

Stereolithography-Based Manufacturing of Molds for Directionally Solidified Castings

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Abstract: Directionally solidified components, such as single crystal turbine blades, are typically grown using shell molds prepared using a lost wax process that begins with injection-molded wax positives. These positives have complex designs, are manufactured in low volumes, and are made using expensive tooling. Here we investigate the potential of replacing these injection-molded positives with plastic patterns created using stereolithography. By using 3D printing instead of injection molding to create the positives, we can dramatically reduce tooling costs and leverage the freedom of design offered by 3D printing to create more intricate turbine blade designs. While using 3D printed positives to create molds for shape castings was one of the earliest examples of rapid prototyping of metallic components, the present work highlights the potential of extending this approach to molds used for growing single crystal parts.

1. Introduction

Single crystal turbine blades used in the hot section of jet engines have complex geometries, with intricate internal cooling channels for flowing air through the blade. They are typically grown using shell molds prepared by the lost wax process, in which layers of a ceramic slurry consisting of ceramic powder and silicate-based liquid binder are applied to a fugitive pattern, which is then burned out. The wax or plastic patterns used in this process are made by injection molding using dedicated master dies. To form the complex network of cooling channels within the blade, a ceramic core is inserted into this master die before the pattern material is injected. The core itself must be injection molded and sintered prior to its use in the wax pattern.

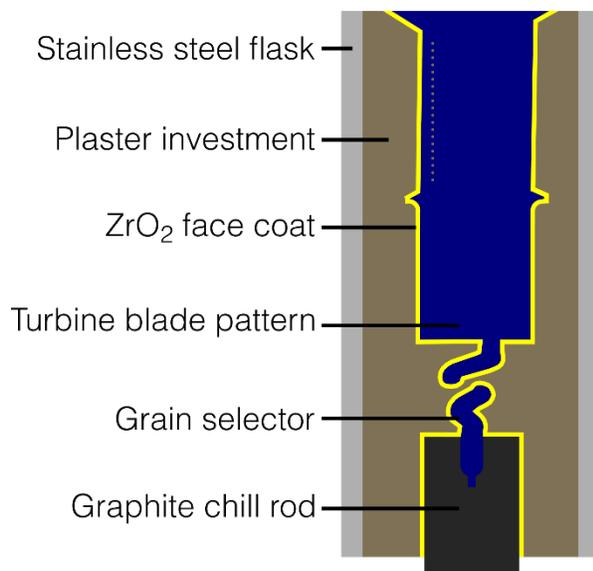


Figure 1. Hybrid mold showing the SLA pattern within a ZrO_2 shell backed by plaster of Paris investment.

Historically, the pattern and the core have been injection molded using master dies machined from tool steel. Because of the high costs associated with making these master dies and the constraints these master dies impose on turbine blade designs, there have been several recent attempts to eliminate the need for them by using additive manufacturing. One approach has been to directly print turbine blades using metal additive manufacturing techniques such as electron beam additive manufacturing (EBAM) [1–3]. However, such direct metal printing techniques present challenges with stray grain nucleation and cracking during printing. Recent work on EBAM has demonstrated encouraging results on small scale, simple geometries (e.g. cubes, cylinders, pyramids) [2,4]. The cores of these specimens

have superior microstructure to as-cast samples, but un-melted powder particles attached to the surfaces of the specimens nucleate stray grains, resulting in polycrystalline exteriors.

Another approach eliminates the overhead cost of the master dies by combining additive manufacturing of ceramics with traditional directional solidification. Researchers have explored using stereolithography-based ceramic 3D printing to print both cores and molds directly [5–8], though binder removal can cause cracking and distortion in larger 3D printed molds [9]. Alternatively, fused deposition modeling (FDM) and stereolithography (SLA) have been used to directly print the plastic patterns; however, both approaches present their own issues. FDM is inexpensive but lacks the capability to produce the fine features required for complex parts like turbine blades and their cores [10]. SLA patterns have a high dimensional accuracy, but the photopolymers used in SLA have larger thermal expansion coefficients than typical wax, resulting in mold cracking during pattern burnout [11]. This weakness is mitigated by printing hollow or semi-hollow SLA patterns, like the QuickCast process developed by 3D Systems [11], yet mold cracking remains an issue.

