

# Integration of 3D printing in the lost wax process for jewelry production, with standardization purposes

## Integración de la impresión 3D en el proceso de cera perdida para la producción de joyas, con fines de estandarización

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### Resumen

Las resinas poliméricas son las más utilizadas en la impresión 3D. Estas experimentan diferentes comportamientos y no pueden ser empleadas bajo las mismas condiciones de proceso que cuando se utiliza cera en el proceso de cera perdida. Con este estudio se buscó definir las condiciones estandarizadas para obtener piezas finales de joyería con acabados de calidad, a partir de un proceso de cera perdida combinado con la tecnología de impresión 3D para la elaboración de prototipos. La selección y comprensión de diversas variables y parámetros de proceso es uno de los principales desafíos para la optimización. Diferentes autores consideran que la etapa de quemado es la más crítica y crucial. Por ello, se proponen cuatro curvas de quemado con el fin de evaluar el comportamiento de dos resinas (B9-Emerald y Tepic 2000) e intentar disminuir el tiempo de quemado, sin afectar la calidad de la pieza. Se obtuvieron piezas de mejor calidad al aplicar una curva con tres rampas de temperatura: 150, 455 y 750 °C, mantenidas durante 40, 30 y 20 min, respectivamente, con un tiempo total de 4,5 h.

**Palabras clave:** cera perdida; resinas poliméricas; impresión 3D; estandarización; tiempo de quemado; calidad.

### Abstract

Polymer resins are the most used in 3D printing. These resins have different behavior than wax (used in the lost wax process) and cannot be used under the same conditions. This study aims to define the standardized conditions for obtaining final pieces of jewelry with good finishes, from a casting process combined with 3D technology for prototypes elaboration. The selection and understanding of the various variables and conditions of the process are one of the main challenges for the optimization. Different authors consider that the burning stage is the most critical and crucial. For this reason, four burn curves are proposed, in order to evaluate the behavior of two resins (B9-Emerald and Epic 2000) and try to reduce the burning time, without affecting the quality of the piece. Parts with better quality were obtained by applying a curve with three temperature ramps: 150, 455 and 750 °C maintained for 40, 30 and 20 min, respectively with a total time of 4.5 h.

**Keywords:** lost wax; polymer resins; 3D printing; standardization; burn time; quality.

## Introduction

The lost-wax process is the technique by which a masterpiece or prototype handmade in wax is covered with ceramic material (plaster) called *investimento*, which resists high temperatures and once hardened adopts the exact geometry of the piece desired. Then, the mold is placed in an oven where the wax prototype is removed by fusion or combustion, leaving a hollow cavity inside the mold where the molten metal is poured to obtain the jewel (Pattnaik; Karunakar; Jha, 2012; Singh; Singh, 2016).

Regarding the elaboration of hand-crafted wax prototypes, the jeweler molds wax blocks using blades and carving tools to achieve the desired shape: ring, snake, stone box, among others (Underhill, 2017). This process is 100% manual, demands the jeweler's total attention and the quality obtained depends on the skills of the craftsman, so it is difficult to achieve all the exact details, symmetries, weight or thickness as described in the design. If a copy is required, the prototype must be re-carved (Campos; Romeiro, 2013; Muñoz-Mesa; Sánchez, 2016).

In recent years, the lost wax process has undergone a considerable evolution with the development of equipment, materials and the adoption of new technologies, which has allowed the opening of new opportunities for integration between design and production processes. Currently, 3D printing is being used to create more complex and personalized prototypes, with a higher level of detail, intricate and intricate features, and dimensional accuracy, with fewer defects and in less time, also have the power to make evaluations and design and specification modifications efficiently and predict errors (Campos; Romeiro, 2013; Pattnaik *et al.*, 2012; Redwood, s.f. a).

This research aimed to establish and define standardized conditions to obtain pieces of jewelry with excellent finishes, using 3D printing for prototyping. In this way, the national jewelry sector would benefit from the reduction of purchases of unnecessary equipment, the reduction of reprocesses, the significant decrease in delivery times and a considerable improvement in productivity and competitiveness (Berman, 2012; Huang; Liu; Mokasdar; Hou, 2013). This is why understanding the relationship between the various controllable parameters involved in the lost wax process is a key point for optimizing the cycle and for achieving a high degree of reliability in the quality of the final product. The proposed experimental plan allowed us to evaluate the incidence of the burn stage, specifically the time and the final quality of the product, considering that this stage is the most critical and crucial.

## Theoretical framework

### Lost Wax Casting

The lost-wax process is widely used in different industries and engineering applications that include jewelry, precision components of the medical, hydro plant, defense, automotive and other tools such as household and commercial equipment (Singh *et al.*, 2016 ). Its main advantage is its flexibility and versatility to meet the demanding specifications of customers, from very fine details and thin sections to intricate shapes, using tools and materials that are efficient in the long term (Singh; Singh, 2015). Likewise, high precision is achieved in the parts, with tolerances of  $\pm 0.005$  inches, with an excellent surface finish (Pattnaik *et al.*, 2012; Singh *et al.*, 2016; Singh; Singh, 2016).

