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Rapid Prototyping Technology for Manufacturing GTE Turbine Blades

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Abstract. The conventional approach to manufacturing turbine blades by investment casting is expensive and time-consuming, as it takes a lot of time to make geometrically precise and complex wax patterns. Turbine blade manufacturing in pilot production can be sped up by accelerating the casting process while keeping the geometric precision of the final product. This paper compares the rapid prototyping method (casting the wax pattern composition into elastic silicone molds) to the conventional technology. Analysis of the size precision of blade casts shows that silicon-mold casting features sufficient geometric precision. Thus, this method for making wax patterns can be a cost-efficient solution for small-batch or pilot production of turbine blades for gas-turbine units (GTU) and gas-turbine engines (GTE). The paper demonstrates how additive technology and thermographic analysis can speed up the cooling of wax patterns in silicone molds. This is possible at an optimal temperature and solidification time, which make the process more cost-efficient while keeping the geometric quality of the final product.

1. Introduction

Blades are one of the most massive and high-loaded parts of GTU and GTE [1,2]. They face higher requirements for geometric precision and surface quality. Due to the lack of developed surfaces for precise basing, one of the most efficient ways (and sometimes the only possible way) to make such blades is the casting of heat-resistant nickel alloys into ceramic molds. Turbine blades are mostly machined by grinding [3], which enables manufacturers to meet high precision and surface roughness requirements [4]. Another, and the most expensive way to machine heat-resistant alloys is dimensional electrochemical machining [5-7]. Making geometrically complex parts by investment casting implies making workpieces with zero stock removal for the airfoil profile and the inner surfaces. Laser melting of heat-resistant composition powders has competitive advantages over casting technology [8]. The main process component that determines the final geometric precision of casting is the wax pattern making process; such models can be produced differently: by using metal [8], FDM [9], or elastic silicone forms [10]. wax pattern making parameters such as casting time, solidification time, and casting temperature are crucial. Thus, controlling these parameters helps avoid defects related to dimensional deviations. One of the biggest disadvantages of investment casting is its high general costs. This is due to the necessity of special machinery, heat-resistant binding materials, and the labor intensity of making molds. Besides, making the metal molds for wax casting is time-consuming. Given all the problems of pilot and small-batch multiple-item manufacturing, making wax patterns for

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turbine blades conventionally by using metal molds seems to be a very long and costly process as well. This is why the authors believe the rapid prototyping technology to be promising, as it reduces costs and simplifies the process. Fast prototyping is primarily discrepant from the classical approach in the following:

– far lesser mold costs and production time values (usually five times less);
– far less usage cycles compared to metal molds.

Fast prototyping is more cost-efficient when one has to make small batches of wax patterns for investment casting [10]. Silicone molds are usually made by using a 3D-printed master pattern. The paper describes the development and use of this technology for making geometrically complex and highly precise products for the aerospace industry. The method can be used for making wax turbine-blade models using silicone molds for subsequent investment casting. The goal of the research is to show how rapid prototyping can be used at a manufacturing facility to make geometrically complex castings of required precision and surface quality.

2. Materials and methods

A blade of an auxiliary GTE power unit turbine was chosen as the object of study. Such blades are made of nickel-based heat-resistant alloy. Table 1 describes the chemical composition of the alloy.
The manufacturing process is staged as follows [11,12]:

– 3D modeling in CAD with due account of shrinkage and stock to be removed when polishing the inner surfaces of the blade;
– growing the master pattern;
– making a silicone mold;
– making wax patterns in the silicone mold;
– assembling the wax patterns using a sprue system (SS);
– applying refractory ceramics and removing the wax;
– casting metal into the ceramic shell;
– removing the SS.

