

Lost Wax Casting: From 3d Printing to Functional Parts

Abdul Hai Alami^{1,2,*}, Mohamad Ayoub^{1,2}, Ahmad Yasin², Adnan Alashkar³, Ayman Mdallal², Siren Khuri², Shamma Al Abdulla¹, Haya Aljaghoub^{2,4}, Fatima Alshemsi¹

¹*Sustainable and Renewable Energy Engineering Department, University of Sharjah, Sharjah, P.O. Box 27272, United Arab Emirates*

²*Sustainable Energy & Power Systems Research Centre, RISE, University of Sharjah, United Arab Emirates*

³*Materials Science and Engineering PhD Program, American University of Sharjah, United Arab Emirates*

⁴*Industrial Engineering and Engineering Management Department, University of Sharjah, United Arab Emirates*

Abstract

The lost wax production process is an intermediate step in converting a design idea that has been 3D printed from Polylactic Acid (PLA) plastic into a functional part via metal casting processes. This work offers an experimental assessment of the benefits accompanied by the lost-wax method, from both energy and economic-related aspects. The methodology of this work is represented by a sequence of steps that involve converting a 3D modeled and printed part (an investment casting tree), into a metal part, which in this case is made out of Aluminum. Aluminum was obtained from recycled products (i.e., beverage cans). The first couple of steps revolve around obtaining a 3D printed part of the desired 3D model, that can be created using a multitude of readily available Computer Aided Design (CAD) software. The 3D printed part is then utilized to create a plaster mold, which is followed by a firing step to get rid of the temporal 3D printed part to leave room for the casting metal. An energy assessment was carried out to compare the lost wax method and conventional machining (i.e., computer numerical control (CNC) machining). It was shown that to obtain the exact same functional part using the lost wax method, 12.124 kWh of energy is required, versus that of 17.297 kWh for CNC machining. Moreover, normalized costs of 0.067\$/g and 0.096\$/g were attributed to the lost wax and CNC machining, respectively, showing an almost 70% reduction in price when opting for the lost wax method.

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Keywords

Lost-wax casting; recycling; 3D printing; aluminum casting

1. Introduction

3D printing, also known as additive manufacturing (AM), is the process of creating a three-dimensional product from a Computer-Aided Design (CAD) file or a digital 3D model (Alasad et al., 2022). Waste dramatically decreases when AM methods are implemented, typically by over 90%, resulting in substantial resource savings. Given that additive manufacturing requires no cutting equipment, lubricants, or additional machinery, this leads to less negative environmental impacts and increases sustainability in manufacturing (Hegab et al., 2023). Manufacturers can depend on the recent developments of rapid and additive manufacturing to ensure product design sustainability from the start, without paying costly expenses or wasting raw materials (Kazakova & Lee, 2022). Even though some 3D printing technologies have been continuously growing in both tooling and material variety, they remain to be seen as expensive and unpredictable in comparison to plastic 3D printing technologies which employ resin and polylactic acid (PLA). Especially metal 3D printers which require hefty sums of money and are significantly large. Nonetheless, integration of design, casting, and 3D printing simplifies this process. Furthermore, techniques such as the lost PLA method allow for seamless integration of 3D printing with modeling and simulation tools to craft various metal components.

The efficacy of employing the lost wax casting method lies in creating different structures of metallic products characterized with high strength and fine detail that can be applied in various applications such as jewelry, dentistry, and art. The ease of conducting this process resides in two steps which include the melting of the PLA material that has been encompassed with a type of mold, followed by the pouring of the liquid metal into the mold (Czarnecka-Komorowska et al., 2020). The integration of 3D printing into the lost wax method has received significant attention due to the faster lead time and less production cost attributed to the elimination of hard tooling it offers in comparison to conventional casting processes which hold values of 89% and 60% in improvement, respectively (Wang et al., 2019). This paper presents a step-by-step process design and assessment of a functional part manufactured by the lost PLA method. The process is similar to the lost wax method, but here PLA material from the 3D printed part. Although the process has been extensively used for jewelry and dental applications, the advent of affordable 3D printing technologies made the process technologically and economically feasible.