The lost-wax process is fully established as the main jewelry production process and as an important tool in fine, artistic and goldsmith jewelry, and there are no signs of any alternative process that can displace it. A brief description of the different stages of the lost wax casting process is shown in Figure 1 according to authors such as Pattnaik *et al.*, (2012) and Singh and Singh (2016), who explain the basic steps of this process.

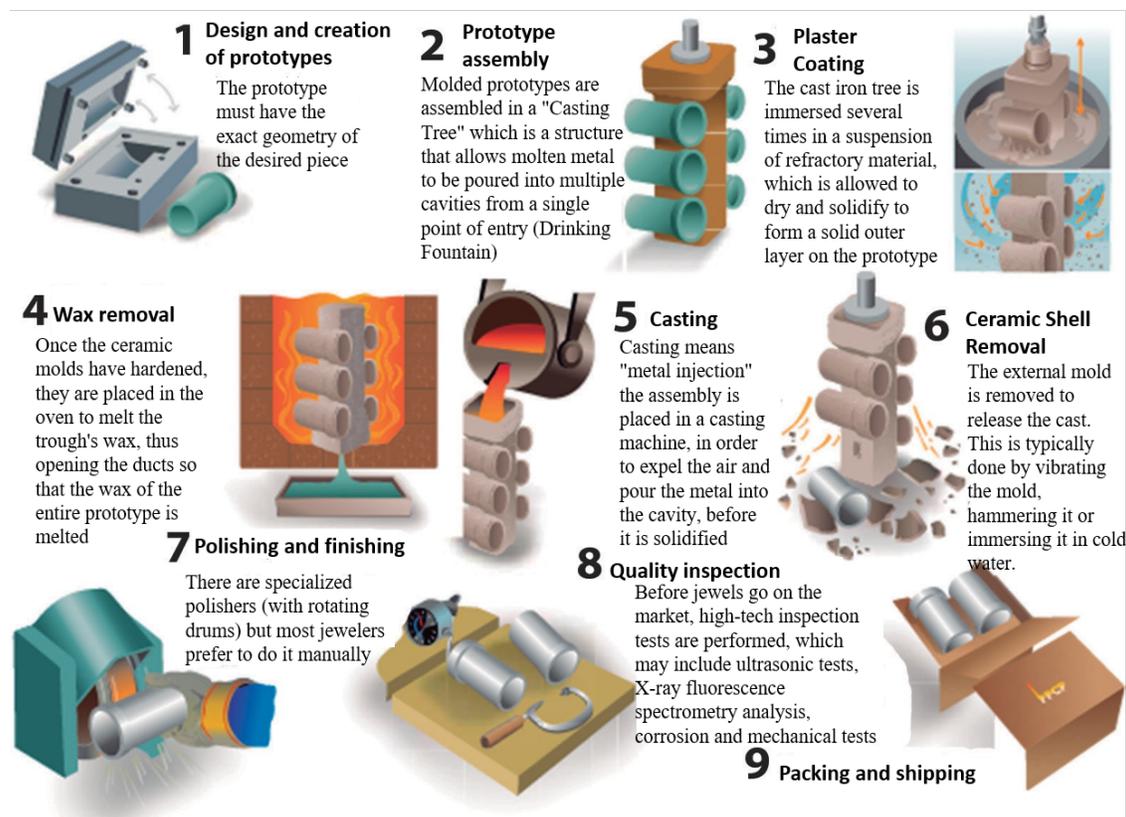


Figure 1. Stages involved in jewelry making through the lost-wax process.  
Source: adapted from Pennsylvania Precision Cast Parts (PPCP).

The first step to produce a unique piece is to create a concept and a design. The creative idea and technology merge perfectly into the design to emphasize personalization and art. In some cases, designers create an integral representation through computer-aided design, (*CAD - Computer-Aided Design*) (Campos; Romeiro, 2013). Some of the best-known software are *RhinoCeros*, *Rhino Gold*, and *Matrix*.

Once you have an established design, you continue with the creation of the prototype or masterpiece. Formerly, prototyping was done by molding a soft material, typically wax, clay or plaster (Hoffman, 2016), using carving tools, which allow transforming a simple block of wax into an exact model of the fine jewels that will be created (Underhill, 2017). The prototype obtained must have dimensional tolerances to compensate for its own volumetric contraction, as well as the solidification contraction of molten metal in the plaster cast (Pattnaik *et al.*, 2012). Similarly, the prototype must be free of defects and imperfections, such as scratches, air bubbles and different joining lines, so that they do not reproduce in the final piece (Sias, 2005).