Table 1. Chemical composition of the heat-resistant alloy

Elements	% content	Elements	% content
Ni	Base	C	0.13÷0.20
Cr	9.5÷12.0	Si	≤0.4
Al	5.0÷6.0	Mn	≤0.4
W	4.5÷5.5	B	≤0.02
Co	4.0÷5.5	Ce	≤0.015
Mo	3.5÷4.8	S	≤0.015
Ti	2.5÷3.2	P	≤0.015

3. 3D model design

When making the master pattern, it is first 3D-modeled with due account of all the drawing-specified technical requirements. The master pattern was built in Siemens NX, a CAD/CAM/CAE package [13]. The authors first formed 2D section profiles, then built their corresponding surfaces that pass through such profiles. One of the obvious advantages of the design process is that when modeling, one can take into account all the stock to be removed in machining, as well as the shrinkage of all the components, i.e.:

– the shrinkage of the wax casting after cast into the silicone mold; this shrinkage depends on the wax in use.
– the shrinkage of the heat-resistant alloy when solidified in the ceramic mold.
– the shrinkage of the ceramic mold itself.

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The shrinkage factor was determined based on the following dependencies:

$$Lw=Lm - Lm\cdot\beta = Lm \cdot (1 - \beta)$$

$$Lb=Lw - Lw\cdot\alpha=Lw\ (1 - \alpha) = Lm \cdot (1 - \alpha) \cdot (1 - \beta)$$

$$Lb=Lm - Lm \cdot (\alpha + \beta) - Lm \cdot \alpha\beta$$

where α is the metal shrinkage factor, β is the wax pattern composition shrinkage factor, Lw is the overall dimension of the wax pattern, Lb is the overall dimension of the cast blade, Lm is the overall dimension of the model.

Given the low values of α and β, the product Lм $\cdot\alpha\beta$ can be deemed negligibly small. Thus, the correction factor for the master pattern is the sum of wax and metal shrinkage factors. When using the heat-resistant alloy per Table 1 as well as the wax pattern composition, α = 0.5% and β = 1%. One should keep in mind that this formula ignores the ceramic mold shrinkage, which is approximately 0.1%. Thus, total shrinkage factor equals 1.5%. 0.2 mm of stock is to be removed when polishing the inner surfaces of the blade.

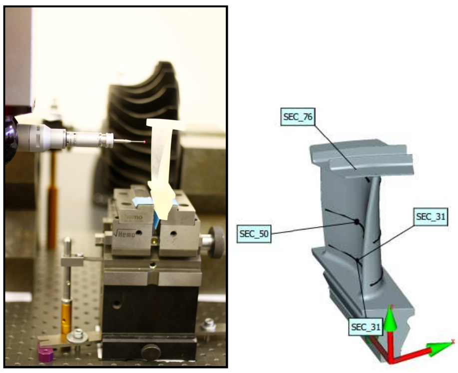
4. Making the master pattern

Fast prototyping quickly and easily produces a 3D physical object based on the 3D CAD model. 3D printer Objet Eden 350 made this master pattern from a photopolymer by means of layer growth. PolyJet-grown products have the following advantages: 3D-model-based production of parts is fast, and such parts can be made large enough. One notable con is the high roughness of the prototype surface.

Before silicone molds were made, the geometry of the master pattern were checked using a DEA GLOBAL Performance coordinate-measuring machine at 20 °C ± 2 °C and a relative humidity of 80%. To control the geometry, the authors used the PC-DMIS CAD ++ Ver. 4.3 MR1 software package.

The master pattern was fixed on the CMM table with a grip at the blade root trim surface, see Figure 1a. Basing was done at the root surfaces. Coordinate location per the 3D model of the workpiece. The master pattern airfoil was measured in three sections, sec_31, sec_50, sec_76, see Figure 1b, which are located 31 mm, 50 mm, and 76 mm away from the blade sole per the 3D model.

As Objet EDEN 350 cannot reach an airfoil profile roughness Ra =1.25…2.5 µm. When modeling, the authors added 0.2 mm of stock to the inner surface and the airfoil of the blade to be removed in polishing. To make wax patterns and metal castings of required precision and roughness, the authors added a master pattern polishing operation to the process. 3D-printed master pattern had a roughness Ra = 3.2 µm, see Figure 2b, whereas design documentation requires an airfoil profile surface roughness Ra=1.6 µm.



a b

Figure 1. CMM measurements of the master pattern

Airfoil and inner surface polishing was done manually in multiple runs. In the first run, the authors removed the initial layer using a P1200 sandpaper; for every consecutive run, finer sandpaper was used until they reached a fineness of P2500. After the airfoil and the inner surfaces were polished, the authors checked the surface roughness using a Hommel-EtamicTesterW55 profilograph, whereas geometry was controlled using the CMM (see Figure 2a). When the master pattern matches the design

