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ADDITIVE MANUFACTURING, METAL CASTING

RESEARCH ARTICLE

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Corresponding author:
Meelis Pohlak
meelis.pohlak@taltech.ee

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Application issues of additive manufacturing in plaster mold casting of metals

Meelis Pohlak, Fjodor Sergejev, Toivo Tähemaa, Mart Saarna, Mart Viljus and Aigar Hermaste

Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

ABSTRACT

Additive manufacturing (AM), commonly known as 3D printing, has emerged as a transformative technology in the field of manufacturing, offering unprecedented flexibility in creating complex geometries. This study investigates the practical application of AM in producing patterns for investment casting using plaster molds for aluminum components. The primary objective is to identify suitable filament materials for printing patterns that can meet the demands of the casting process while ensuring high-quality aluminum castings. As the process of investment casting in plaster molds involves burning out the pattern, it is important that the burn-out process of the 3D-printed pattern leaves as little residue as possible in the mold.

An experimental approach was adopted to evaluate various polylactic acid (PLA) filament materials. Each material was assessed based on the amount of residue remaining after the burn-out process during mold making.

The results indicated that some types of PLA filaments behave considerably differently from others. Some filaments leave significantly less residue and can ensure better casting quality.

The study provides suggestions for using low-cost filament extrusion-based 3D printers in the plaster mold casting of aluminum products. The findings contribute to the broader adoption of AM in foundry applications by providing insights into material selection and process optimization. Future work will focus on refining the balance between print efficiency and casting quality.

1. Introduction

Aluminum alloys have been used in various applications for more than 100 years. Aluminum is the second most widely used metal in the world (after iron), with 69 million tons mined in 2022 [1]. There are many aluminum alloys available, offering different properties and manufacturing approaches. One widely used manufacturing technology for aluminum alloys is casting. There are several possible aluminum casting approaches to select from, each having its own strengths and weaknesses. Some of them (e.g. using metal tools) can ensure high-quality products but require high initial investments. Moreover, these methods are economically feasible for large lot sizes, limiting this selection to mass production [2]. Some other techniques are preferred if the lot size is small. One family of techniques is based on using a plaster mold that is poured around a pattern. The pattern is made based on the final product being manufactured. It is made of a material that can be burned out or melted out later, before the final casting operation. Thus, during the process, the pattern is created first, followed by making the plaster mold around it. The plaster is a mixture of water, plaster powder and sand. After some time, the plaster mixture solidifies, trapping the pattern inside. The pattern is then removed by heating the entire mold, so that the pattern disintegrates and leaves a cavity for casting. [2,3]

Nowadays, the pattern can be 3D printed. There are special 3D printers and specially developed pattern materials for such applications. However, it is also possible to use a universal, consumer-level, low-cost filament extrusion-based printer [4] to print sufficiently accurate patterns for plaster mold casting of aluminum. Due to its lower cost, this could be an economical alternative for many educational institutions and hobby enthusiasts.

The current study focuses on aluminum casting using plaster molds and patterns made with a low-cost filament extrusion printer. For this technology, the cheapest and most widespread material is polylactic acid (PLA). PLA is a thermoplastic material. It has become a popular material due to its economical production from renewable resources and its potential for use in compostable products [5]. PLA polymers range from amorphous glassy polymers to semi-crystalline and highly crystalline polymers, with a glass transition temperature of 60–65 °C, a melting temperature of 130–180 °C and a Young's modulus of 2.7–16 GPa [6]. As the melting temperature is relatively low, it is a suitable material for creating melt-away (or burn-out) casting patterns.

There are many material producers, and a variety of printing materials can be selected. However, in casting applications, it is important that after melting out, the pattern will leave as little residue as possible, because it will mix with the molten material and degrade the quality of the castings. The amount of residue depends on the additives used in the material. Experience has shown that the amount of residue varies significantly. However, producers do not specify the additives used and their quantities on the material package. Therefore, the suitability of the filament material for printing casting patterns cannot be determined without further investigation.

PLA is widely used in casting technology for the quick and cheap production of complex-shaped parts. The easiest approach is to produce the plaster mold using a PLA 3D-printed pattern. In this case, the printed model is placed on a flat surface and the mold walls are added (mold box). The size of the mold varies depending on the size of the pattern, but there are few limits, as the plaster mold process is quite flexible. Parts ranging from quite small (a few grams in mass, such as jewelry) to medium-sized (with a casting mass of up to a hundred kilograms) can be manufactured. The size of the oven is the limiting factor for the casting size.

