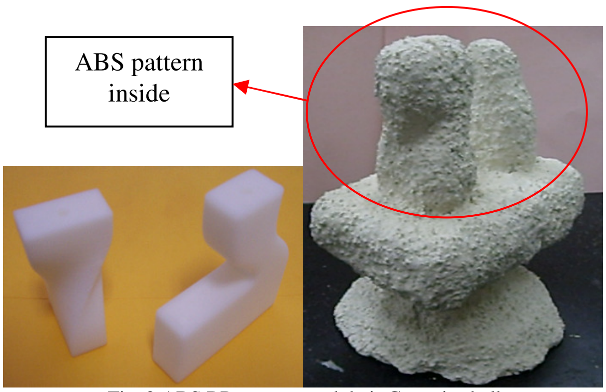

Fig. 2 ABS RP patterns and their Ceramic shell

For the success of this work, special attention was paid for thick wall or bulk solid geometries of above patterns. In fact, there are two ways to treat the inner solid of a bulk solid pattern:

(I) A "Shell" function in CAD software could be applied to create cavities wherever possible (Fig. 4, middle). For the cavities, the RP software will automatically create support structure with support material that is very lose and/or could be washed out, if particular passage is designed (for water soluble supporting material).

(II) If the "Shell" function was not applied or difficult to excuse, usually the RP software provides the option of "Sparse Inner Structure" (Fig. 4, right).

For the same design (a cylinder of 30x20mm) as shown in Fig. 3:

In case (I) the color of the support material is gray and could be washed out, while in case (II) the inner sparse web structure is made of the model material that is not water soluble.

Moreover, the support web in case (I) is loser than in the sparse web structure of case (II).

All of these efforts are for the material to collapses inwards much easier, rather than expands outwards, cracking the ceramic shell during heating. By comparison, the hollow structure is no doubt better than the sparse web structure. However, the best practice may be that both functions (Shell in CAD and Sparse in RP) be used in combination to minimize thermal stress.

Fig. 3 Cross sections of a cylinder (30x20mm)
(I) Middle: Designed hollow with CAD's "Shell" command;
(II) Right: Designed solid but formed "Sparse web" in RP software.

The cross sectional view of a casting pattern of Fig. 2 is shown in Fig. 5. This is a sparse web structure.

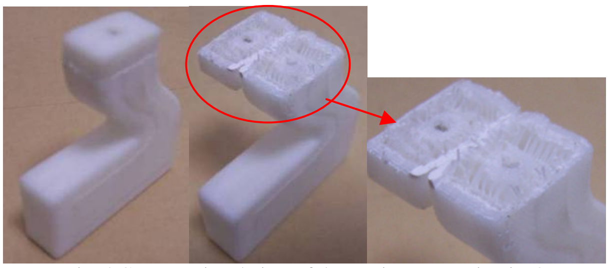

Fig. 4 Cross sectional view of the casting pattern in Fig. 2

As an example, the ceramic shell and quick-cast metal piece are presented in Fig. 5. The major geometries of the patterns are bulk solid.

Fig. 5 Ceramic shell and steel parts with gate and feeding base

B. Thin wall pieces or pieces with thin walls

For generality, the test samples were a real set of tap-water valve design, one was the valve body and the other was the handle. Unfortunately even with carefully prepared RP patterns and the ceramic shell, the experiment stops at step e and failed: when the piece was removed from the steam autoclave, serious shell crack was observed (Fig.6).

Fig. 6 Shell crack after regular De-Wax process up to 180 °C

Looking from the back side of the shell, although the wax was completely melted and removed, there was serious plastic flow due to thermal expansion (Fig. 7). It is believed that since the glass transition temperature is bellow 180°C, the plastic material had long time to expand during de-wax heating.

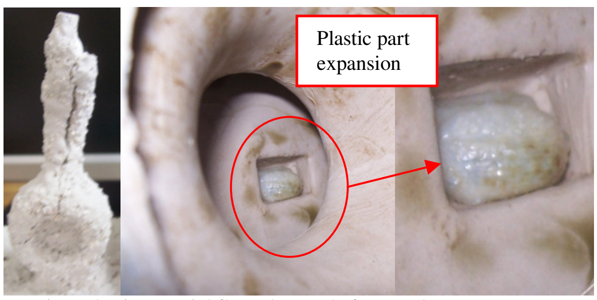

Fig.7 Plastic material flow observed after regular De-Wax process

C. The Hot-Water De-wax Process

To address above mentioned problem with thin walled structure, the Hot-Water process was introduced to avoid excess thermal expansion of the RP plastic part: Instead of conventional de-waxing steam autoclave, the base of the shell is submerged in hot water for about one and half an hour, to melt and remove the wax inside the shell (Fig. 8).