Depending on the elaborate jewels, the molded or printed prototypes are assembled in a "cast iron tree". Depending on the size, weight, and metal to be poured, two or more prototypes are attached to a vertical structure known as a drinking fountain, which allows molten metal to flow into multiple cavities from a single point of entry (Sias, 2005; Singh; Singh; Hashmi, 2016). Finally, the trees are located in a circular rubber base and inserted in a stainless steel or aluminum jar, since they are preferred materials because they have high thermal conductivity (Singh; Singh, 2016). Next, the molds are prepared with investment, where the gesso of Paris is one of the favorite materials for the elaboration of jewels in gold and silver alloys. According to the measurements of the stainless steel container, a mixture of water is made: gypsum, this mixture is emptied to exceed the height of the tree, allowed to dry and solidify to form a uniform solid outer layer, which reproduces every detail of the prototype ( Prasad, 2012). Thus, the complete drying of the mixture for the mold can last from 16 to 48 h, which

allows the coating to cure (harden) and obtain a mold as strong as possible (Corti, 2010; Prasad, 2012). However, it should be taken into account that gypsum cannot be used for casting metals with melting points higher than 1000 °C, because the gypsum begins to degrade sulfur compounds, mainly calcium sulfate, with temperatures of foundry between 1100 and 2000 °C (Beeley; Smart, 1995; Sias, 2005).

On the other hand, once the plaster molds have completely cured, the rubber base is removed and the containers are placed in an oven so that the wax melts and/or vaporizes, resulting in a cavity. The mold should be heated so that the surface layers of wax melt and thus avoid cracking and even destruction of the mold, which could be caused by the differential thermal expansion between the wax and the plaster (Pattnaik *et al.*, 2012; Prasad, 2012). Generally, different heating stages are established in the oven, with a temperature that does not exceed 800 °C especially when plaster is used, since, at higher temperatures, the reaction between calcium sulfate and silica causes the investment to rupture, when generating CaSiO<sub>3</sub> (Mohd; Ismail; Ahmad; Isa, 2015; Sias, 2005). This stage may take 12 to 16 hours, depending on the size and quantity of the trees inserted in the oven, the size of the metal jars and the materials used for prototyping.

Subsequently, when all the wax is removed from the plaster mold, the smelting of the metal or casting begins, for which the metal jar is placed in a casting machine with vacuum assistance. This facilitates the discharge and expulsion of air through the plaster and the pouring of the metal into the cavity before it solidifies. The metal or its alloy melt in a crucible, which ensures that viscosity is over-regulated, which allows filling the fine details of the cavity (Campos; Romeiro, 2013; Singh *et al.*, 2016). The pouring temperature should not be very high, because it could break the plaster cast and should not be very low, because defective parts would be produced (Singh *et al.*, 2016).

Then, the plaster is removed to release the piece by mechanical shock, immersing it in cold water, applying a high-pressure water jet (6-10 ksi) or chemically dissolving it with liquid nitrogen frozen at 195 °C or molten sodium hydroxide between 482 and 537 °C (Corti, 2010; Prasad, 2012). Once the piece of jewelry has been removed, it is cut from the casting tree. One of the biggest advantages of the lost wax process is that parts that normally require little or no finishing work are produced, which saves time, reduces costs and speeds up production (Pattnaik *et al.*, 2012).

## **Additive manufacturing or 3D printing**

The term additive manufacturing or 3D printing encompasses a large number of processes and technologies that offer a full spectrum of capabilities for the production of solid parts and products by joining materials (wax, powder or plastic), generally layer upon layer from 3D model data, unlike subtractive manufacturing methodologies such as traditional ASTM F2792-12a machining. (ASTM International, 2012), (Mellor; Hao; Zhang, 2014). 3D printing has significant advantages over other techniques derived from its production capacity, customer customization and product development with complex structures (Schniederjans, 2017; Stansbury; Idacavage, 2016). Other advantages include high flexibility in the manufacture of parts, affordability and rapid evaluation of designs, ability to facilitate the optimization of molding parameters, material savings by reducing subtractive manufacturing processes and savings in delivery time in the development of tools for high volume production (Berman, 2012; Holmström; Partanen; Tuomi; Walter, 2010; Pattnaik *et al.*, 2012; Petrovic *et al.*, 2009).

Currently, there is a diversified market that requires the manufacture of customized products, so 3D printing is being used to produce medical and dental parts, spare parts for electronic products and appliances, topographic models, lighter aircraft parts, prosthetic devices customized, among others (Kearney, 2014; Bhandari; Regina, 2014; Petrick; Simpson, 2013; Ramya; Vanapalli, 2016; Schniederjans, 2017). Also, it is being used by fashion and jewelry designers for prototyping, custom products and artistic pieces (Kearney, 2014; Yap; Yeong, 2014).

## Stages of the 3D printing process

3D printing consists of two phases: a virtual phase (modeling and simulation) and a physical phase (manufacturing). To transform a 2D design (sketch) into a 3D design, a computer-aided design software (3D-CAD) is used to create a digital model, which is then virtually divided into many horizontal thin layers necessary to complete the model piece (Vanderploeg; Lee; Mamp, 2017).

The stages of the printing process are schematized in Figure 2.