The plaster mold is made from three main components – plaster, sand and water. In our case, all three are used in equal mass proportions (1:1:1), with water usually being added last, and plaster and sand being pre-mixed to avoid the formation of agglomerates.

Mixing should be performed slowly for 2–3 minutes to prevent air from entering, as this is very important for the casting details and overall quality. The plaster slurry should also be poured slowly to avoid the entrapment of air bubbles. After pouring, it takes 20 to 30 minutes for the plaster to set, and then the mold box can be unmounted. Depending on the size of the casting, the plaster mold should settle at room temperature – preferably for 24 hours – before the burning out of PLA, to avoid cracking due to excess moisture in the mold material.

It is important how the thermal treatment of the molding tool (plaster mold with the PLA pattern) is performed, as the treatment serves two main functions. First, it removes moisture from the plaster mixture, entrapped there during the plaster casting process. Second, it removes the 3D-printed pattern, leaving the tool cavity that will define the shape of the casting. [3]

The burning temperature plays a significant role in determining the amount of residue left by various PLA plastic materials in plaster mold casting. PLA undergoes thermal degradation, and the residue amount is influenced by the burning temperature. Higher temperatures generally lead to more complete degradation, reducing the amount of solid residue [7,8]. Studies have shown that the initial decomposition temperature ($T_{2\%}$) of PLA is 315 °C, and the maximum weight loss temperature (T_{max}) is 375.5 °C [9].

In the current study, PLA filaments used in 3D printing were analyzed to assess their suitability as melt-out patterns in plaster mold casting processes. The filament samples were heated in an oven using heating cycles similar to those used in regular plaster mold casting processes. Then residues of the material were examined to determine the suitability for casting.

2. Experimental study

In the study, an experimental investigation was performed. Five different widespread PLA printing filament materials were used (see Table 1). General-purpose materials were selected, with the only difference being the color. Preliminary experience with different materials has shown that different colors can result in very different amounts of residue in the mold.

The filament samples were placed in ceramic containers and heated in an oven using heating cycles similar to those used in regular plaster mold casting processes. The heating cycle is shown in Fig. 1. The first stage, up to 100 °C, is for drying the mold; the second stage, below 300 °C, is for

Table 1. Materials investigated in the study

Material name	Designation
Ultimaker Silver Metallic PLA	A
Ultimaker White PLA	B
Ultimaker Black PLA	C
Ultimaker Magenta PLA	D
Ultimaker Transparent PLA	E

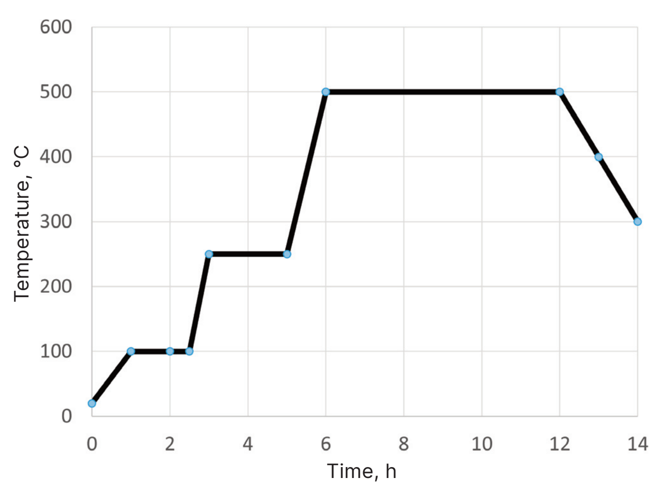

Fig. 1. Heating cycle used in the experimental study.

further drying the mold and melting the PLA. The third stage, at 500 °C, is for burning out the PLA. Cooling after the treatment should be very slow to avoid mold cracking. Generally, the duration of the stages depends on the size of the mold. [3]

The PLA burn-out cycle shown in Fig. 1 is based on the information found in [10], but it should be noted that there is limited evidence in research literature regarding the parameters of the PLA burn-out cycle. The cycle consists of three temperature increase steps. The first step is related to water evaporation from the plaster mold. For this, the mold is heated up to 100 °C at a speed of 1.6 °C/min and held for 1.5 hours. The next step is heating to 250 °C at a speed of 5 °C/min, or above the PLA melting point (180 °C), and holding for 2 hours. This step is needed to melt the 3D-printed pattern. The holding time may depend on the size of the casting, but a minimum of 2 hours is confirmed by practice. The third step involves heating at a speed of 4.2 °C/min to 500 °C and holding at this temperature for 6 hours. Heating well above the maximum weight loss temperature of PLA (375.5 °C) ensures the burning out of the plastic from the plaster mold cavity. After 6 hours at the highest temperature, the mold is allowed to cool down along with the oven. This allows us to prevent cracking of the mold but drastically increases the total burn-out cycle length to 16 hours or more.

