GELCAST MOLDING WITH RAPID PROTOTYPED FUGITIVE MOLDS

Vikram R. Jamalabad, Philip J. Whalen
AlliedSignal Research and Technology, Morristown, NJ 07962.

John Pollinger
AlliedSignal Ceramic Components, Torrance, CA 90509.

Mukesh K. Agarwala, Stephen C. Danforth
Rutgers University - Center for Ceramic Research, New Brunswick, NJ 08854.

ABSTRACT

A technique for the rapid manufacture of ceramic components has been developed using rapid prototyping to generate molds for the required components. The process entails the fabrication of fugitive tooling using rapid prototyping techniques from which ceramic articles are formed using gelcasting. In the gelcasting process, the mold cavities are filled with a fluid suspension of ceramic powder which sets to a solid form through the polymerization of gelling additives and application of heat. The mold is carefully removed by dissolution or heat treatment leaving the intact gelcast part. The "green" gelcast part is subsequently dried and sintered to full density. Computer aided manufacturing of the tooling using solid freeform fabrication techniques allows for complex shapes to be manufactured with minimal tooling cost. The technique is ideal for the manufacture of ceramic parts in small batch conditions or for prototyping of functional parts in design cycles. Cost and time reduction of a magnitude can be achieved.

KEYWORDS: Solid Freeform Fabrication, Molds, Gelcasting, Ceramic Processing, Structural and Functional Ceramics.

INTRODUCTION

Solid Freeform Fabrication (Rapid Prototyping / Manufacturing) is fast maturing into a means for the manufacture of structurally sound functional components. Until recently, only plastic and polymeric parts have been manufactured by SFF techniques. 3D Systems' Stereolithography[1], the earliest of the techniques, is used for manufacturing plastic parts. Apart from design purposes, these parts are used as investment casting positives. Structural use of SLA parts is limited. Griffith *et al*[2] have used ceramic suspensions in the SLA resin bath and have shown some progress in generating ceramic parts.

Extensive work has been reported in the use of Selective Laser Sintering (SLS) by Bunnell *et al*[3] for the freeform fabrication of metal parts. Cima *et al*[4] have demonstrated the 3 Dimensional Printing (3DP) process for both, metal and ceramic parts. Fused Deposition of Ceramics (FDC), based on Fused Deposition Modeling (FDM™) has been shown to be feasible (Agarwala *et al*[5]). In addition, some novel technologies that are in early stages of development (SALD, by Zong[6] and Marcus) could lead to the manufacture of structural components.

Indirect methods of manufacturing structural components using solid freeform fabrication have been used since the inception of these techniques. Part positives for investment casting can be made by almost all SFF processes. Investment casting wax parts (Stratasys Inc's FDM™ machines), paper parts (Helisys Inc's LOM™ machines), polymeric parts (Sanders-Prototype Inc's MM-6PRO Model Maker™, MIT's 3DP machines) and photopolymeric parts (3D Systems Inc's SLA™ series machines) have been utilized. Ceramic slurry (usually a refractory like silica) is set around the part positives before the parts are melted away to leave a cavity for casting.

The development of complex shaped ceramic structural components and devices is severely hampered by the high cost of ceramic prototype manufacturing and the overheads of short production runs. Machining of sintered, fully dense ceramic articles is extremely hard, time consuming and expensive. This has led to the development of many net shape fabrication techniques. Injection molding and slip casting are two of these techniques. Both require some form of precision tooling, effectively driving up cost.

The overall cost of a component will, in most cases, be driven by the cost of the tool fabrication. Time consuming and expensive machining operations are required for tool preparation. The necessity of this tooling also precludes the use of iterative approaches in design, since changes in component design require significantly high levels of re-investment in time and capital. For injection molding, high quality water-cooled dies are required. At the same time, these need to be rapidly dis-assemble to eject the part. Very large cross-section parts also cannot be manufactured due to binder burnout problems. Complex porous tooling is required for slip casting. Variations in particle distribution lead to warpage and an inability to hold tolerances.

RAPID PROTOTYPED MOLDING FOR GELCASTING

Ceramic gelcasting is a process whereby a ceramic slurry containing appropriate monomers is poured into a tool and then "gelled" through a catalyzed reaction. This gelation polymerizes the monomer resulting in a relatively rigid solid. Metal and ceramic particles in the suspension can be gelled in this manner. Low cost multi-part metal (aluminum) tooling is used for ceramic gelcasting. While this works for relatively simply shaped parts, for complex parts, fugitive tools or molds which are removed by dissolution can be used. Gelcast tooling must have several key features. The tool must be stable at the temperatures required for gelling (40 to 60 C). In addition, the tool must be structurally sound to support the ceramic suspension during the gelling process.

