Development of a method for manufacturing ceramic tooling for precision casting of blades made of heat-resistant alloys using additive technologies

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Abstract. The technology traditionally used to produce castings of gas turbine engine (GTE) blades involves a large number of alterations, high labor costs due to the large amount of manual labor required, and complex and expensive equipment and tooling. This technology is only suited for large-scale production due to its use of expensive reusable metal molds. The ceramic shell mold for turbine cooled and uncooled blades can be manufactured more quickly and cheaply. This is especially important for fast hardware redesign and reconfiguration. This proposal describes an approach for producing a shell mold including with an internal rod using three-dimensional (3D) printing with refractory ceramic pastes that does not involve a lengthy and time-consuming process of designing and manufacturing forming equipment for the production of castings based on smelted models.

1. Introduction

The blades of a gas turbine engine are made of heat-resistant nickel alloy, which is difficult to machine [1]. Typically, gas turbine engine blades are cast in ceramic molds. However, this method is laborious and expensive, requiring the design and manufacture of new foundry molds, since it is impossible to use the foundry molds of the prototype [2, 3].

The process flow diagram for investment casting manufacturing includes the following steps:

1. Designing the casting blank in accordance with the drawing of the part and the technological allowances for machining;
2. Designing the casting model in accordance with the drawing of the casting blank, taking into account the shrinkage of the model composition and the melted alloy;
3. Manufacturing the casting model;
4. Designing and manufacturing detachable metal molds with machining methods;
5. Manufacturing the investment castings (pressing the model composition into the mold and extracting the model of the future casting after it has cooled and hardened in the mold);
6. Making the molds:
   - assembling several models to a riser in order to form a gate system,
   - forming a mold by coating the model assembly with a suspension, sprinkling it with ceramic powder, and then drying it (these operations are repeated up to 12 times),
   - removing castings from the casting mold,
drying the shell mold in an electric furnace at a temperature of 900–1000°C to remove residue from the investment mass lost by calcination;

7. Casting the blades (heating the casting molds, pouring them after melting, removing the cooled castings from the flask, removing the ceramic casting mold from their surface, separating the castings from the riser, and leaching the ceramic residues from the castings);

8. Controlling the geometric parameters and quality of the casting material.

The most laborious step is manufacturing the metal molds to obtain a shell and rod that simulate the channels of a cooled blade. For each new version of the blade, new metal molds must be manufactured. To achieve the required geometric dimensions are necessary next technology operations. Blanks of the metal molds usually are produced from the forgings, stamping or castings from the tool steels. Then the blanks must go through preliminary processing, machining on the CNC machines, locksmithing and heat treatment must be done. The blanks of the mold parts must be finished on metal cutting machines, and the most critical surfaces of the blanks of the mold parts must be fine-tuned with special machines or by methods of locksmithing dimensional processing, or methods of benchmarking. At last, control assembly, and molds testing.

Using the traditional technology for manufacturing GTE turbine blades, production takes 4–6 months. Automating some parts of the model design processes can reduce the time for metal molds production to 2 months [3]. However, necessity of the manual final processing of the profile of the working part of the blades, which is performed on special grinding machines with abrasive wheels without cooling, remains difficult. In addition, this method of manufacturing gas turbine engine vanes is only suitable for large-scale productions.

In contrast, the production process for shell molds can be shortened by replacing individual, time-consuming, and labor-intensive operations with three-dimensional (3D) printing of the molds [4], burnt or smelted models, or ceramic rods. With this approach, manufacturers can also directly shell the molds themselves.

Therefore, the manufacture of metal molds can be replaced by synthesis them from stainless steel powder using the selective laser melting (SLM) method [5–7].

The ceramic kernel for cooled blades can be manufactured using additive technologies. For example, stereolithography (SLA) involves the layer-by-layer curing of the ceramic paste with incomplete sintering at a temperature of 1300°C, the burning of the binder, annealing, and using the obtained rods in assembly with the models of the shell molds of the blade [8], as described above.

An interesting method for manufacturing ceramic molds for casting using silicone instead of metal molds for the wax models was proposed in [9]. The essence of the method is to grow a master model of the scapula, manufacture a silicone mold, pour wax into it, cover the wax with ceramics, and remove the wax. As a result, the cost and preparation time are reduced due to the exclusion of mechanical operations. However, the geometric accuracy is lower than with the standard approach.

