APPLICATION OF POLYSTYRENE PROTOTYPES MANUFACTURED BY FDM TECHNOLOGY FOR EVAPORATIVE CASTING METHOD

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The paper describes possibilities of using additive manufacturing technologies to manufacture single use casting tooling. The foundries usually cooperate with pattern workshops, which manufacture tooling using conventional processes. In case of patterns of complex shapes, it translates into higher costs and longer time of production. An alternative can be use of additive manufacturing (3D printing), proposed by the authors. The additive manufacturing allows to manufacture complex shapes as quick and cheap as simple shapes, being more fit for the more demanding patterns. The studies performed in this paper were aimed at determination if it is possible to effectively manufacture polystyrene (HIPS) patterns using the low-cost machine working in Fused Deposition Modelling technology and use them directly to manufacture castings out of GJS500-7 cast iron in the investment (burnt pattern) casting process. The paper presents examples of products that can be manufactured this way and also shows problems that appeared during the manufacturing processes.

KEYWORDS

fused deposition modeling, evaporative casting, Rapid Tooling, 3D printing

1 INTRODUCTION

The Additive Manufacturing Technologies (AMTs), widely known under the name of 3D printing, are more and more widespread in various industry branches. They have become a crucial tool, allowing the companies to significantly reduce time of preparation of a product for manufacturing, which results in a significant reduction of costs of implementing a new product into market. Among many advantages of the AMTs, the most important are: lack of need for manufacturing of special tooling, manufacturing directly from the digital CAD model, wide range of available devices and applied materials (ceramics, plastics, waxes, metals) [Kuczko 2015].

Among many AMT methods, the Fused Deposition Modeling is one of the most widespread and globally available technologies. The reason for this is a relatively low cost of buying and using a machine for production, as well as a non-complex and eco-friendly process (odorless and non-toxic material, minimal waste volume, low energy consumption). The mechanical properties of the FDM products are good enough to use them as visual or concept prototypes, mock-ups or design aids. In case of production of short series of products or functional, often strength of the FDM-made products is not satisfying [Nouri 2016, Gorski 2014].

A final product manufactured using the Fused Deposition Modelling technology can be characterized by some coefficients, which are influenced by many factors [Gorski 2015, Gajdos 2013]. Each set of the process parameters: orientation of the product in the working chamber, layer thickness and method of filling of the layer contour, will make the part structure look different, which will result in different values of coefficients such as weight, strength, accuracy or surface quality [Nidagundi 2015, Zeleny 2014]. In the modern software for 3D printing process planning, these parameters can be changed almost at will, giving many possibilities of obtaining various products for different applications, such as visual prototyping, rapid tooling preparation and many more.

Foundries are production plants which have a very high need for functional prototypes, especially if it comes to specialization in short series of individualized castings. Manufacturing of special tooling through conventional machining is very costly and is economically ineffective in many cases. An alternative is manual prototype production by experienced model-makers. Disadvantage of this method is an insufficient accuracy of obtained models and time consumption. That is why foundries are constantly looking for new solutions. The research work focused on possibility of application of Rapid Prototyping or Rapid Tooling techniques (utilizing the AMTs) in foundry are conducted widely in the world [Hanus 2011, Nyembwe 2012]. However, applications of prototypes made with the FDM technology are usually limited patterns for making silicone molds, which are further used to cast wax models for the investment casting [Cheah 2005. Agapovichev 2015]. As the FDM technology gets less and less expensive, there are attempts at using available materials, such as PLA and ABS, as single-use patterns for sand molding [Olkhovik 2013]. It was also found in recent studies, as in [Kumar 2015], that FDM can be used to manufacture patterns for investment casting process and that allow obtaining castings of accuracy acceptable as per the international tolerance grades. The sintering additive technologies can be also used for direct metal parts manufacturing, obtaining similar quality as using the regular casting methods [Atzeni 2015].