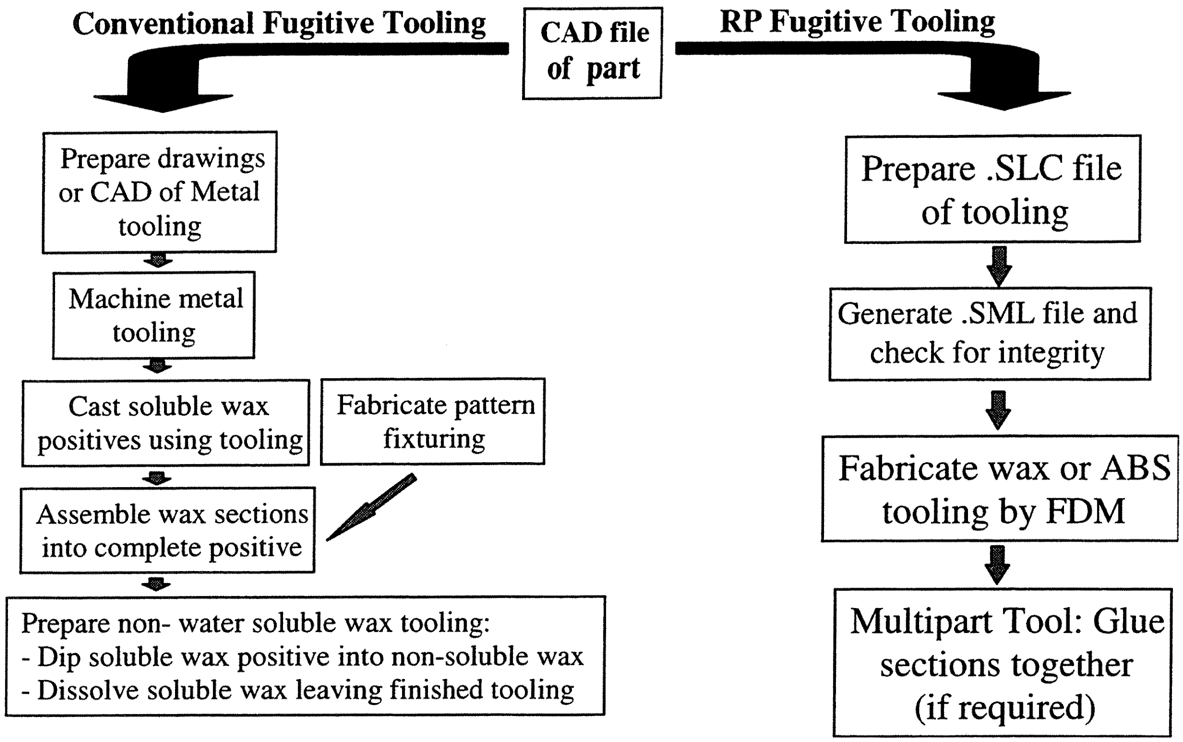


Figure 1. Process for fabrication of Fugitive Tooling

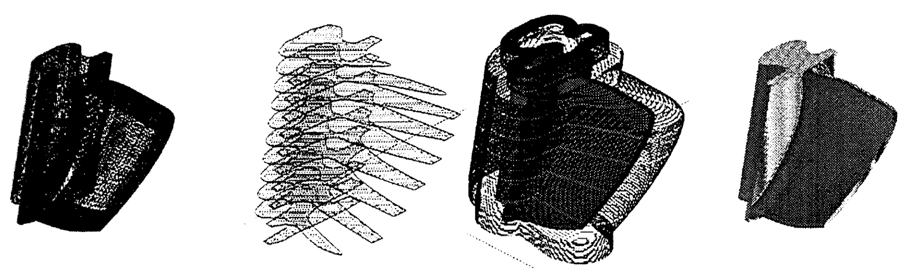
The fabrication of conventional fugitive tooling is a very labor intensive process with long lead times. Figure 1 shows how the fabrication of fugitive tooling can be significantly simplified through the use of solid freeform fabrication techniques. Using a large ceramic turbine nozzle doublet component (Figure 3) as an example, the cost savings of using rapid prototyped fugitive tooling was examined (Tables 1 & 2). The results show that significant time and cost savings can be realized for both the production of the initial part and subsequent components.