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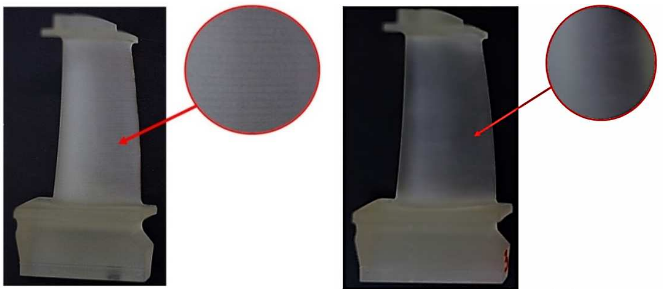
requirements in terms of geometry and roughness, the next step is to make silicone molds and wax patterns.



a b

Figure 2. Master patterns: a - before polishing, Ra 3.2;
b - after polishing, Ra 1.25

According to the authors' checks, the master pattern made matched the requirements for airfoil profile geometry deviations. The deviations did not exceed the allowance of +0.2 mm -0.15 mm.

5. Making an elastic silicone mold

After the sprue system was fully assembled, the authors began making a silicone mold. The first stage for that is to assemble a Plexiglas container for the master pattern. The container is filled with silicone, vacuumed and placed in a climatic cabinet to solidify, where it is kept for 4 hours at 40°C. The chemical reactions thus triggered result in the solidification of the mold. After the mold is fully solidified and cooled down, the Plexiglas container is disassembled along the joint lines, and the master pattern is taken out. The mold is then assembled, and wax is liquated and vacuumed in a vacuum chamber; it is then cast into the silicone mold. After the wax solidifies, the mold is disassembled, and the finished wax pattern is taken out. A silicone mold can survive about 80-100 castings depending on the geometric complexity of the pattern. This process is significantly cheaper than conventional mold making.

The precision of the wax pattern depends on the casting parameters, i.e. the melting temperature, the exposure time, and the mold temperature. The casting temperature and the exposure time are more important for dimension-related precision. Exposure time must be selected based on the cooldown rate, the wax pattern shape, and the wax composition casting temperature. As a part of this thermographic experiment, the authors studied the effect of exposure time and casting temperature on the shrinkage and the final geometric precision of the wax pattern, with a goal of optimizing the casting parameters. For that purpose, the authors did a series of test castings. Casting was done at various temperatures. Silicone molds were cooled down by forced cooling (blowing) and without it. Thermographic experiment results showed that when using forced blowing, the wax pattern in a silicone mold cools down to room temperature in 2.5 hours; without forced cooling, it takes 4 hours, or 1.7 times more time, see Figure 3.

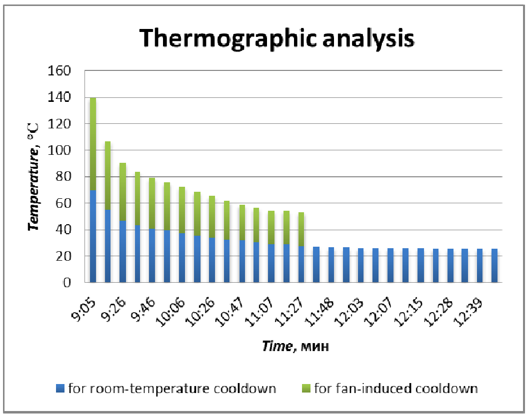


Figure 3. Thermographic analysis of the silicone mold cooldown

Forced blowing of the silicone molds resulted in lesser shrinkage of the wax pattern. To sum up, it should be noted that forced blowing is necessary for saving time when making a single wax pattern with lesser shrinkage.

CMM was then used to measure the inner surfaces of the wax patterns made; the procedure was the same as for the master pattern. The model was checked for shape and surface positions relative to the blade root.

Figure 4 shows the blade airfoil profile control process by measuring the drawing-specified sections with a CMM.