Evaporative casting is a special investment casting method, where a single-use, lightweight pattern, usually made out of polystyrene foam, is used to build a ceramic mold, usually out of quartz sand. The pattern is removed by burning, which occurs during pouring of a liquid metal [Birkel 1988]. This method of casting is often used when there is a need of manufacturing of a small series of products of complex shapes – as patterns are of single-use and they are never removed out of the molding sand as a whole, there is no need to consider typical molding limitations.

Additive manufacturing processes have not been extensively used in assistance of evaporative casting processes, however certain examples can be found, e.g. using a Selective Laser Sintering to obtain a pattern out of HIPS material [Yang 2008] or laser sintering to manufacture single-use patterns out of a CastForm two-phase special material [Dotchev 2006].

This paper focuses on possibility of using 3D printed products as patterns for the evaporative casting method. As the so-called low-cost and open source 3D printing machines emerged in the last decade, it has become possible to use a wide range of different materials in the FDM process. One of them is polystyrene, usually applied as a dissolvable support structure. The authors of this paper performed an industrial study, aimed at determination if using 3D printed lightweight structures for evaporative casting is a viable option.

2 MATERIALS AND METHODS

2.1 Research problem and concept

The aim of the study was to manufacture a scaled model of a water hydrant (Fig. 1) out of GJS500-7 cast iron. The main concept was to use a low-cost 3D printing machine and a HIPS material to manufacture a pattern of the product for the evaporative casting method, maintaining as low weight of the pattern as possible by using internal filling of layers (infill) close to 0%. The 3D printed pattern was then used to make a sand mold and evaporative casting was applied to burn out the pattern and obtain a product in the same operation.

The research questions were as following:

- what infill parameters should be used for the FDM process?
- will the accuracy and strength of the 3D printed pattern be satisfying for the casting process?
- is it possible to obtain an acceptable casting using a typical cast iron and pouring parameters?

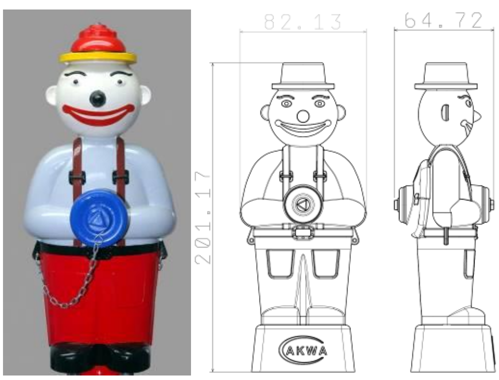

Figure 1. The test product made in the studies and its main dimensions

2.2 Methodology of 3D printing processes

For the manufacturing of a single-use pattern for the evaporative casting, a MakerBot Replicator 2X machine was selected. This machine realizes the Fused Deposition Modeling process – layered deposition of a thermoplastic material in form of threads, extruded from a heated nozzle, out of a raw material in form of a filament. A standard HIPS material supported by the machine producer was used in the studies. This material is normally used for manufacturing of dissolvable support structures in regular products made out of ABS or PLA materials [Kaveh 2015].

Preparation of the 3D printing process consisted of the following stages:

- preparation of a solid CAD model in the CATIA v5 system and its conversion to a STL mesh,
- import of the STL mesh to the MakerBot software and selection of the proper parameters of the print (Fig. 2),
- generating (Fig. 3) and exporting the 3D printing program to the machine via SD card and realization of the process; two different models were manufactured with two different infill parameters (see Tab. 1);

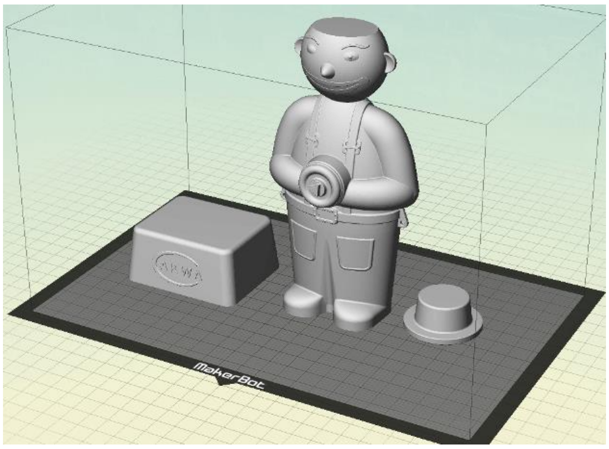

Figure 2. Divided mesh of the product prepared for 3D printing program generation