The containers were weighed in their empty state, then after filling them with filament material, and finally after burning away the filament. The weight of the residue characterizes the suitability of the filament material. It is important to note that in plaster mold casting, it is possible to some extent to clean the mold cavity from the residue using vacuum or compressed air. However, as the mold is very brittle, it is still quite challenging due to the high risk of breaking the mold. Therefore, it is quite probable that some filament residue remains in the mold cavity and is mixed with the molten metal in the casting, causing material contamination and surface defects. It means that the composition of the residue could also be an important issue.

Thus, the residual material was analyzed using the energy dispersive X-ray (EDX) microanalysis system to characterize its composition.

3. Results and discussion

The amount of residue is shown in Fig. 2. As can be seen, the highest level of residue was found in the cases of “A” (Silver Metallic PLA) and “B” (White PLA). In the case of “A”, the residue appeared visually as fine aluminum powder. In the case of “B”, it resembled white coarse powder, similar to the residue in the case of “D”.

The result for specimen “E” (Transparent PLA) was not surprising, as this material is transparent and does not need any coloring additive, and some additives could also impair the transparency. This specimen had a visually very small amount of white, cotton-like residue.

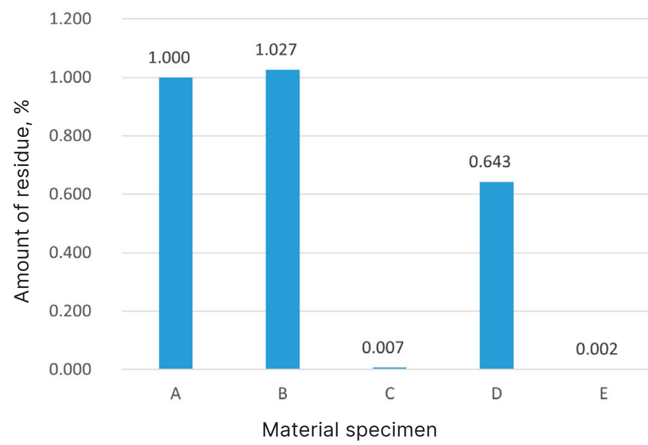

Fig. 2. Amount of residue from the burning out of PLA specimens.

However, the real surprise came from specimen “C” (Black PLA). The amount of residue was very small (although more than three times greater than in the case of “E”), it appeared visually as whitish particles.

As the residue could mix with the molten metal in the casting operation, the composition of the residue was also analyzed chemically. The results of the analysis are shown in Table 2.

The chemical analysis of the residue shows that three main oxides can be found – TiO_2, Al_2O_3 and SnO_2. The PLA specimens with the highest amount of residue – “A”, “B” and “D” – contain Al_2O_3 and TiO_2. The “A” or Silver Metallic PLA residue contains approximately two-thirds of aluminum oxide by weight. Both “B” (White PLA) and “D” (Magenta PLA) contain titanium dioxide, more than 95% in both plastic residues. White PLA was expected to contain titanium oxide due to the color, but it was an unexpected result for the Magenta PLA filament. The melting point of titanium dioxide is 1843 °C and that of aluminum oxide is 2072 °C. The low temperatures used in the PLA burn-out cycle do not allow this residue to melt. Moreover, it is not feasible to heat the plaster mold to such high temperatures, as the main component of the plaster mold – gypsum ($CaSO_4 \cdot 2H_2O$) – will transform into anhydrite ($CaSO_4$) and become more brittle. This transformation will lead to an increase in the Mohs hardness of the plaster mold material from 2 to 3.5. As a result, the mold becomes too brittle to sustain the mechanical load exerted during the pouring of the molten metal into the mold and may fracture.

Both filaments that resulted in the smallest amounts of residue – “C” (Black PLA) and “E” (Transparent PLA) – have a high proportion of stannic oxide (SnO_2), as indicated by the white color of the residue. The melting point of stannic oxide is 1630 °C. It is lower than the melting points of the main residue components in other filaments. However, it still cannot be fully burned out due to the transformation of gypsum into anhydrite during the high-temperature heating.