Another method for manufacturing a ceramic tool that is integral to casting cooled turbine blades is being developed at the University of Michigan. Large area maskless photopolymerization (LAMP) technology [10, 11] directly produces complex ceramic cores and molds for casting blades according to computer-added design (CAD) file models using a selective layer-by-layer curing of the ceramic photocurable resins. The layers are formed by continuously projecting high-resolution ultraviolet raster images onto the resin layer. Then, the molds are subjected to heat treatment until the required state for the foundry is reached.
However, the resulting thick-walled ceramic injection molds are prone to cracking, which can lead to casting failures.

2. Modeling

In modern foundries, where the variety and complexity of issues related to the design and production of high-quality, accurate castings are significant, automation systems are becoming increasingly relevant for the design process and modeling of foundry processes. These systems ensure that the optimal and most economical technologies for the manufacture of castings are developed. The ProCAST system (USA) is one example. Using this system, it is possible to evaluate the quality of the gate-feeding system and the temperature-time parameters of the casting processes on a computer model based on a simulation of the thermal conditions of solidification of the casting.

The simulation is based on the finite element method (FEM) and consists of several stages: building a 3D electronic model of the casting taking into account allowances are applied, creating a gate-feeding system, building a grid for the electronic model of the casting, simulating mold heating and thermal processes during solidification, and forming macroporosity and microporosity in the casting. This work used the ProCAST system when modeling the ceramic shell of the mold for casting a blade.

If the ceramic equipment for casting blades is immediately made using 3D printing, most of the stages of traditional manufacturing castings can be removed. The developed ceramic shell equipment manufactured by 3D printing should meet the following basic requirements.

- The shell mold should be suitable for traditional methods of precision casting of heat-resistant nickel alloys;
- the shell mold material should be similar to the material (e.g., aluminum oxide or silicon oxide) used in the manufacture of ceramic tooling for the traditional precision method of casting turbine blades from heat-resistant nickel alloys;
- the density of the finished shell material should be about 85% to 99.6% of the density of the monolith of aluminum oxide (3.95 g/cm3) or silicon (2.65 g/cm3);
- the wall thickness should protect the shell from distortion in its shape, violation of its integrity, and damage during the casting process and subsequent cooling;
- the calculation of the dimensions should take into account the shrinkage of the model composition and the casting metal during cooling;
- the bending tensile strength of the material (at temperatures from 1300°C to 1350°C) should be at least 8–11 MPa;
- the shell mold should be easily removed by shock or hydraulic explosion without damaging the casting.

The design of a casting model is created on the base of the original CAD model of the blade, taking into account the metal shrinkage and machining allowances along the contact cavities. Then, a 3D shell model is created for 3D printing from the selected ceramic material in consideration of the requirements and limitations of the 3D printing technology, including shrinkage after annealing based on the choice of residual porosity and the strength needed to prevent cracking while heat-resistant nickel alloys are poured into the molds. At the same time, in the 3D model of the shell, a place for fastening to the model-foundry block is provided and the gate system is designed. Next, the design of the technological additive process is carried
out, which ensures that the shell mold is manufactured according to the specified geometric dimensions, density, and strength parameters.

Based on the model of an uncooled shrouded blade for the impeller of a small-sized turbine (Fig. 1a), a 3D model of the shell shape was developed with sufficient coverage for foundry shrinkage and machining allowances along the contact cavities (Fig. 1b).

![Figure 1. Models of the blade and shell mold: a) 3D model of the blade b) 3D model of the shell mold](image)

Places of this model have been identified where the removal of non-polymerized paste will be difficult. The 3D model has been optimized in accordance with the technological limitations and printing requirements of the CERAMAKER 900 equipment (Fig. 2). In particular, the following steps have been taken:

- the dimensions along the axes of the shell mold have been changed, taking into account the shrinkage of the material during sintering in a nitrogen furnace; to this end, the wall thicknesses in the profile part of the blade and scallops of the shroud have been reduced to 6 mm;
- conical-shaped technological holes (12 pcs.) have been designed in the scallops to allow for the effective removal of residues of unpolymerized paste.

![Figure 2. Optimized model of shell shape: a) 3D model of optimized shell shape, b) sectional view, c) location of holes](image)
3. Material and equipment for printing ceramic shell mold

For 3D printing the shell mold, any modern technologies for 3D printing with ceramic materials that can control the level of porosity, the hot and cold strength, and the accuracy and roughness specified by the requirements for casting will be suitable. These properties are possessed by ceramic stereolithography (ceramic SLA) printing technologies, as well as 3D printers based on Digital Light Projection (ceramic DLP) technology.