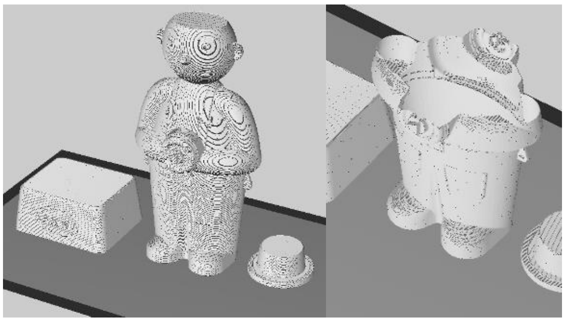

Figure 3. Visualization of the 3D printing program no. 2 – visible machine path and empty infill

As visible in Fig. 2 and 3, the model was divided in three parts. It was a necessary operation to perform, due to limited workspace of the Replicator 2X machine (no scaling was allowed), but also to avoid building of support structures. It would be very difficult to remove support structures mechanically with the applied infill parameters, as it would most likely cause separation of layers and threads of the product. Also, majority of low-cost 3D printers available on the market are equipped in a single head – if a foundry buys a 3D printer it will most likely be a single-head machine. In such machines, it is recommended to avoid support structures, as they can only be manufactured out of the same material as the product and are difficult to remove. It is therefore advisable to prepare the 3D model in a way to avoid necessity of supports.

Two different sets of infill parameters were used. They are presented in Tab. 1, along with obtained mass and manufacturing time and cost of the product. The cost was calculated as a raw cost, including only value of used material and time of operation of the machine, not including human labor on model preparation and post-processing.

No.	Layer thickness [mm]	Infill [%]	No. of shells	Weight [g]	Man. time [min]	Cost [EUR]
#1	0.3	5	2	78	283	45
#2	0.3	0	1	35	140	22

Table 1. Infill parameters for the 3D printed polystyrene patterns

After manufacturing, the model was assembled by gluing it together using a cyanoacrylate, preceded by removal of appropriate closing layers of its parts. The final pattern is presented in Fig. 4.

Figure 4. Final lightweight polystyrene pattern manufactured using the FDM technology

2.3 Methodology of casting processes

A typical evaporative casting process was applied in the studies. The mold was made out of a quartz sand, hardened by blowing with carbon dioxide. Thanks to this, there was no need of manual nor mechanical sand thickening, which reduced strength requirements towards the 3D printed pattern and allowed reduction of its weight.

In the first approach, with #1 set of infill parameters (see Table 1), the mold was open. The product was placed upside down and poured from the top. In the second approach, with #2 set of infill parameters, the product was placed in its using position. In both cases, the gating system was manufactured out of foamed polystyrene (standard grade used in the evaporative casting method) and put together with the printed pattern (Fig. 5). After preparing the pattern set, the mold was created, as presented in Fig. 6.

Figure 5. The polysterene pattern with the gating system, placed in the molding box

Figure 6. Making the quartz sand mold

The cast iron GJS500-7 was poured into the mold (Fig. 7). In the case of #1 set of pattern 3D printing infill parameters, the full casting was not obtained – less than half volume of the mold was filled with liquid metal, melted polystyrene was compressed and it blocked the metal flow in the mold. In the #2 set of process parameters, the pattern was lighter and there were no such problems, the polystyrene was burned and its remains were pushed away from the mold. After the metal solidified, the casting was knocked out of the mold and preliminarily processed before evaluation – the gating system was removed.