Mold design is a relatively mature area of work. Rapid prototyping procedures provide an efficient means of manufacturing molds directly from the envisioned CAD models. Minimal tooling investment is required, apart from the prototyping machinery itself. Complex shapes with non-extractable surfaces and blind holes can be designed with ease. The direct fabrication of fugitive tooling from a CAD file significantly reduces the time and cost of fabricating complex net shape ceramic components by eliminating excessive machining. The additional benefit is that changes in the component design can be easily accommodated without additional capital equipment investments. The details of fabricating gelcast tooling using rapid manufacturing techniques and using that tooling for ceramic gelcasting, shown schematically in Figure 2, is described below.

1. The CAD model of the component is scaled up to allow for shrinkage.
2. A mold is designed for the component with the following features -
    - Part orientation for minimal mold overhangs and elimination of air pockets.

- A solid lining for the mold cavity, created by conformally offsetting the component surface and building a part "perimeter."
- A honeycombed mold support structure behind the mold cavity. The honeycomb structure increases the ratio of surface area to volume of the mold material and results in more efficient dissolution.
- Add appropriate reservoirs, gatings and risers for easy filling of the slurry.

3. If a mold design has large overhangs or sections in which support structures are hard to remove, multi-part molds are built and assembled using appropriate adhesives. Locating holes are built into the mold to enable accurate alignment of the parts.
4. Support structures are added as required. These are preferably of materials dissimilar to the part material.
5. The molds are built on the appropriate RP platform of acetonitrile butadiene styrene (ABS) or investment casting waxes.
6. Molds are tested for integrity by filling with water and holding for a period of time.
7. The ceramic gelcasting slurry is poured into the cavity of the mold so that all air pockets are removed.
8. Gelation is then achieved by elevating the temperature.
9. The entire assembly is immersed in a bath of solvent (acetone, alcohol, toluene) and the mold is dissolved. In the case of wax, elevated temperatures can be used to melt away the mold.
10. The formed ceramic component that is left behind is dried and sintered.



(a) CAD (b) Processing (c) Mold (d) Final Part

Figure 2: Schematic of the Gelcasting Process for a Ceramic Turbine Blade.

The cost advantages of this technique are manifest in the following: (a) Minimal machining is required in the fabrication of a complex ceramic component. (b) Rapid generation of molds with varying component parameters enables quick turnaround in iterative part design. (c) Defects and part rejection caused by problems with mold disassembly are minimized. (d) Doing away with physical means of removal ensures that thin sections and delicate protrusions can be manufactured.

EXAMPLE

To demonstrate the feasibility of using rapid prototyped fugitive tooling to fabricate complex ceramic components the entire process was exercised on a ceramic turbine nozzle doublet based on a metal nozzle design used on the Pegasus[α] engine. A CAD file was developed by reverse engineering a full size metal component using CAT scanning techniques. This file was used to prepare a fugitive tool using the procedure described above. Several tools were produced and parts were gelcast using AS800 silicon nitride. The parts were dried and sintered to high density. Figure 3, shows a turbine nozzle doublet tool fabricated using a Stratasys FDM1600™ and silicon nitride gelcast part that was cast in an RP tool.