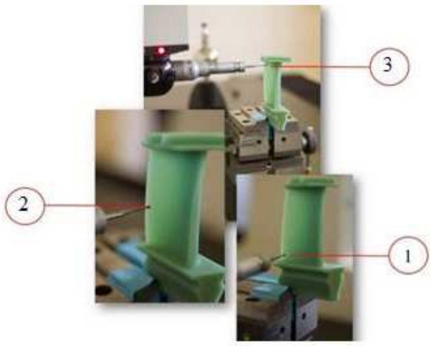


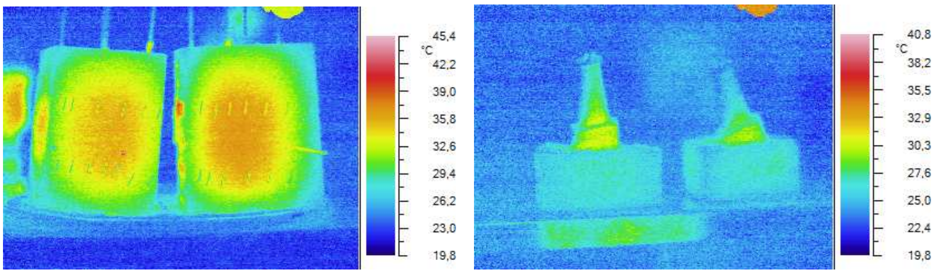
Figure 4. CMM measurement of the wax pattern

Table 2 specifies maximum errors in the airfoil profiles of the wax pattern relative to the master pattern depending on the wax composition casting temperature.

Table 2. Maximum error

# of section	**Section 1**	**Section 2**	**Section 3**	**Section 1**	**Section 2**	**Section 3**	**Section 1**	**Section 2**	**Section 3**	**Section 1**	**Section 2**	**Section 3**
°C	95 °C			100 °C			105 °C			110 °C		
Total error, mm												
Max	0.25	0.29	0.25	0.64	0.64	0.90	0.84	1.13	1.46	1.06	1.2	1.73

According to the data in Table 2, casting at a temperature of 95°C results in the least shrinkage-related dimensional deviations. As the upper parts of the blade have less stock and are thinner, they cool down faster. A shrinkage cavity emerges in the blade root as it is the most massive part of the wax pattern. The emergence of the shrinkage cavity is confirmed by wax pattern measurements and is compensated by the implied removal of stock in subsequent machining at the modeling stage, see Figure 5.



a b

Figure 5. Cooldown thermography: a - at the onset of cooldown; b - when the wax pattern is removed from the silicone mold

Based on the results of these experiments, the authors have optimized the following parameters of casting wax into silicone forms: cooldown (the best option is forced blowing), exposure time (2.5 hours), and casting temperature (95°C).

6. Ceramic mold making and casting

Wax patterns produced were assembled into casting blocks, 4 patterns per block. The sprue system (SS) components were designed using ProCast software per the methodology described in [14]. Casting blocks were cast using the conventional investment casting technology [15-21].

7. Economic comparison of wax pattern making technologies

To analyze the cost and time of making wax patterns by rapid prototyping and by using metal molds on a CNC machining center, the authors calculated time consumption, see Figure 3.

Table 3. Comparison of GTE blade wax pattern production methods

Name	Making wax patterns by additive technology	Making wax patterns by conventional technology
Prototype printing	7807.27	-
Making a mold	13964.2	58011
Making wax patterns	239532.5	237950
Total time	10 days	30 days
Total	265029.98	295961

8. Results

DEA Global Performance was used to measure 220 wax patterns and castings. Analysis of data obtained by comparison to the 3D model showed that the blade geometry and the airfoil twist angle were within the allowed range.

The authors have determined the optimal conditions for casting wax into silicone molds and for making wax patterns.

Silicone molds can be used to make geometrically complex wax patterns for multiple-item small-batch or pilot manufacturing, thus eliminating the need for CNC production of metal molds.