During this de-waxing, liquid wax has to be wiped out several times due to the small dimension of the hot-water container. Because the upper part was not exposed to heat during this de-wax process, plastic material did not expand to cause any shell crack.

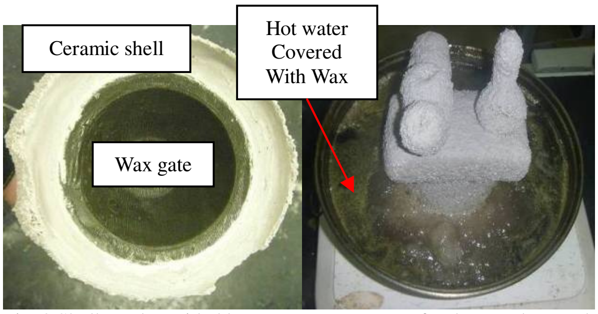

Fig. 8 Shell crack avoided by Hot-Water-De-Wax for the wax-base only

After the hot-water de-waxing, the back side of the shell is clean and there is no shell crack or plastic flow was observed (Fig. 9).

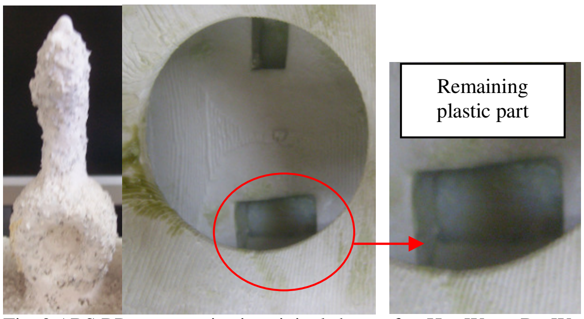

Fig. 9 ABS RP part remains in original shape after Hot-Water-De-Wax

Then, the shell containing the ABS RP patterns was moved into the flash furnace at about 1,100°C for two purposes: burnout the ABS material and strengthen the ceramic shell. This time, the ceramic shell did not crack and it is clear that the plastic part was burn-out almost completely (Fig. 10).

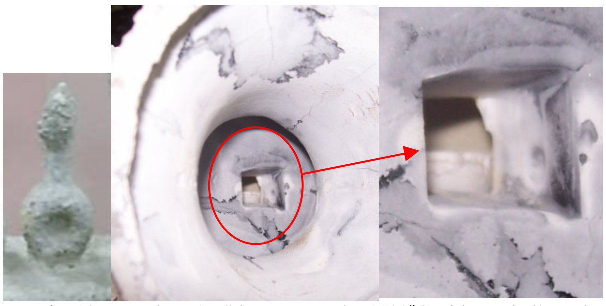
Fig. 10 Very clean ABS burn-out under 1100°C without shell crack

The new method of de-waxing that consists in:

a) First using hot water to melt the portion of wax, leaving the plastic pattern intact, and
b) Then taken into an 1100˚C oven to burnout the plastic pattern.

The successfully quick-casted metal parts with thin walls are shown in Fig. 11.


Fig. 11 Successful quick-cast metal pieces with thin walls

III NUMERICAL ANALYSIS

To further understand the heating process, especially the difference between de-wax and burnout, theoretical analysis for the prediction of thermal stresses during heating was conducted. Numerical Analyses of heat transfer, coupled with structural mechanics, were done in order to study the probability of ceramic-shell cracking due to thermal expansion, using COMSOL multi-physics software. 2-D Transient analysis and non-linear material properties are applied in the simulation. Details of the numerical analysis were discussed in another paper [8].

During simulation only one quarter of the cylindrical model is needed because of symmetry (Fig 12). The outside layer represents the ceramic shell and inside is the plastic sparse web structure (left). As mentioned above, the idea of sparse structure is to build the pattern such that it collapses inwards under the influence of heat, rather than expanding outwards and cracking the ceramic shell. On the right side of figure 12, triangle meshes are generated by the software automatically.