A method recently developed by our research group uses SLA printed patterns, but reinforces a plaster of Paris investment mold with a stainless steel flask [12]. This reinforcement enables us to use solid SLA patterns to make molds, and allows a greater range of possible pattern geometries by simplifying the mold making process. These molds incorporate a graphite chill rod at the base that makes physical contact with a low temperature heat sink and ensures uniaxial heat flow along the growth axis of the casting, promoting directional solidification. So far, we have used this method to fabricate single crystals, bicrystals and tricrystals, making it a promising alternative for prototyping and manufacturing single crystal turbine blades. In addition to control over the microstructure, this method can rapidly produce a single pattern that models both the internal cooling channels and the airfoil of a turbine blade. In this paper, we explore the possibility of

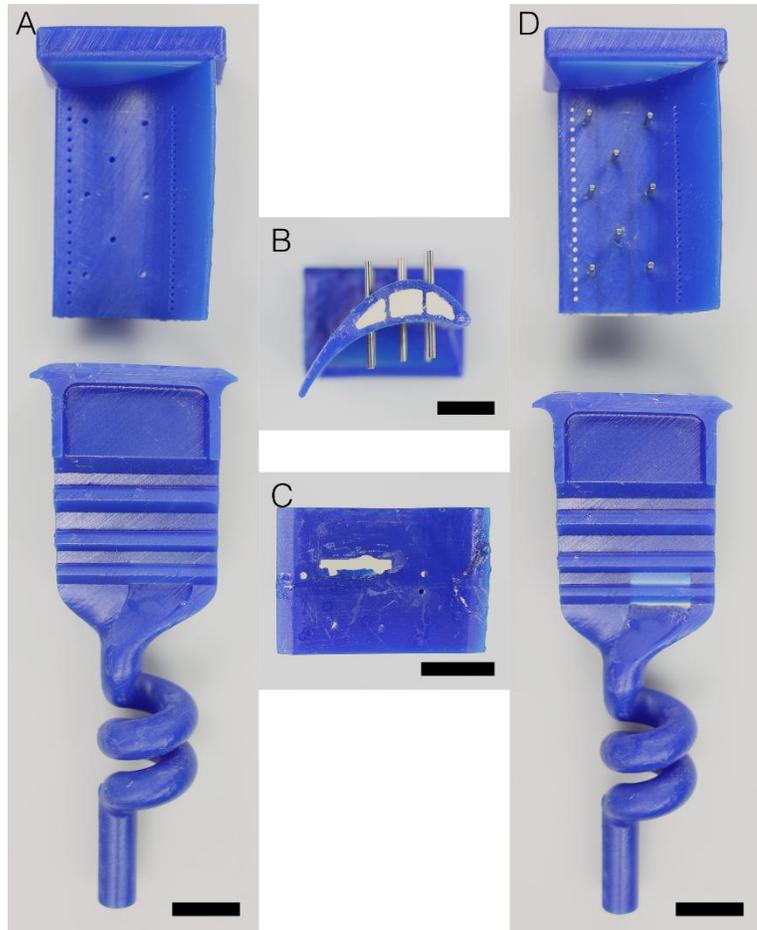


Figure 2. (A) SLA positive of turbine blade, printed and cured. Lengthwise views of (B) the top half and (C) bottom half of the pattern, filled with the ceramic core. (D) Turbine blade pattern filled with ceramic core and steel pins inserted. All scale bars indicated 1 cm.

manufacturing an integrally cored turbine blade mold using this hybrid additive manufacturing process.

2. Mold-making procedure

In the traditional mold-making process used to manufacture turbine blades, ceramic shell molds are formed around an injection molded wax pattern containing ceramic cores held in place by metal pins. The wax pattern is then burned out and the mold is sintered before it is used to grow a turbine blade. Our approach is essentially the same except we print the fugitive pattern using SLA. To demonstrate this mold-making approach, we created molds for the directional solidification of an aluminum casting alloy, A356. A schematic cross section of an example mold is shown in **Figure 1**. Note that the molds consist of multiple parts, including a graphite chill rod, plaster of Paris backing, stainless steel flask, and ZrO₂ face coat. We began the mold-making procedure by printing the turbine blade pattern in two separate pieces, as shown in **Figure 2A**, using a Formlabs Form 2 SLA 3D printer and Formlabs Castable Resin. By printing the pattern in two pieces, we can pour the cores into the patterns directly. **Figures 2B** and **2C** show the cores within the upper and lower half of the pattern, with steel pins inserted to hold the cores in place after the pattern is burned out. After the cores were poured and cured, we joined the two halves using a small amount of wax and inserted the grain selector into a graphite chill rod.

In our previous work [12], we used a monolithic plaster of Paris mold. However, because the Si in plaster of Paris can leach into molten Al through a displacement reaction [13], we incorporated a ZrO₂ face coat into the mold in the present work to act as an inert layer that



Figure 4. Mold after burnout showing a cracked core.