Figure 7. Pouring the mold with the liquid cast iron

3 RESULTS AND DISCUSSION

The obtained casting is presented in Fig. 8. The main goal of the work was reached – it was proven that it is possible to use 3D printed patterns for the evaporative casting method.

Figure 8. Obtained cast iron casting, with visible defects (fracture at the base)

The most important observation regarding the casting process is that the patterns should be as lightweight as possible – the #1 set of process parameters, with 2 shells (wall thickness roughly 0,7 mm) and 5% infill was too heavy for the metal flow to be fluent enough and the casting process was not finished with a successful result. There should be no more than 1 shell (wall thickness approx. 0,3 mm) and the inside of the pattern should be empty. However, comparing patterns manufactured with the 2 different sets of process parameters, it was observed that the lighter pattern was also manufactured with many more defects, mostly visual flaws related with low rigidity of the manufactured object during the layer deposition process. The following defects were observed:

- if a material thread was not correctly joined with a previous layer, the subsequent threads were deposed incorrectly, causing minor shape errors (Fig. 9a),
- if a layer contour was broken in an unplanned point (e.g. due to weak adhesion of threads caused by positioning error), this error was continued in subsequent layers and a vertical crevice occurred (Fig. 9b).

These problems do not occur when there are 2 shells (i.e. 2 contour threads), but a 2-shelled contour was found to be too thick for the evaporative casting method.

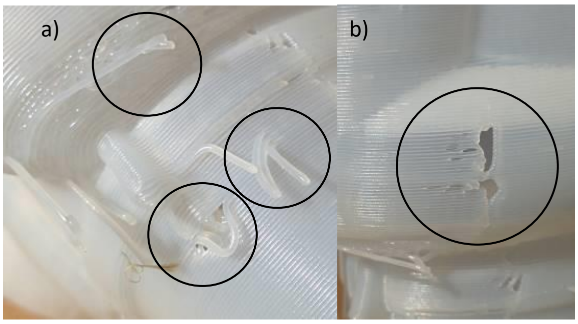

Figure 9. Defects of final 3D printed polystyrene pattern, a) various shape errors due to incorrect thread join, b) broken contour resulting in a vertical crevice

The casting itself was evaluated positively in terms of obtained shape accuracy and detail representation. There are only minor defects, such as a small fracture-like line in the bottom part of the casting (visible in Fig. 8), which was probably caused by fracture of the pattern while it was covered in the mold sand.
Time of obtaining of the casting was evaluated by the foundry employees as approximately half of the casting preparation time using conventional techniques (NC machining of polystyrene foam).
As the realized process was an industrial order, the casting was inspected by a quality controller from the recipient's side. Various features were checked, such as shape accuracy and surface quality. It was found that the obtained casting stays within acceptable values of quality parameters (despite some shape errors) and it was accepted with no need for corrections from the foundry side.

4 CONCLUSIONS

The conducted studies allowed to find out that it is possible to use 3D printing and polystyrene material to manufacture single use patterns for the evaporative casting method. The 3D printing allows rapid obtaining of a desired shape, which then can be used to build a mold and pour it with liquid metal to get a casting. There are certain limitations – it is not possible to obtain a shape of any complexity, as there should be no support structures in the 3D printed pattern, the workspace of the used 3D printer is also limited. There are also certain shape errors, caused by necessity of using a layer contour containing only one thread of material (one shell).
To sum up, it can be stated that the presented case is yet another successful use of 3D printed products in foundry and it opens possibilities of commercial use, as well as new studies. However, one experiment seems to be not relevant enough to fully support this conclusion. The authors plan to further develop the presented methodology, to decrease amount of defects and increase effectiveness of manufacturing – it can be achieved by selecting proper parameters of the material extrusion process, as well as by changing the material itself. Future studies will be conducted in strict cooperation with selected foundries. It is planned to perform 3D scanning for accuracy of obtained castings, as well as patterns. Non-destructive testing will be also carried out on finished castings, to find any potential damage inside the parts.

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