This work highlights the advantages of the process for engineering applications, indicating that virtually any part that can be 3D printed could be converted into a functional metallic part by subsequent processing. There are, however, many provisions that have to be considered to arrive at the final product, such as operational parameters of 3D printing, mold making, and casting processes as well as postprocessing of the final part, including possible multi-part assembly, testing, surface modifications and corrosion protection. While currently there is a lack of normalized parameters comparing the lost wax method to conventional machining, such as CNC, this work presents energy consumption and cost metrics to highlight where these techniques stand on the spectrum of functional parts manufacturing.

2. Experimental Setup

The experimental setup and methodology followed in this work aim to facilitate a rapid idea-to-product process, which ensures precision, repeatability, and quality. The process can be broken down into different steps starting from initial CAD modeling and ending with post-processing of the final product to expose a smoother representable surface.

2.1 CAD Model Preparation, Slicing, and 3D Printing

The initial step of this process sets a solid ground for the steps that follow. A 3D model of the proposed baseline shape is developed using Fusion360 CAD software, which takes into account the casting stem and runner that will aid the aluminum's flow to the targeted shape in the mold to be made, as shown in Figure 1. It is also worthy to note that this step dictates the level of detail in the final product. The exported CAD model is subjected to a slicing step using Flashprint software, which was chosen based on its compatibility with the used 3D printed. The resultant sliced model was then printed using the FlashForge Creator 3 Pro printer.

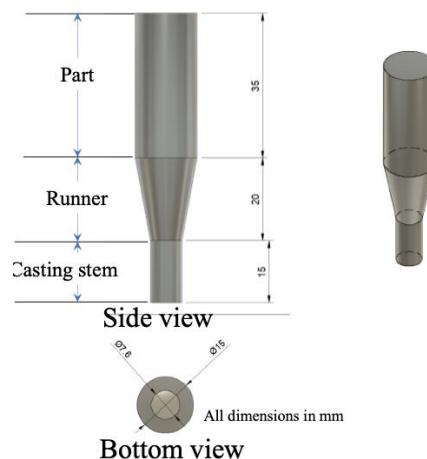


Figure 1. Proposed 3D Model

2.2 Mould Preparation and PLA Firing

The plaster mold was prepared by mixing 1kg of Prestige ORO Plaster and 380ml of water, and subjected to a vacuum, provided by Kaya Vacuum Casting apparatus, for 5 minutes. Then, the 3D-printed model was secured in place using a rubber accessory to a vacuum-casting flask. The prepared plaster was poured in to cover the 3D-printed model within the casting flask. Finally, the casting flask harboring the plaster mold was subject to another 5 minutes of vacuum. Following the mold preparation, the plaster mold underwent a hardening and a PLA firing step at 600 °C, using Thermolyne Premium Muffle Furnace for two hours, in order to achieve better mechanical properties of the plaster, and melt the PLA away leaving behind a detailed hollow hardened mold.

2.3 Aluminum Melting and Casting

Aluminum was melted using an MIFCO induction furnace, a process which was done by heating an aluminum-containing crucible to 930 °C, which took approximately an hour to achieve, with an average temperature step of 15°C/min. After ensuring the liquefaction of the aluminum, it was poured directly into the plaster mold, which was then allowed to cool, enabling a gradual solidification of the aluminum within the defined contours of the plaster mold.

2.4 Mould Removal and Post-Processing

Following the cooling period, the plaster mold, which dissolves under exposure to water, was washed with a high-pressure hose, to reveal the cast aluminum piece. After this, a series of post-processing steps took place, which included the removal of excess aluminum that solidified in the runner region of the mold, as well as a sanding step to achieve a desired smooth surface finish. The entire process can be summarized in Figure 2.

