Study of FDM technology applications in the casting production of GTE details

A V Balyakin, R A Vdovin* and R R Kyarimov
Samara University, 34, Moskovskoe sh., Samara, 443086 Russia

*vdovin.ssau@gmail.com

Abstract. FDM is an additive manufacturing technology that can be effectively used to make investment casting models. This method is considered economical in a single production, since it does not require the manufacturing of expensive equipment. However, the roughness of models surface made by FDM printing is significantly lower than wax models obtained by traditional way - using metal and elastic silicone molds, that ultimately affects the roughness of castings. In this work, was studied the use of FDM printing technology for materials: REC CAST, PVA and Wax3D from company the "Filamentarno!", used in molds to obtain models, as well as a combined method for wax models production. FDM printing technology is especially suitable for producing models with internal channels and cavities through the use of water-soluble support materials.

1. Introduction
Additive manufacturing (AM), also known as 3D-printing, the process of adding layer by layer material to produce a product using a three-dimensional model, an alternative to traditional subtractive production methods. Over the 40-year period of the AM development, many new AM processes have been appeared, that used in aerospace, automobile, biomedical, digital technology, architecture, design, etc. [1]. In recent years, there has been an exponential increase in AM technology, and continues to grow due to its flexibility and low cost for rapid prototyping. All these characteristics, combined with the ability to manufacture complex structures and geometry, with a resolution of up to a micrometer, have helped AM grow into a multi-billion dollar industry [2, 3].

FDM is an additive manufacturing technology that creates layer by layer parts, by heating and extruding a filament. This is an effective process for creating parts from conceptual models to producing parts in a short time [4, 5]. The economic effect of using FDM technology is the lack of need for the production of the metal mold necessary to obtain a wax model. It is advisable to produce a metal mold with a serial nature of production and impractical for single and piece production. For example, the manufacture of individual parts while design iterations, prototyping and functional testing. In addition, to make any changes in designing, each time a new metal matrix is required, that again increases the cost and time. On the other hand, using FDM printing technology, any design changes can be easily adapted by simple 3D model changing.

Using REC CAST and Wax3D materials, prototypes with a high degree of detail and low ash content can be created (0.1% for REC CAST and 0.01 for Wax3D from Filamentarno!) [6, 7]. To create parts with complex geometry, especially internal channels and cavities, two types of materials are required: a supporting material acting as a base, which will constitute the final part or prototype
and support material. The equipment used in this work allows the use of several materials simultaneously, due to which it is possible to use easily soluble material to support [8].

Support materials FDM act as a frame to support the object during printing. Currently, either the same material or a water-soluble auxiliary material is used for this that can be removed by soaking the product in an aqueous or water-soluble solution. Now, more attention is paid to PVA-based materials for 3D printing use. PVA is the most popular water-soluble and biocompatible synthetic polymer with high tensile strength, flexibility, and a high barrier to oxygen penetration [9, 10].

2. Experimental
To conduct research, object of study must be selected. First of all, the part must be used in real production and since its design must be modified, at the same time it must be suitable for mass production. In addition, the complexity of the mold was considered to easily remove the wax model from the mold. Considering all these factors, the piping detail of the gas turbine engine NK-36 was selected (figure 1).

For manufacturing a physical master model on the FDM printer, 3D models were created in the NX software from Siemens, considering shrinkage of materials. After that, all 3D models were converted to STL format. It should be noted that the actions described above are not a production part. From the point of view of commercial application, this action template, preparation of the master model described for the FDM technology can be used for many other processes, such as vacuum molding, vacuum casting, lost-wax casting, etc [11]. The purpose of the study is to understand whether the models obtained by FDM technology have the required quality parameters for their further use in gas turbine engine manufacturing and other industries. The input parameters for this study are: model material; support material, technology for obtaining a wax model, manufacturing cost, manufacturing time and productivity – dimensional accuracy and roughness of manufactured samples.

3. Materials and equipment
3D printer RAISE 3D N2, that has a double extruder and a building area of 305 x 305 x 305 mm. Printer case is completely closed, that allows you to adjust the temperature during printing. The table can heat up to 110 °C. The diameter of the nozzle is 0.4 mm, the temperature of it can reach 300 °C.

To measure the roughness parameters on the fabricated parts, we used a Hommel profilograph – EtamicTester W55, using the contact probe method [12-14].

After the master models fabrication, support material was removed. External measurements of linear dimensions of the samples were carried out using MK smooth micrometers with a measurement range of 0–25, 50–75, and 75–100, having a division value of 0.01 mm and an allowable error of ± 0.004 mm [15].

Material from the company REC CAST plastic - a material based on polymethyl methacrylate with the addition of special plasticizers. The material is specially prepared for printing objects used in
casting on burnable models, the mass fraction of ash is less than 0.1% of the mass of the printed object when it is burned at a temperature of 405 °C. The main parameters of printing on a 3D printer RAISE 3D N2: nozzle temperature 235 °C; table temperature 110 °C; blowing is not recommended [16].

REC PVA – REC polyvinyl alcohol. Solid, colorless, non-toxic substance, odorless, it is recommended to use for printing auxiliary structures in objects with complex geometry, which can then be easily removed. The main printing parameters: nozzle temperature 205 °C; table temperature 70 °C; blowing is desirable [17].

WAX3D from the company "Filamentarno!" – wax for printing on 3D printers using FDM technology for subsequent investment casting from metals. Models printed by this wax may be subjected to post-treatment in the burner flame or polished with a solvent to smooth the layers and give gloss. Extremely low ash content (less than 0.01%). The main printing parameters: nozzle temperature 130 °C for the first layer, 110 °C for subsequent layers; table temperature 105 °C for the first layer, 0 °C for subsequent layers; airflow is extremely desirable.