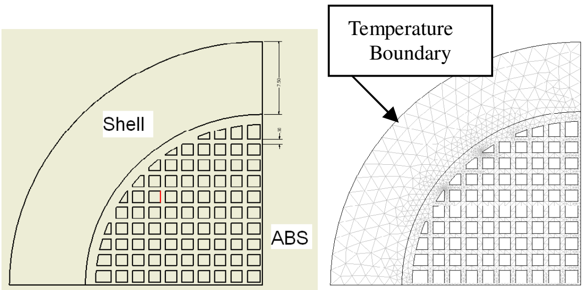

Fig.12 Physical model and mesh situation from COMSOL Multi-physics[R]

Temperature propagation towards inner structure is presented in Fig. 13. From the picture, it seems that the development of temperature in the structure is quite a long process.

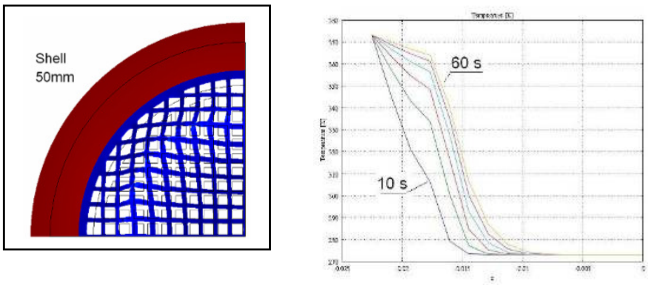

Fig. 13 Temperature propagation towards inner structure

Comparisons are made for thermal stresses when the patterns and shell are subjected to the autoclaving de-waxing and burnout processes.

It is very obvious that burnout create far less thermal stresses. (Refer to Fig. 14 and Fig. 15). The plotted first principal stresses are in the ceramic side and at the conjunction with the plastic material.

For 1mm wall plastic pattern, the maximum thermal stress in the de-wax process is about 44% higher than during burnout (Fig. 14).

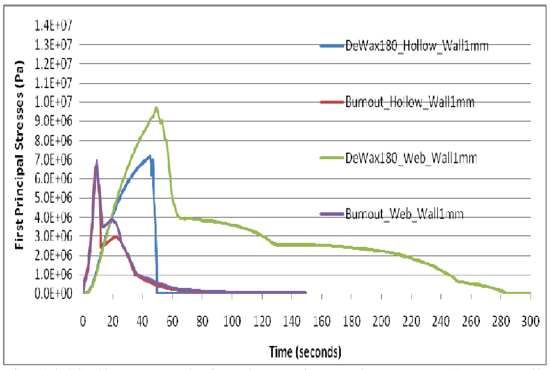

Fig. 14 Shell stresses during de-waxing and Burnout (1 mm Wall)

While for 2mm patterns, the maximum stresses are almost doubled, from the comparison of burnout results with that of De-Wax heating (Fig. 15).

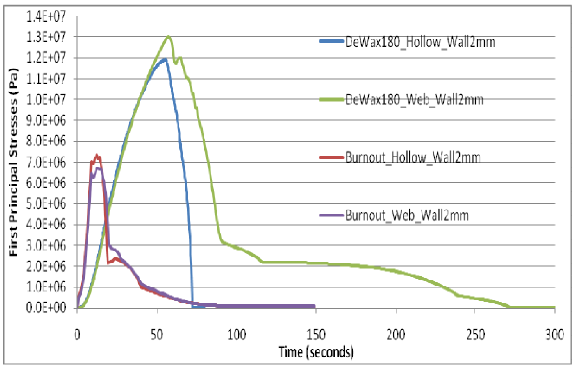

Fig. 15 Shell stresses during de-waxing and burnout (2 mm Wall)

This mechanism very well explains the advantage of the proposed Hot-Water De-Wax process.

IV. RESULTS AND DISCUSSIONS

For Rapid Prototype ABS patterns used directly to investment casting, successful results were obtained for varies of geometrical shapes: bulk solid as well as thin walls. Major achievements and observations are listed as the following:

1) Workable procedures were experimented and listed as the direct standard for production to follow.

2) For the process to be more stable and repeatable, careful preparations for the plastic patterns are necessary even as early as at the CAD stage.

3) To reduce the possibility of ceramic shell crack, the Hot-Water De-Waxing procedure was proved to be a good option for this process. The mechanism behind is revealed by our transient, non-linear CAE analysis.

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