During the designing process, the porosity of the shell is determined by the properties of the main (external) material of the casting mold, allowing the shell to maintain its crack resistance while it is calcined and filled with molten metal. Pouring usually takes place at a temperature of ~1600°C with overheating of up to 80–100°C, a casting speed of up to 100°C/s, and a crystallization rate of 104–105°C/s.

It should be noted that shell molds without residual porosity would be preferable due to the high bending strength that would be obtained. However, residual porosity reduces the coefficient of thermal expansion, the elastic modulus of the shell mold, the tendency of the shell mold to crack during heat exchange, and the gas evolution as the metal is poured. Therefore, the manufacture of a ceramic shell mold with a porous structure is preferred. Production tests for pouring the molds of uncooled blades were conducted and proved the correctness of this approach. The shell molds withstood the load.

The most common material for producing ceramic shell molds and rods for casting turbine blades from heat-resistant Nickel alloys is electrocorundum, or aluminum oxide (Al₂O₃).

3D printing with ceramic materials is based on the layer-by-layer ultraviolet (UV) curing of a special paste, which is a mixture of photopolymer and ceramic powder.

In this work, 3DMIX Ceramic Paste ALUMINA, a ceramic material developed by S.A.S. 3DCeram-Sinto (France), was used to manufacture the shell molds (Table 1).

Table 1. Properties of aluminum oxide produced by 3D Ceram

| Property                               | Norm          | Value       | Designation |
|----------------------------------------|---------------|-------------|-------------|
| Density (g/sm³)                        | NF EN 623-2   | 3.9         | ρ           |
| Granulometric composition (μm)         | -             | 2-10        | D           |
| Microstructure                         |               |             |             |
| Composition:                           |               |             |             |
| • aluminum oxide Al₂O₃                 | 55-75%        |             |             |
| • the polymer of ethylene              | 45-25%        |             |             |
| • plasticizer                          | 5%            |             |             |
| The mechanical properties              |               |             |             |
| Vickers hardness (GPa)                 | NF EN 843-4   | 16.4        | HV1         |
| Fracture resistance (MPa·m⁴/²)         | -             | 4           | K₁C         |
| Elastic modulus (GPa)                  | NF EN 843-2   | 300         | E           |
| Shear modulus (GPa)                    | NF EN 843-2   | 145.4       | G           |
| Poisson ratio                          | NF EN 843-2   | 0.242       | ν           |
| Flexural strength (MPa)                | NF EN 843-1   | 400         | σ₁          |
To refine the technological process, samples were made from this material (Fig. 3), and then their physicochemical and mechanical properties were determined.

![Figure 3](image-url)  
Figure 3. Porous samples for testing for strength, density, roughness: a) The sample of 78 x 12 x 4 mm after printing, b) The sample of 50 x 12 x 4 mm

The thickness of the cured layer was set at 50 μm. The dimensions of the printing platform were 110x110 mm. The sample printing time was 4 hours. The binder removal took 72 hours. The sintering lasted 20 hours. The chemical composition of the prepared samples was 99.6%–99.8% Al₂O₃. The geometric accuracy of the samples was within 0.2 mm.

The tensile strength of the samples was determined by three-point bending at temperatures of 20°C and 1600°C. The results are presented in Table 2.

| №  | Length, Height, Width, mm | Porosity, % | Density, g/cm³ | Roughness, μm | Tensile strength in bending, MPa |
|----|---------------------------|-------------|--------------|--------------|--------------------------------|
|    |                           | 33.4        | 3.81         | 6.8          | T=20°C | T=1600°C |
| 1  | 78.19x4.00x12.00          |             |              |              | 48     | 14.2    |
| 2  | 78.20x3.95x12.00          |             | 3.82         | 6.4          | 49     | 14.5    |
| 3  | 50.20x3.95x12.00          |             | 3.95         | 6.6          | 50     | 14.8    |
| 4  | 50.19x4.00x12.00          |             | 3.94         | 6.4          | 50     | 14.7    |

The physicochemical and mechanical properties of the manufactured samples corresponded to the requirements for foundry ceramic molds.