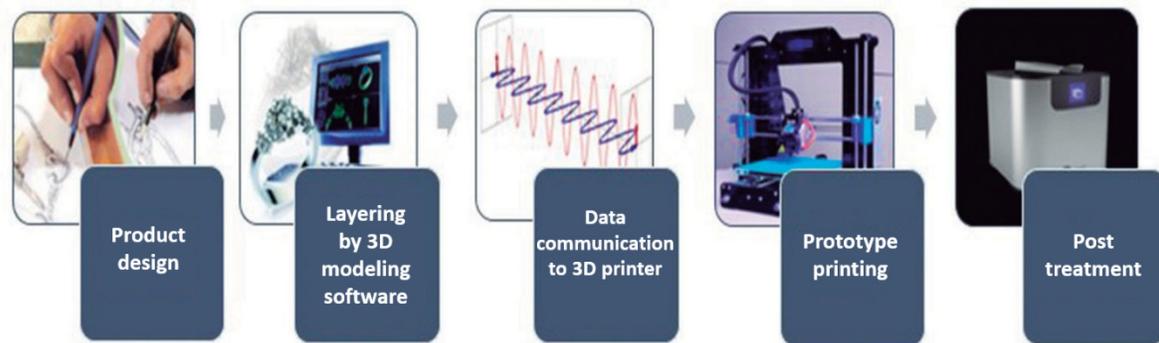


Figure 2. Stages of the printing process.

Source: own elaboration from (Chua; Leong; Lim, 2010; Vanderploeg; Lee; Mamp, 2017).

The first step of 3D printing is the generation of a solid digital or 3D printable surface model (three-dimensional), which describes and mathematically depicts the external geometry of an object (Gibson; Rosen; Stucker, 2015). This model is generated by a computer-aided design (CAD) software, using online services provided by 3D printing platforms (*Thingiverse, Shapeways or Sculpteo*) or by generating a digital model of an existing object using 3D scanner, which, then It is divided into thousands of layers (according to the resolution) through preparation software (Gao *et al.*, 2015; Rayna; Striukova, 2016). Rhino 3D is one of the most used programs in 3D design modeling for clothing and jewelry products, which allows working with complex curved surfaces (Yap; Yeong, 2014).

Subsequently, the closed external surfaces of the CAD model are represented by *standard triangulation language format* (STL), this format is imported into a segmentation program that converts it into G code, which, It is a programming language for machines that work with Computerized Numerical Control (CNC) and that provides step-by-step movement instructions for the printer (Balletti; Ballarin; Guerra, 2017; Redwood, sf b). The *STL* file is sent to the printer and according to the layers that have been obtained, the model is cut into cross-sections (Chua; Leong; Lim, 2010). The printing of the piece may take several minutes to several hours to complete depending on the size and complexity of the model and the type of machine used.

## Printing technologies

The technologies that can be used to build successive layers are varied and at different levels of development. 3D printing processes can be direct and indirect.

Direct processes selectively melt the bed of metal powder using an energy source such as a laser beam or electrons, to manufacture the metal parts directly (Yap; Yeong, 2014). The 3D technologies of this group are selective laser fusion (*SLM*) and electron beam fusion (*EBM*), which can generally be used for medium to high volume production (Cheah; Chua; Lee; Feng; Totong, 2005).

On the other hand, indirect 3D printing does not produce the final parts directly on the metal; instead, a prototype manufactured from standard materials with properties known as resin is used, which are then used for investment casting (Cheah *et al.*, 2005; Gebhardt, 2012; Yap; Yeong, 2014). Thus, the quality of the mold depends mainly on the quality of the prototype. Some of the technologies of this type are laser stereolithography (SLA), fused deposition modeling (FDM) and digital light processing (DPL)) (Cheah *et al.*, 2005; Guo; Leu, 2013).

### 3D printing application in prototyping

Currently, modern 3D printing technology is combined with traditional metal casting for jewelry creation. To do this, it begins with the printing of a 3D resin model. The support structures are printed together with the prototype to ensure that it does not break. Next, the support structures are removed and the prototype is cleaned. Then, the traditional lost wax process is continued. The complete process is presented in Figure 3.