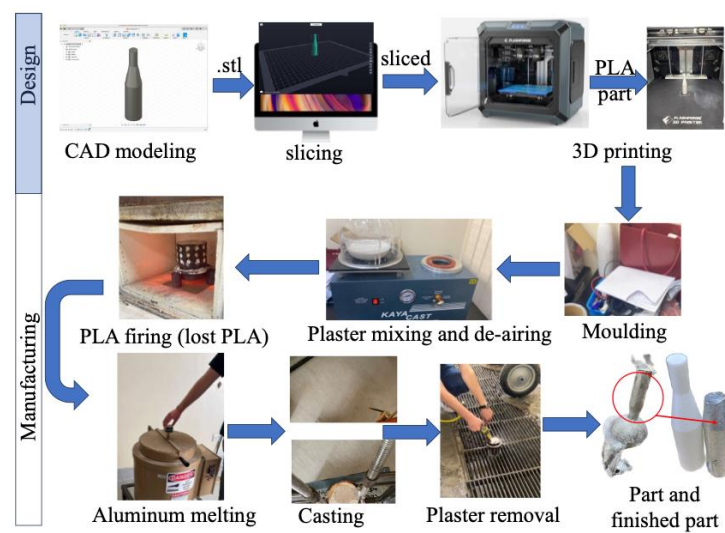


Figure 2. Flowchart of the proposed lost-PLA casting method

3. Results and Discussion

3.1 Final Product Properties

The structure of both the 3D printed PLA component and the aluminum part produced through casting are depicted in Figure 3. Analysis of the image reveals a significant resemblance in the microstructures of the cast aluminum part and the PLA part. This similarity strongly supports the effectiveness of the lost PLA method for manufacturing aluminum parts. The presence of the 3D-printed PLA lines within the microstructure of the cast aluminum part clearly depicts this resemblance.



Figure 3. PLA Part and Aluminum Cast Part

3.2 Circular Economy

Circular economy employs the underlying principles of minimizing environmental impact and resource consumption while improving revenues which can be a positive result of manufacturing attempts to promote sustainable manufacturing (Kazakova & Lee, 2022). More than 30% of the overall energy is consumed by the manufacturing sector (Salonitis & Ball, 2013). The process applied in this study contributes directly to the circular economy by minimizing energy consumption (in the process of aluminum melting) and therefore, greenhouse gas emissions, in addition to using recycled aluminum for the production of functional parts. The use of alumina to produce aluminum requires a melting point of above 2050 °C, which means higher energy consumption (Alasad et al., 2022). Furthermore, by applying the reported technique, an engineer or an enthusiast could create finished products with high accuracy and minimal expense, and an overall budget of under \$1,000.

3.3 Energy Efficiency

To assess the effectiveness of the lost PLA technique, an examination of energy consumption is conducted. This assessment considers the power rating of all equipment utilized during the manufacturing process. The energy expenditure linked with producing aluminum stands at 17,000 kWh per metric ton (Claisse, 2016). The cost linked to energy consumption is determined as 0.10 USD per kWh, aligning with the electricity tariff of the Sharjah Electricity and Water Authority (SEWA). The outcomes demonstrate that energy consumption related to lost PLA casting is lower compared to conventional Computer Numerical Control (CNC) methods, leading to reduced production expenses. Furthermore, conventional CNC processes generate significant waste, as 100 grams of aluminum are needed to create the desired form. A detailed comparison between lost PLA and CNC machining is presented in Table 1.

Table 1. Table 1. Energy and Cost Comparison - Lost PLA vs CNC

	Lost PLA			CNC			
	Power (kW)	Time (hour)	Rating (kWh)		Power (kW)	Time (hour)	Rating (kWh)
3D printer	0.50	0.67	0.335	Al production (100g)	-	-	1.7 (Claisse, 2016)
Casting	0.37	0.17	0.063	CNC	10.3	1.5	15.45
Furnace (PLA melting)	4.40	1.5	6.600	Grinding	0.74	0.17	0.126

Furnace melting)	(Al	5.00	1	5.000	Milling	0.12	0.17	0.021
Saw Machine		0.74	0.17	0.126				
Total		12.124 kWh			Total	17.297 kWh		
Cost (USD/gram)		0.067			Cost (USD/gram)	0.096		

As can be seen from the tabulated values, only 70% of both energy and cost are required for the lost wax method compared to that of conventional machining. It was shown that to obtain the same functional aluminum part (weighing 100g) using the lost wax method, 12.124 kWh of energy is required, versus that of 17.297 kWh for CNC machining. Finally, a normalized cost of 0.067\$/g was obtained for the lost wax, whereas 0.096\$/g was obtained for CNC machining.