9. Conclusions

Fast prototyping is a cost-efficient solution for small-batch manufacturing of GTE blades. Silicone molds have a number of advantages over the conventional technology, mainly faster production and lower costs. Studies have shown that silicone molds can be used to make blades as they provide necessary accuracy. However, the conventional metal-mold technology is still better for large-scale manufacturing as metal molds survive longer and have a greater output rate

References

[1] Xu Z, Chen X, Zhou Z, Qin P and Zhu D 2016 *18th CIRP Conf. on Elec. Phys. and Chem. Mach. (ISEM XVIII).* **42** 125-130

[2] Shimanov A A, Dovgyallo A I 2017 Possibility of using pulse turbine usage in compressor technology. *AIP Conference Proceedings* 1876

[3] Khaimovich A I, Skuratov D L 2017 New damage criteria for machining considering contact friction for FE analysis. *Key Engineering Materials* **736** 147-152

[4] Skuratov D L, Fedorov D G 2017 Temperature fields in grinding by abrasive wheels. *Russian Engineering Research* **37 (6)** 557-560

[5] Qi J, Zhang D, Li S, Chen B, Qi J 2017 Modeling of the working accuracy for robotic belt grinding system for turbine blades. *Advances in Mechanical Engineering* **9(6)**

[6] Smirnov G V, Pronichev N D, Nekhoroshev M V 2017 Effect of technological heredity on the fatigue strength in the manufacture of gas turbine engine blades. *IOP Conference Series: Materials Science and Engineering* **177 (1)**

[7] Nekhoroshev M V, Pronichev N D, Smirnov G V 2014 Computer simulation of high-speed anodic dissolution processes of geometrically-complex surfaces of GTE details. *Open Mechanical Engineering Journal* **8** 436-440

[8] Smelov V G, Sotov A V, Agapovichev A V 2016 Research on the possibility of restoring blades while repairing gas turbine engines parts by selective laser melting. IOP Conference Series: Materials Science and Engineering **140 (1)** 012019

[9] Gorski F, Kuczko W, Wichniarek R, Bun P, Szymanski P 2017 *Application of polystyrene prototypes manufactured by FDM technology for evaporative casting method. MM Science Journal.*

[10] Vdovin R A, Smelov V G 2017 Design and optimization of the micro-engine turbine rotor manufacturing using the rapid prototyping technology. *IOP Conference Series: Materials Science and Engineering* **177 (1)**

[11] Budzik G 2007 Possibilities of using vacuum casting process for manufacturing cast models of turbocharger impeller. Journal of KONES Powertrain and Transport **14(3)** 125-130

[12] Agapovichev A V, Balaykin A V, Smelov V G 2015 Application of additive technologies in the production of aircraft engine parts. *Modern Applied Science* **9(4)** 151-159

[13] Balaykin A V, Bezsonov K A, Nekhoroshev M V, Shulepov A P 2017 Developing parametric models for the assembly of machine fixtures for virtual multiaxial CNC machining centers. *IOP Conference Series: Materials Science and Engineering*

[14] Vdovin R A, Smelov V G, Pronichev N D, Bolotov M A 2016 Paths of improving the technological process of manufacture of GTE turbine blades. *Innovative Technologies in Engineering.* **142** 1–8

[15] Shimanov A A, Biryuk V V, Sheludko L P, Shabanov K Y 2017 Gas-turbine expander power generating systems for internal needs of compressor stations of gas-main pipelines. *AIP Conference Proceedings* 1876

[16] Gell M 1980 The development of single crystal superalloy turbine blades. *Superalloys* **1** 205–214

[17] Szeliga D P, Burbelko A, Motyka M 2014 Modeling of directional solidification of columnar grain structure in CMSX-4 nickel-based superalloy. *Materials Engineering and Performance.* **23 (3)** 1088–1095

[18] Szeliga D P, Kubiak K, Sieniawski J 2015 *The unidirectional crystallization of metals and alloys (turbine blades). The faculty of mechanical engineering and aeronautics department of materials science* (Rzeszow University of Technology, Polish)

[19] Takeshi N, Takeshi O, Kuniyuki I 2014 Development of CMC turbine parts for aero engines. *Engineering Review* **47 (1)** 29–32

[20] Zhou Y Z, Volek A, Green N R 2008 Mechanism of competitive grain growth in directional solidification of a nickel-base superalloy. *The Minerals, Metals & Materials Society*. **56 (1)** 2631–2637