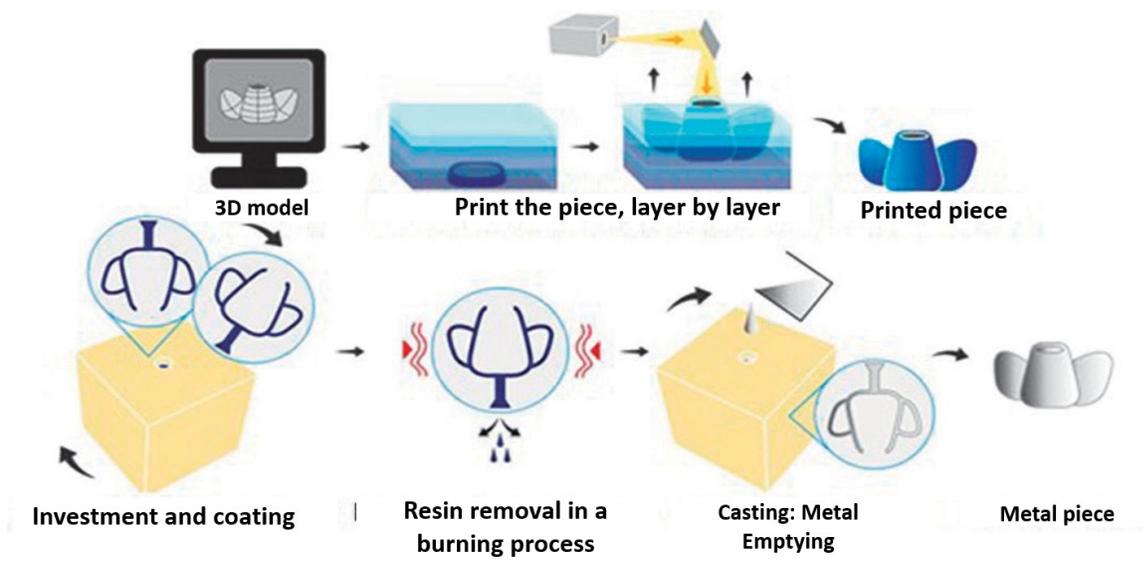


Figure 3. Stages of the Lost Wax Process with 3D printed patterns. Courtesy of Sculpteo.

Source: courtesy Sculpteo Sculpteo. (n.d.). Sculpteo. Retrieved October 20, 2018, from <https://www.sculpteo.com/en/glossary/3d-printed-wax/>

The 3D printing integrated to the lost wax process allows the creation of very complex and customized prototypes; production of multiple designs in a single print; production of pieces with a very high level of detail; significant reduction of delivery times and cost compared to traditional prototyping techniques (CNC in wax, cast aluminum molds, among others); quality improvement and precision; error minimization; production flexibility by eliminating line balance problems and production bottlenecks and achieving more precise control and monitoring of processes (Campos; Romeiro, 2013; Huang *et al.*, 2013; Muñoz-Mesa; Sánchez, 2016; Redwood, s.f. a). In this way, 3D printing has become a useful tool for prototyping and design development in an economical and effective way in less time (Redwood, s.f. c). Thus, thanks to the variety of material it is possible to manufacture the complete jewel with 3D printing; However, the main effort has been focused on finding materials with which there are no problems of cracking in the plaster, incomplete combustion or presence of residual ash after the burning stage (Marwah; Sharif; Zainol; Ibrahim; Mohamad, 2013).

Jewelry companies worldwide are using this new technology, such as *Tripsion*, *Sharebot*, *American Pearl*, *Lupeon* and *Makebu*, which not only benefit from 3D printing at the production stage but also as a marketing strategy (Muñoz-Mesa; Sánchez, 2016).

## Methodology

### *Design selection and prototyping*

The design of the piece of jewelry that was selected has a complex surface, with curved and flat surfaces, with small text and letters formed by very thin and difficult to reproduce crossbars; Therefore, it was considered as an intricate piece that requires demanding quality standards. The design is presented in Figure 4.

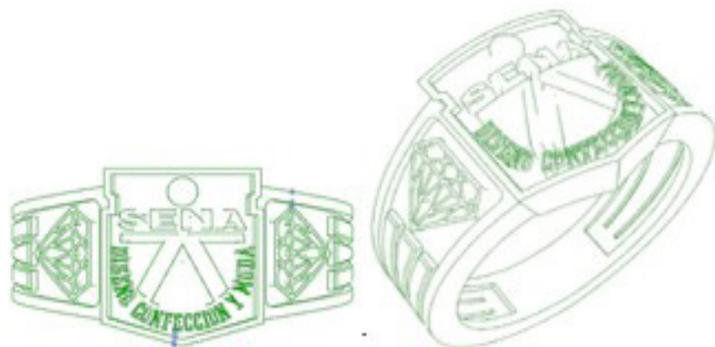


Figure 4. A CAD model of the ring for 3D printing.  
Source: self-made.

For printing, two polymeric resins were selected: Emerald Green (provided by B9 Creator) and Epic 2000-Green (manufactured by Jamghe MSDS). Printing was done on a B9 Creator V1.2 printer and a Makex Model U50 printer for the mentioned resins, respectively. For the curing stage, a high-intensity UV LED curing chamber was used (40 mW/cm<sup>2</sup>).

### *Investigation Preparation*

In the preparation of the investment, a ratio of 1 g (or mL) of water per 2.5 g of plaster was used, which is considered by Actis Grande, Forno, Klotz, and Tiberto (2011) as the most optimal. 38.1 mm x 63.5 mm stainless steel jars (1.5 in diameter x 2.5 in high) were used).

### *Burning and casting stage*

At this stage, different burning conditions were tested as presented in Figure 5.