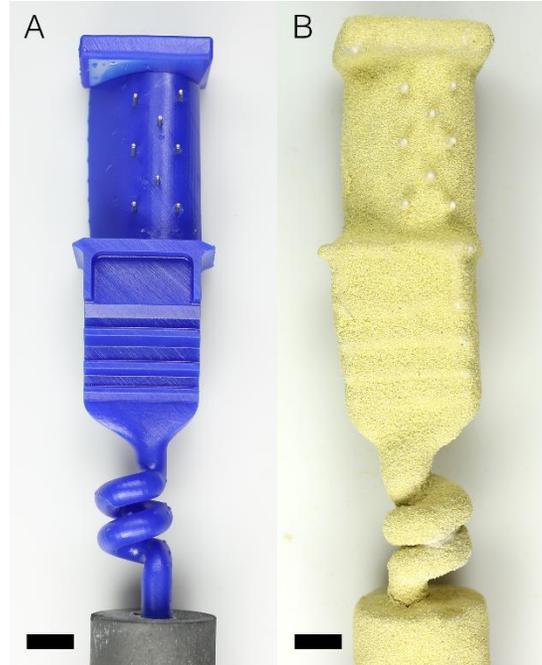


Figure 3. (A) Optical photograph of the assembled pattern (with grain selector printed directly onto the airfoil) inserted into graphite chill with internal ceramic cores. (B) The assembled pattern with ceramic shell face coat and steel pins holding the core in place. Scale bars are 1 cm.

prevents reactions between the molten metal charge and the mold. The ZrO₂ shell was made with a mixture of 325 and 50-100 mesh size ZrO₂ powders, as well as an acetic acid-based colloidal ZrO₂ binder. One part ZrO₂ binder was mixed with five parts 325 mesh ZrO₂ powder by weight and deaerated for ~3 hours in air. After applying this slurry to the pattern and the uppermost part of the chill rod, we coated the pattern with a coarser 50-100 mesh ZrO₂ powder. This ZrO₂ powder has a larger particle size that strengthens the shell mold and ensures the plaster investment backing media adheres to the shell surface. To ensure even coating and provide extra strength, we applied two layers of this shell mold. The first coat was cured in air

for 1 hour, then a second coat was applied using the same method. **Figure 3** shows a side-by-side comparison of the assembled pattern, including the graphite chill rod, before (**Figure 3A**) and after coating with slurry and stucco (**Figure 3B**). Once the second coat was cured, the pattern was inserted into a stainless steel flask and a plaster of Paris backing was added (38 parts deionized water, 100 parts Ransom and Randolph Plasticast powder). The investment was poured into the flask and allowed to cure for 30 minutes. The plastic positive was removed by heating in a burnout furnace to 823 K at a rate of 117 K/hr, then holding at temperature for 3 hours. Contrast in the thermal expansion coefficients of the pattern, steel pins, and ceramic core led to cracking during the subsequent burnout. To reduce this cracking, we replaced the steel pins with 0.127 mm diameter wire, but cracking was still observed. **Figure 4**, for example, shows a cracked core, some of which fell into the mold cavity.

3. Directionally solidified castings

After burnout, we cast A356 into the mold and directionally solidified the metal charge using a Bridgman furnace maintained under a vacuum of $\sim 5 \times 10^{-2}$ mbar. To ensure a steep temperature gradient within the melt, the graphite chill rod and the base of the stainless steel flask were placed in contact with a steel pipe held at room temperature. The furnace velocity and temperature were 1.27 cm/hr and 1023 K, respectively.

Figure 5 shows one directionally solidified casting of an A356 turbine blade with apparent incomplete filling of the mold near the trailing edge of the blade. This image also shows exposed fragments of the core, which remained intact during the burnout, casting and directional solidification steps. While this result highlights some of the challenges with growing directionally solidified components in molds made using this hybrid approach, the fine level of detail seen in the cores is an encouraging result. Further optimization of this process has the potential to produce viable molds, reducing the cost and lead time of producing single crystal turbine blades. Being a hybrid additive manufacturing process, this method combines an established additive manufacturing technique with the traditional methods of casting and directional solidification, and can replace the use of wax patterns seamlessly within the established manufacturing lifecycle. This approach circumvents many of the challenges with directly printing either the ceramic molds or the blades themselves, providing an accessible alternative to improve a complex manufacturing process.



Figure 5. Optical photographs of an A356 turbine blade showing dislodged cores. Both scale bars are 1 cm.

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