Table 2. Chemical composition of the residue

Material spec.	Composition, weight %														
A	Element	O	F	Na	Mg	Si	S	Cl	K	Ca	Fe	Al	Ti	Cu	Sn
	Weight %	**43.86**	–	**0.36**	**0.38**	**7.12**	–	–	**2.59**	**0.36**	–	**32.63**	–	–	–
	Standard deviation	0.62	–	0.05	0.01	0.02	–	–	0.06	0.01	–	1.02	–	–	–
B	Element	O	F	Na	Mg	Si	S	Cl	K	Ca	Fe	Al	Ti	Cu	Sn
	Weight %	**52.81**	–	–	–	**0.57**	–	–	–	–	–	**1.34**	**45.28**	–	–
	Standard deviation	0.92	–	–	–	0.07	–	–	–	–	–	0.19	1.18	–	–
C	Element	O	F	Na	Mg	Si	S	Cl	K	Ca	Fe	Al	Ti	Cu	Sn
	Weight %	**53.8**	–	**17.1**	–	**0.3**	**1.5**	–	–	**0.6**	**1.6**	–	–	–	**25.2**
	Standard deviation	4.34	–	0.64	–	0.05	0.3	–	–	0.12	0.4	–	–	–	4.11
D	Element	O	F	Na	Mg	Si	S	Cl	K	Ca	Fe	Al	Ti	Cu	Sn
	Weight %	**45.59**	–	**0.52**	–	**0.46**	**0.16**	–	–	**0.26**	–	**1.37**	**50.88**	–	**0.77**
	Standard deviation	3.35	–	0.08	–	0.05	0.09	–	–	0.02	–	0.24	4.02	–	0.24
E	Element	O	F	Na	Mg	Si	S	Cl	K	Ca	Fe	Al	Ti	Cu	Sn
	Weight %	**32.34**	**18.94**	**21.24**	–	**0.42**	**0.24**	**0.26**	–	**0.79**	**0.39**	–	–	**0.38**	**25.02**
	Standard deviation	3.66	4.96	1.6	–	0.28	0.06	0.06	–	0.15	0.04	–	–	0.22	3.04

4. Conclusions

The analysis shows that the least amount of residue resulted from using Transparent PLA filament. However, this material is not so common. The study indicates that a much more common alternative could be Black PLA filament. This is probably one of the most widely used materials in filament extrusion 3D printing, and the amount of residue is also very low.

The very small amount of residue – 0.002% in the case of the transparent filament and 0.007% in the case of the black-colored filament – should be considered a possible contamination of the casting alloy. With the use of aluminum alloys, the residue is expected to contaminate the alloy, as the melting temperatures of the residue components (mostly stannic oxide, SnO_2) are much higher (almost 2.5 times higher) than that of the casting alloy, preventing them from melting along with it.

Data availability statement

All research data are contained within the article and can be shared upon request from the authors.

Acknowledgments

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Lisandtootmise rakendusprobleemid metallide kipsvormivalus

Meelis Pohlak, Fjodor Sergejev, Toivo Tähemaa, Mart Saarna, Mart Viljus ja Aigar Hermaste

Lisandtootmine, mida laiemalt tuntakse 3D-printimisena, on tootmisvaldkonnas kerkinud esile murrangulise tehnoloogiana, mis võimaldab erakordset paindlikkust keerukate geomeetriate loomisel. Uuring käsitleb lisandtootmise praktilist rakendamist valumudelite valmistamiseks kipsvormivalus alumiiniumdetailide tootmisel. Uuringu peaeesmärk oli tuvastada sobivad filamendid, mille abil 3D-prinditud mudelid vastaksid valuprotsessi nõuetele ja tagaksid kvaliteetsed alumiiniumvalandid. Kuna kipsvormivalu protsessis põletatakse 3D-prinditud valumudel vormist välja, on oluline, et põletamisel jääks vormi võimalikult vähe jääkmaterjali. Katselises osas hinnati erinevaid polüpiimhappest (PLA) filamendimaterjale ning võrreldi neid põletamisjärgse jäägi hulga alusel. Tulemused näitasid, et erinevat tüüpi PLA-d käituvad põletamisel märkimisväärselt erinevalt: näiteks must ja läbipaistev PLA jätavad põletamisel oluliselt vähem jääke ja tagavad parema valukvaliteedi.