3.4 Lost PLA Production Rate vs Conventional Processes

Conventional casting techniques have been utilized for centuries and continue to be widely employed across various industries. It enables the production of a diverse array of products, ranging from basic metal components to complicated sculptures. According to a study conducted by N. Hawaldar and J. Zhang (Hawaldar & Zhang, 2018), the process of casting using 3D printed molds is estimated to take only a quarter of the time compared to conventional sand-casting methods. In addition to saving time, there are several other benefits that result from this, including saving on sand usage and allowing for design flexibility. Table 2. presents a comparison of various casting methods, highlighting the fact that investment casting exhibits the highest production rates when compared to the other methods, which is attributed to the ability of constructing a tree (similar to the one presented in this study), which contains various parts that can all be cast at once.

Table 2. Table 2. Conventional Casting Methods Production Rates (Swift & Booker, 2003).

Casting Method	Production Rate
Sand Casting	1–50/h (depending on the size)
Gravity die casting	5–50/h (depending on the size)
Pressure die casting	200/h
Centrifugal casting	50/h
Investment casting	1000/h
Ceramic mold casting	10/h
Plaster mold casting	10/h

CNC (Computer Numerical Control) is a highly precise manufacturing process that involves the use of computerized controls and machine tools. It is used to remove material from a workpiece in order to create a final part or product with exceptional accuracy (Mamadjanovich et al., 2021; Michalik et al., 2012). This process is broadly utilized in various industries to manufacture complicated and accurate components. The CNC machining process begins by creating a computer-aided design (CAD) model that outlines the desired dimensions, geometry, and specifications of the part. This CAD model is then converted into a computer-aided manufacturing (CAM) program, which contains the instructions for the CNC machine. The CNC machine is equipped with automated tools such as drills and cutters. It securely holds the workpiece on its worktable using fixtures.

The CAM program is responsible for generating a toolpath that directs the CNC machine's movements to achieve precise shaping according to the design specifications. Material removal takes place when the CNC machine carries out cutting, shaping, drilling, or milling operations based on instructions provided by CAM. Monitoring systems and sensors are responsible for managing operations to ensure conformity and minimize errors. After the machining process, it is common to use additional processes like polishing or heat treatment to achieve the desired properties. Table 3. presents studies comparing the lost wax method with alternative manufacturing techniques (including CNC), in the context of dental applications.

Table 3. Table 3. Studies comparing the Lost Wax method with alternative manufacturing techniques.

Study	Findings	Ref
A review on the accuracy of CAD & computer-aided machining (CAD-CAM) versus the lost wax method for single metal crown copings	The lost-wax method resulted in obtaining metal copings with better marginal accuracy, compared to that of CAD-CAM.	(Yang & Li, 2022)
Testing three different methods for gold crown copings (Hand waxing, milling, and printing)	The lost wax method and milling showcased similar patterns. Printed crowns showed higher mean and maximum margin discrepancy.	(Munoz et al., 2017)
Review of different procedures for orthopaedic screws manufacturing	The lost wax casting has the potential to be maximized across the different steps involved in the process, making it more efficient compared to other alternatives.	(Aziz et al., 2018)
Evaluating the marginal fit of metal copings manufacturing using milling, stereolithography, and lost wax	The lost wax method showed the best marginal fit compared to milling and stereolithography. Although all three methods showed acceptable clinical metrics	(Khaledi et al., 2020)

4. Conclusion

In this work, the process of lost wax is applied to 3D printed parts to present a transformative approach bridging concepts and functionality. A simple cylindrical part was drawn in 3D CAD software, 3D printed, molded in plaster, then cast from aluminum. The surface quality of the produced part was compared with the original 3D printed one, while the energy and economic aspects indicate that the lost wax process has many advantages over conventional processes. Such conventional processes include traditional machining (material removal) that will result in material waste to arrive at the final dimensions and desired surface finish. The conducted energy and cost analysis concluded that lost wax bears energy and cost demands of only 70% compared to that of conventional machining. The proposed lost wax method can also be advantageous for multiple parts that can be added to a product tree and result in high-fidelity metallic parts that have a good surface finish with intricate details. The recycling of nonferrous and/or precious metals provides a low energy bill, where the only drawback being the long firing time (up to 12 hours) for the PLA to melt and plaster mold to cure.

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The authors declare that there is no competing interest.

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