The results of study were: dimensional accuracy and surface roughness of fabricated master models; manufacturing cost; production time and performance.

In the experiment, 3 exemplars of the part were made of CAST plastic and WAX3D. The so-called rods were also made of PVA material, which exactly repeat the surfaces of internal channels and component cavities. All printed models were tested for dimensional accuracy and surface roughness in two directions (figure 2).

![Figure 2. Surface and dimensional measurement scheme.](image)

Tables 1 and 2 present the results of size and surface roughness measurement of models and rods. Printed rods were used in the technology of manufacturing wax models using elastic silicone molds. This method of using 3D-printed water-soluble rods made of PVA material is being applied for the first time. The scheme for measuring the dimensions and roughness of printed rods from PVA material is shown in figure 3.

The surface roughness of the obtained wax models, FDM printing and the combined method, cannot be measured using the probe method using a Homemel – EtamicTester W55 profilograph. In investment casting, the surface roughness of wax model is inherited by the metal casting. The castings roughness measurement showed that it does not exceed $Ra = 0.69 \, \mu m$ for the combined method and $Ra = 1.86 \, \mu m$ for the wax model printed on FDM printer, with an allowable roughness according to the drawing castings $Ra = 3.2$ microns.

The cost estimate and manufacturing time of three models from each material are given in table 3.
Figure 3. Rod configuration and size and surface roughness measurement scheme.

Table 1. The results of the model size measurement in mm.

| №  | A   | B   | C   | D   | E   |
|----|-----|-----|-----|-----|-----|
| 1  | 61.20 | 22.44 | 7.14 | 20.40 | 12.00 |
| 2  | 61.00 | 22.00 | 7.00 | 20.00 | 12.00 |
| 3  | 61.23 | 22.51 | 7.4  | 20.41 | 11.95 |
| 4  | 61.25 | 22.53 | 7.5  | 20.45 | 11.75 |
| 5  | 61.26 | 22.90 | 7.5  | 20.46 | 11.73 |
| 6  | 61.19 | 22.46 | 7.15 | 20.41 | 11.98 |
| 7  | 61.22 | 22.47 | 7.14 | 20.42 | 12.05 |
| 8  | 61.21 | 22.46 | 7.14 | 20.40 | 12.02 |
| 9  | 61.05 | 22.40 | 7.16 | 20.40 | 12.05 |
| 10 | 61.08 | 22.37 | 7.15 | 20.30 | 12.10 |
| 11 | 61.06 | 22.39 | 7.15 | 20.30 | 12.06 |
| 12 | –     | –     | –    | –    | 12.05 |
| 13 | –     | –     | –    | –    | 12.10 |
| 14 | –     | –     | –    | –    | 12.06 |

Table 2. The results of models roughness measurement Ra, μm.

| №  | A   | A*  | B   | C   |
|----|-----|-----|-----|-----|
| 1  | 0.90 | 0.87 | 0.95 | 1.23 |
| 2  | 0.85 | 0.85 | 0.84 | 1.03 |
| 3  | 0.84 | 0.84 | 0.83 | 0.99 |
| 4  | 0.84 | –    | –    | –    |
| 5  | 0.80 | –    | –    | –    |
| 6  | 0.83 | –    | –    | –    |

A* – roughness of the inner channel
Table 3. Estimation of the cost and production time of models.

| №  | Material, g | Time, h min. | Cost, rub. | Reference |
|----|-------------|--------------|-----------|-----------|
| 1  | 72.40       | 12h 00 min   | 868.80    | CAST      |
|    |             |              |           | With support material |
| 2  | 84.20       | 16h 10 min   | 1263.00   | WAX3D     |
|    |             |              |           | With support material |
| 3  | 17.70       | 2h 55 min    | 212.40    | PVA rods  |
|    |             |              |           | Combined method with remote PVA rod |
| 4  | 60.00       | 7h 35 min    | 850.00    | Given the cost of manufacturing an elastic silicone mold |
|    |             |              |           | Final combined method |
| 5  | 77.70       | 10h 30 min   | 1062.40   | Three wax model |

4. Results and discussion

The surface roughness of the manufactured models based on FDM printing is about 0.85 μm (Ra), confirming acceptable quality for most parts in industry. For the data from table 1, a statistical analysis was carried out for the nominal sizes A, B, C, D and E to analyze the capabilities of the process. As analysis of size E showed, for a Cpk value of 1.5, the area under the normal curve is 0.999993198. Similarly, the values of Cp and Cpk were calculated for other measurements (A, B, C and D). The Cpk value for all sizes is > 1.33. The results of the study suggest that the FDM process is in the range of ± 4.5 sigma (σ), with regard to the dimensional accuracy of the plastic component.

5. Conclusions

Based on the results of experimental studies confirmed by manufactured models using FDM technology, the following conclusions can be drawn:

- dimension tolerance of the parts fabricated on a RAISE 3D N2 3D printer and models made using casting in flexible silicone molds correspond to the allowable deviation range in accordance with ISO UNI EN 20286-I (1995), as well as in accordance with DIN16901;
- FDM is a highly efficient process as RDPM solution. It is noted that the “Cpk value” for all five critical measurements in this study is > 1.33. Since Cpk values of 1.33 or more are considered industry standards, this process will produce valid models while it remains in statistical control;
- a new combined method for obtaining the wax models with internal channels and cavities was developed and tested;
- the cost, production time and productivity of each methods presented and described in this work were estimated.

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