4. Production of ceramic shell molds
The process of manufacturing ceramic shell foundry molds involves several stages: layer-by-layer curing of the ceramic paste; purification of the unpolymerized paste; binder removal in the oven; sandblasting; and solid phase sintering to obtain the required overall dimensions and level of residual porosity and control.

The specially designed shell molds were printed from 3DMIX Ceramic Paste ALUMINA on CERAMAKER 900 equipment using a developed process. Binder removal was carried out in an oven at ~600°C, and solid-phase sintering of the shell forms was undertaken at ~1700°C. Figure 4 shows a photograph of the manufactured ceramic shell molds for casting a shrouded blade.
Figure 4. Fabricated Ceramic Shell Molds

The total production time for the ceramic shell molds (excluding the modeling time) was 137.5 hours. Within 96 hours of being manufactured, the shell molds were cleaned (45 minutes per mold) and the binder was removed. After removal, the binder form was calcined at a temperature of 1300°C in a nitrogen oven for 20 hours to give the forms their final dimensions.

Non-destructive testing was carried out on a VT-600XA computed tomography scanner to control the geometric deviations of the internal cavities and to detect flaws in the manufactured shell mold. In addition, the shell molds were scanned with a step of 10 mm in the area of the locks and with a step of 7 mm in the profile part of the blade and scallops of the shroud. Figure 5 shows tomographic images of the sections of the ceramic shell shape.

Figure 5. Tomographic images of slices of ceramic shell form

5. Casting the blade

To test the synthesized ceramic molds during metal pouring, the molds were mounted on a manufactured gate-feeding system (Fig. 6a), where three layers of refractory slurry were applied and electrocorundum was sprinkled. The forms were attached in a standard way to a melting and casting machine UVNK-8P for casting by the directional crystallization method of high-temperature Nickel alloys. Then, the forms were calcined following a standard regime: stepwise heating to a temperature of T = 1100°C, holding for 7 hours, and cooling to 20–100°C with a furnace. The filling of the shell molds was the heat-resistant nickel-base alloy ZhS-32 at T3 = 1560°C. During pouring, the ceramic molds were not damaged. Figure 6b shows the results of the pouring.
Figure 6. Prepared molds (a) and castings (b)

Figure 7 shows the shrouded blade cast into a grown ceramic shell mold.

Figure 7. The shrouded blade obtained using the grown ceramic mold

An inspection of the blades revealed a characteristic defect of small castings: an underfilling of the thin cavities. Here, the elements were the scallops of the shroud.

In this case, this defect was caused by several factors:

- the minimum allowance for machining,
- the selection of protective ceramics and the number of layers applied,
- the filling of all shells in one mode,
- the inability to adjust the casting conditions and optimize the entire casting process, which is critically necessary for small-sized foundry products.

In addition, the modeling of the shell mold was carried out according to the model of the blade, not the model casting. Some surface roughness defects were due to a delamination of the first cladding layer. Subsequent machining will easily eliminate these defects.

6. Casting control

Non-destructive testing using a GE vTomex M300 computed tomography scanner detected the defects in the manufactured castings. Scanning was carried out with a micrometric resolution at a temperature of 22°C, a humidity of 48%, and an atmospheric pressure of 747 mm Hg.

Figure 8 shows a 3D image of the casting of the blade that was obtained by x-ray computed tomography.
Several defects related to the machining allowance were found. Subsequent finishing operations will remove these defects. The nature of the defects suggests that they appeared as a result of ceramic fragments entering the mold as the mold was prepared for casting.

In the future, in order to avoid defective castings, it will be necessary to refine the preparation of the shell mold before it is filled with metal.

7. Summary

This proposal described a method for manufacturing ceramic tooling using 3D printing with refractory ceramic pastes. In regards to the technological process for manufacturing ceramic shell molds, this method can solve a number of problems concerning porosity and strength that are caused by insufficient resistance crack resistance during the pouring of liquid molten metal and subsequent cooling.

Using uncooled blades as an example, models, technological processes, and ceramic shell molds were developed. A trial casting of an uncooled blade was performed that produced satisfactory results. The main design, the technological problems in the design, and the technological processes for manufacturing the ceramic shell molds were described. In addition, solutions to the problems were outlined.

Thanks to this approach, all of the production stages for manufacturing foundry accessories can be integrated into a single technological process without any pre-staging operations, and significant economic benefits can be realized.
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