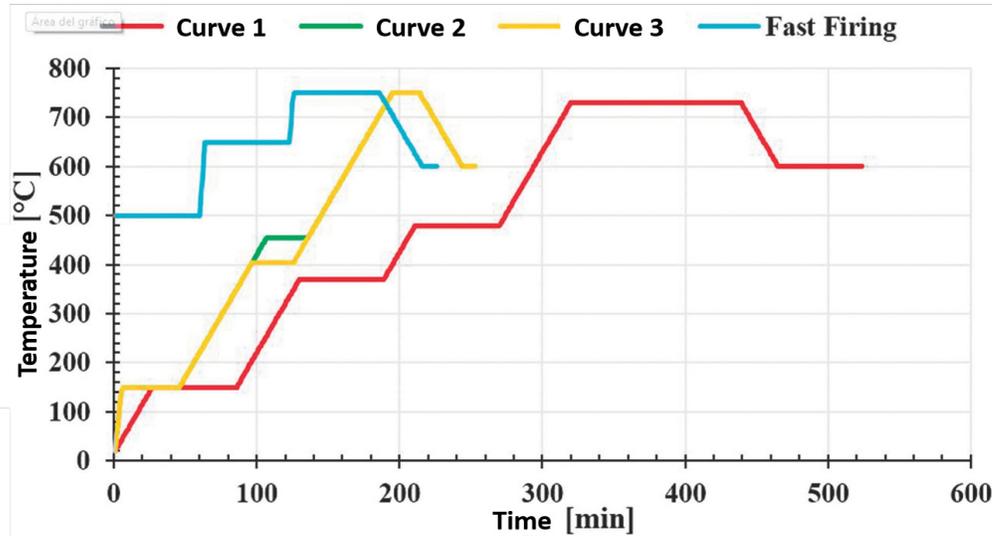


Figure 5. Burning curves tested.  
Source: self-made.

Therefore, it could be shown that **curve 1** (conventional curve): consists of four ramps at 150, 370, 480 and 732 °C, with a heating rate of 5 °C/min maintained for 1 h. The last stage was maintained for 2 h. This curve was tested with the two resins selected.

**Curve 2:** consisted of three different ramps at 150, 455 and 750 °C. From room temperature, the temperature was increased to 150 °C, at 30 °C/min and maintained for 40 min. From 150 to 455 °C a heating rate of 5 °C/min was used, which was maintained in the last stages. This temperature was sustained for 30 min and then increased to 750 °C, remaining constant for 20 min. This curve was tested with the two resins selected.

**Curve 3:** consisted of three different ramps at 150, 405 and 750 °C. From room temperature, the temperature was increased to 150 °C, at 30 °C/min and maintained for 40 min. From 150 to 405 °C a heating rate of 5 °C/min was used, which was maintained in the last stages. This temperature was sustained for 30 min and then increased to 750 °C, remaining constant for 20 min. This curve was tested only with the Epic 2000 resin.

**Curve 4:** it was a *fast-firing* cycle. The containers were placed in the oven directly at 500 °C. After 60 minutes of support, the oven temperature increased rapidly to 650 °C and was maintained for 60 minutes, 5 minutes before that time, the jars were removed from the oven to inject compressed air. Then they were inserted back into the oven to continue with rapid heating up to 750 °C. This curve was tested with the two resins.

In the end, the vessels were cooled to 600 °C and kept at that temperature for 10 min, except in curve 1 where this temperature was maintained for 1 h.

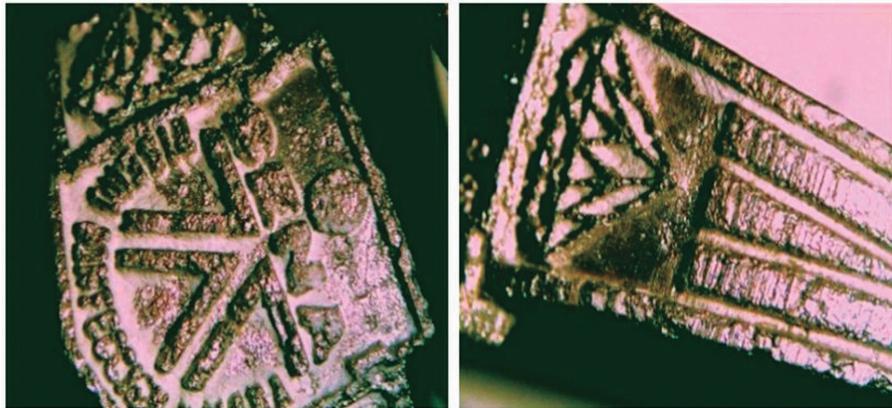
The burn stage was carried out in an oven with *Venturi Neyoulcan 3-550 A* system and a *Lamicol* brand *Vacuum* with suction specifications of 10 to 30 Pa (pascals) was used to empty the metal).