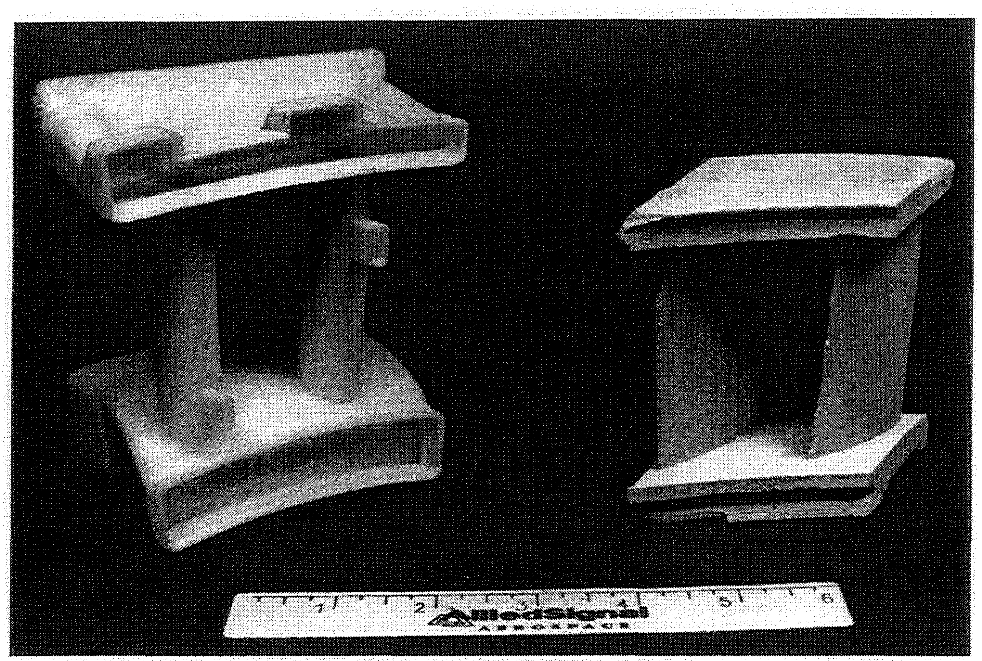


Figure 3: Fugitive Tooling and a Ceramic Gelcast of a Doublet

<u>FUTURE DIRECTIONS IN THE DEVELOPMENT OF RP FUGITIVE TOOLING.</u> While the feasibility of using RP tooling for gelcasting ceramic articles has been demonstrated the true cost savings of using this approach will not be realized until significant experience in handling this process is obtained. In particular, the ability to obtain a crack free part on the first iteration is highly dependent on mold design. Issues with eliminating designs which trap air and excessive mold material on certain parts of the tool need to be addressed. Work on the development of more suitable fugitive tool materials will also help move this technology forward. Surface finish issues which are relevant to most layered manufacturing techniques will also need to be resolved.

CONCLUSIONS

By combining the processes of rapid prototyping to fabricate tooling and ceramic gelcasting to fabricate parts, a means of manufacturing ceramic components in a rapid and inexpensive manner has been developed. Complex shaped parts that are hard to machine, slip cast or injection mold can be manufactured by this method. The cost

[α] Rolls Royce engine component, supplied by the Office of Naval Research.

benefits are realized by time savings by eliminating costly tool machining procedures. The technique enables the use of iterative design and the fabrication of parts with unique structures (complex protrusions, thin sections).

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Process	One Time Cost per mold design	Time (hours)	Outsourcing or Material Costs ($)	Labor (hrs)	
				Professional	Technician
Obtain CAD file of part and convert to .STL					
Determine best orientation for mold build: create .SLC files and iterate to minimize support	**XX**	**4**	**-**	**4**	
Design and create mold file (.SLC)	**XX**	**4 to 16**	**-**	**4 - 16**	
Generate .SML file and check integrity: fix aberrations	**XX**	**4**	**-**	**4**	
Build mold on Stratasys FDM 1600		**44**	**$70 (ABS)**		**1**
Multipart Mold: Glue sections together		**4**	**< $1**		**4**
Clean up mold and check mold for leakage		**4**	**--**		**1**
TOTALS		**60 - 76**	**$ 70**	**12 - 24**	**6**
				@ $78/hr	**@ $ 55/hr**
TOTAL $			**$ 70**	**$ 936 - $ 1872**	**$ 330**

First iteration would take 60 to 76 hours and cost from $ 1116 to $ 2272. Subsequent iterations of the same mold would take 48 - 52 hours at a cost of $ 180 - $ 400/mold.

Table 1. Cost Analysis for ABS FDM tooling for Gelcasting the Ceramic Turbine Nozzle Doublet

Process	One Time Cost per mold design	Time (hours)	Outsourcing or Material Costs ($)	Labor (hrs)	
				Professional	Technician
Obtain CAD file of part and convert to .STL					
Prepare drawings or CAD of metal tooling	**XX**	**4 weeks**		**120**	
Machine Metal tooling	**XX**	**6 weeks**	**$20,000**		
Cast water soluble wax positives using metal tooling		**5-10 hrs**	**~ $ 1**		**5 - 10**
Fabricate pattern fixturing	**XX**	**3 weeks***	**$2,000**		
Assemble wax sections into a complete positive		**6 hrs**			**6**
Prepare non-water soluble wax tooling					
-Dip soluble wax positive into non-soluble wax		**24 hrs**	**~ $ 1**		**3**
-Dissolve soluble wax leaving finished wax mold		**36 hrs**			**4**
TOTALS		**11 weeks**	**$22,002**	**120**	**18 - 23**
				@ $78/hr	**@ $ 55/hr**
TOTAL $					

* Concurrent with metal tooling fabrication

First iteration would take ~ 11 weeks and cost from $ 32352 to $ 32627. Subsequent iterations of the same mold would take 71 to 76 hours at a cost of $ 990 to $ 1265/mold.

Table 2. Cost Analysis for the Fabrication of Standard Wax Tooling for Gelcasting the Ceramic Turbine Nozzle Doublet