## Results and Discussion

Resin prototypes are difficult to burn completely when using a burn curve traditionally used for wax. That is why the pieces produced under these conditions have a poor surface finish and require extensive polishing

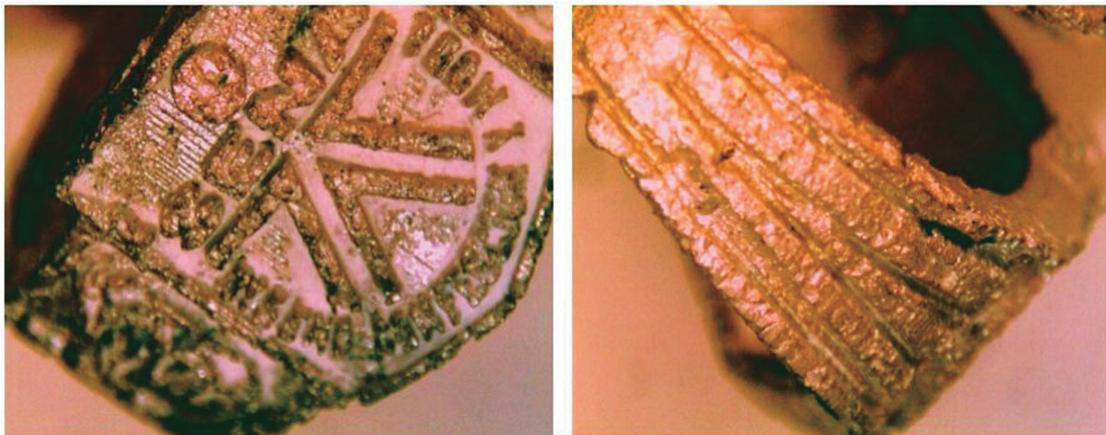
work, so it is more profitable to repeat the part by the process conditions. The choice of the burn cycle suitable for the resins used is based on the quality of the final piece. In this case, the burning conditions were selected with which a balance of the quality obtained in the thick and thin parts of the cast was achieved. The visual inspection was the first quality test that was performed on the parts, followed by the use of a Motic SMZ168 Stereo Zoom microscope, which has a magnification range of 7.5 to 50x, in which the parts were examined, and guarantees a greater level of detail.

The castings obtained from the burning of the resins under the conventional curve-curve 1, showed a rugged and rough surface (see Figure 6). Additionally, they presented perforations and holes.



*Figure 6. Surface details of cast parts printed with B9-Emerald resin under conventional burn conditions (Curve 1).  
Source: self-made.*

Similar results were obtained with the Epic 2000 resin, whose piece also presented an irregular surface with very visible pores and perforations, as shown in Figure 7.



*Figure 7. Surface details of castings printed with Epic 2000 resin under conventional burn conditions (Curve 1)  
Source: self-made.*

Regarding curve 2, in which the support time in the different stages was reduced, a better balance between the thick parts and the details of the piece was evidenced. The surface roughness improved for the B9-Emerald resin, compared to the results obtained in curve 1 as shown in Figure 8.

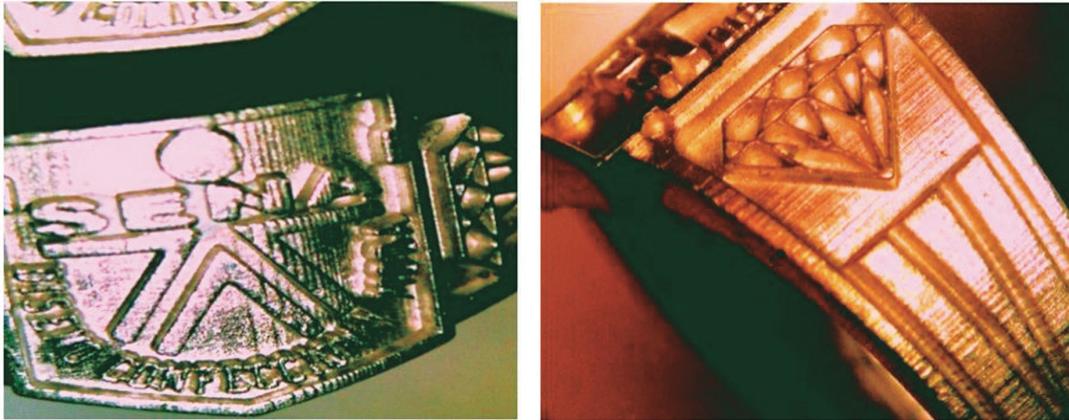


Figure 8. Surface details of cast parts printed with B9-Emerald resin under curve 2 burn conditions.  
Source: self-made.

In the case of the pieces printed in Epic 2000, there is a presence of pores in the front part of the piece, specifically in the upper part of the word “clothing” (see Figure 9).



Figure 9. Surface details of castings printed with Epic 2000 resin under Curve 2 burn conditions.  
Source: self-made.

The pieces obtained under the conditions of curve 2 have a good finish, so it would require a normal polishing to remove them. Curve 3 was only tested with the Epic 2000 resin. As shown in Figure 10, it was possible to show the presence of cracks and perforations on the surface, possibly related to the strong thermal stresses experienced by the plaster. Even, in one of the pieces, it is possible to appreciate large and aligned pores that could have been generated by an existing bubble in the plaster mold, which when broken generated internally united pores. However, the letters looked good and the print lines are visible.

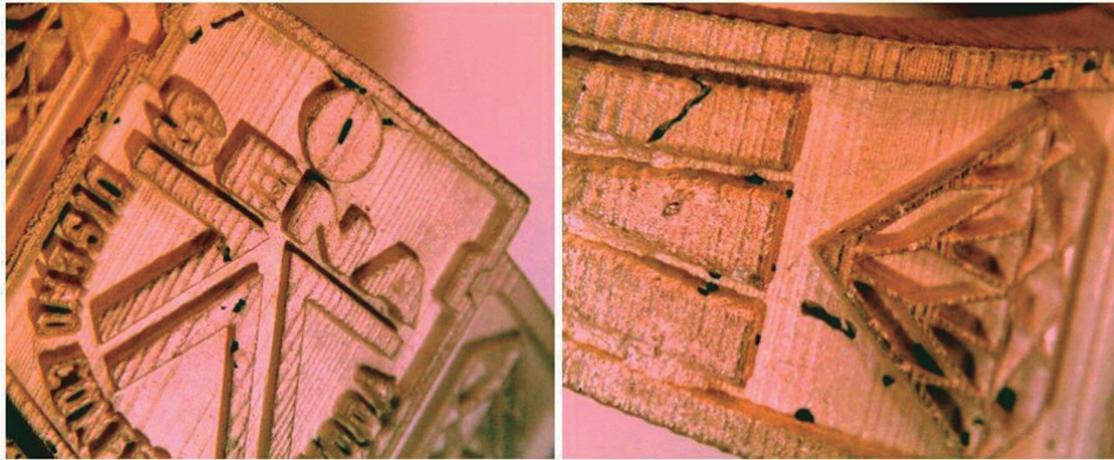


Figure 10. Surface details of castings printed with Epic 2000 resin under Curve 3 burn conditions.  
Source: self-made.

On the other hand, the quick burn curve 4 was tested in order to determine if the plaster would tolerate a similar treatment and if a piece with an excellent finish could be obtained in the shortest possible time. However, the immersion of the jar in the oven at 500 °C, followed by heating at 730 °C, was not beneficial to improve the quality of the emptying of jewelry pieces. The cast, whose prototype was made with Epic 2000 resin, showed more damage and a more rough surface compared to the piece obtained from B9-Emerald resin. (See Figures 11, 12).



Figure 11. Surface details of cast parts printed with B9-Emerald resin under rapid burn conditions.  
Source: self-made.

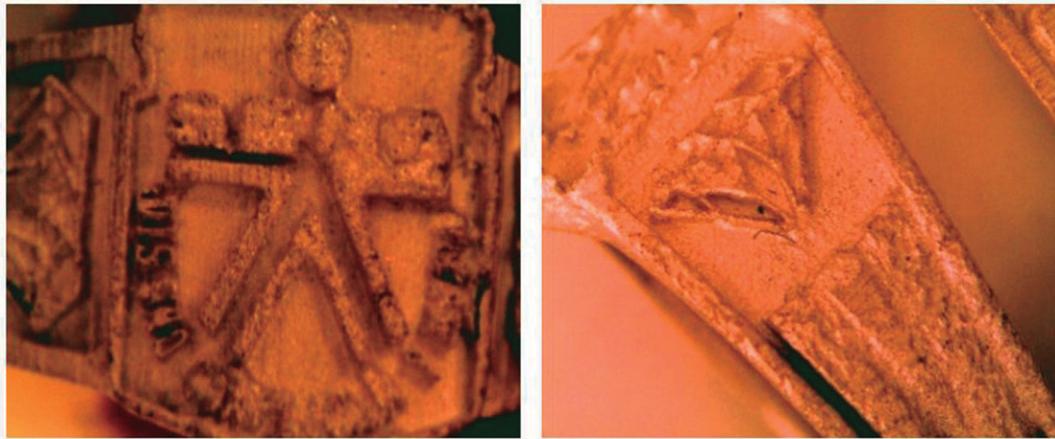


Figure 12. Surface details of castings printed with Epic 2000 resin under rapid burn conditions.

Source: self-made.

According to the technical experts consulted, most of the jewelry pieces obtained look low quality, due to the presence of pores, cracks, accumulation of material, prominence, high toughness, and illegible letters.

## Conclusions

3D printing has gained importance and has become a technology with disruptive potential, due to its versatility for the direct production of physical objects from digital design data, providing benefits in terms of cost, ability to comply with solutions Complex design and time-saving. The jewelry industry is an example of its application in which freedom of design is needed, to create pieces with a high degree of innovation and customization, with exact specifications and dimensions, without the high surpluses generated by being uniquely manufactured. To promote the widespread use of resin parts in the lost wax process it is important not to alter the process and keep it as traditional as possible, allowing jewelry companies to benefit from the convenience offered by the use of 3D printing.

In general terms, satisfactory results were obtained with a curve that has three ramps at 150, 455 and 750 °C, maintained for 40, 30 and 20 min, respectively. However, the pieces presented details that affect their quality, so it is difficult to say exactly which process variable had the highest incidence. Therefore, it is important to analyze other variables such as plaster composition, water: plaster ratio, setting time, location of drinking fountains, type of oven used, the actual temperature of the molds, among others. Likewise, to strengthen this research it is necessary to make an analysis of the interaction between resins and plaster, taking into account the burning conditions.

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