

Study of Investment Casting Process For 3D Printed Jewellery Design

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Abstract. Manufacturing processes are increasingly complex with the growing demands of advanced technology in the production processes, especially in the handicraft industry. The complex jewellery designs are complicated to be produced by hand, considering the international demand and dynamics in the jewellery industry. However, advanced production processes and 3D printers are changing the way jewellery designers and manufacturers work and making it easier to produce quality products with fewer production and labour input hours. This study examines the investment casting process of 3D printed design as an option for jewellery manufacturing. The research aims to access jewellery manufacturing processes and its technology application by using trending 3D printing as a rapid prototype. It used the design and production process of 'OneCent Africa' as a case study to describe the process in the investment casting of jewellery products. The investment casting was conducted by prototyping, and the lost wax jewellery casting stages using the vacuum casting machines and burnout oven, with the casting process monitored in parts. This research results led to a better understanding of the experimental casting outcomes and described the potential for the future technological development of jewellery businesses.

1 introduction

Presently, jewellery industries are experiencing growing demand to produce composite and assorted products in lesser production stages, aiming to accomplish a lesser amount of overall cost with improved quality [1]. As product production time and cost decrease, the manufacturers are gradually more under pressure to produce quickly, at lower cost and accurately [2]. As the jewellery manufacturing firms experience an increasing demand for rapid prototyping (RP) technology, particularly computer-aided design (CAD), it has shown substantial potential in product development. Compared to the traditional manufacturing techniques, investment casting has the advantages of short processing times and a good surface finish. Consequently, investment casting techniques are improving and are becoming

increasingly popular among jewellery manufacturers. This study aims to inform beginners on how to design, develop, and produce 3D printed jewellery products to experiment, prove, and understand the production process, equipment and materials needed for the application of technology in precious metal production of enterprises in the jewellery manufacturing.

The investment casting process is economical to mass-produce jewellery with complex shapes using different metal materials. To produce wax models for the investment casting process, the adoption of conventional tools is frequently used in the machining process. Instead, using conventional tooling for producing wax models may lead to extra cost and time, causing a reduction in total output and reducing the advantage of using such an approach, especially for multiple model productions [3]. The applications of rapid prototyping technology and its process can substantially reduce the cost and time of design and production [4]. This application is a direct production of wax models required for investment casting. Applications of wax models require the types of processes that can produce the final design of the jewellery with necessary detail near replica design with minimum requirements.

This research uses the investment casting technique to produce the final jewellery products. The paper attempts to highlight the present jewellery industry's need for a flexible and innovative new technology that will help jewellery entrepreneurs respond to the customer's demands for more individually designed and personalised jewellery products. In South Africa, the jewellery firms have not fully adopted the typical jewellery manufacturing processes like lost-wax investment casting and, more significantly, the design and production flexibility. This paper is intended to present the production process and knowledge to speed up the jewellery industry application of the new design and production capabilities offered by the lost-wax investment casting processes for working with precious metals.

2 Research Methodology and Case Study

For the jewellery manufacturing process, visual content is presented with initial sketches, which were transformed into exquisite jewellery created using 3D printing technologies. To attain exact modelling of the proper detailed objects, a 3D programme called Blender was used to support the entirety of the model. The model was created according to the necessities of the preferred 3D printing technology by considering the weight of each final jewellery piece, which may not be excessively heavy to wear, mainly printed metal pieces [3]. This is case study research of OneCent Africa jewellery enterprise located in Cape Town, South Africa. Firstly, the 3-D model of the product was created in Tiertime UP Box+ 3D Printer. The investment casting approach for the design of loss experiments was applied to this research. The designed concept and drawings were used as a model to produce the unique piece of Jewellery [5]. Figure 19 shows this investment casting as a multistage process of eleven separate stages from the initial idea to the finishing of the jewellery. The stages do not allow errors and must be strictly followed as any negligence in the process will result to a potential defect in the finished product [6]. Arriving at a completed casting after fabrication of the wax pattern involves the following three steps: (1) investing-surrounding the wax pattern with a material that can accurately duplicate its shape and anatomic features; (2) burnout-removal of the wax pattern so that a mould is created into which the molten alloy can be placed, and (3) casting-introducing the molten alloy into the previously prepared mould.

3 Analysis and Results

3.1 Stage 1: Concept Sketch

Conception represents the birth of the idea and the moment of drawing a rough sketch of a new jewellery product. To manufacture the exclusive OneCent Africa product, the first step is creating a sketch of the concept, as shown in figure 1a below. For the jewellery manufacturing process, visual content is presented with initial sketches, which were transformed into exquisite jewellery created using 3D printing technologies.

3.2 Stage 2: Design Making

To attain exact modelling of the suitable detailed objects, a 3D programme called Blender was used to support the entirety of the model, including sprue needed for adequate cast. Figure 1b shows the digital model of the OneCent Africa pendant with a designed decorative outer surface. The surface is smooth and consistent, giving a surface and form ready for casting and final finishing. It is essential to create the models following the necessities of the preferred 3D printing technology by considering the weight of each final jewellery piece, which may not be excessively heavy to wear, mainly printed metal pieces [3]. For this study, the CAD software JewelCAD was used to take the parts from concept to 3D printed pattern. [5] contributes that the designed concept and drawings were used as a model to produce the unique piece of jewellery.

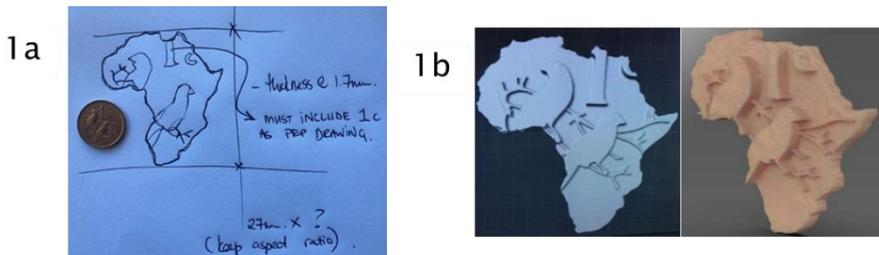


Figure 1: Digital 3D model of OneCent Africa pendant

3.3 Stage 3: Printing

According to [7] 3-D printer is used with the aim of guaranteeing rapid prototyping of the models. 3-D printers are based on the principle of “additive manufacturing” and are created with different technologies. One of the preparation processes of getting the 3D print ready for moulding is filling and polishing to achieve a precise surface finish. Slight corrections are done to ensure it has a clean and detailed appearance. A castable wax 40 resin was used. This is a high wax content direct wax resin with excellent castability. Figure 2 shows the Resin Print with specifications: Length of print: 27.2mm; Thickness of print: 1.4mm. The thicker wall of the model tends to perform better in casting and with attachment to the sprue stem. After the print, the master pattern is cautiously prepared before it is duplicated. An engraving tool was used to craft out the fine details on the master model.



Figure 2: Printed 3D model of OneCent Africa Pendant for investment

3.4 Stage 4: The Mould

In the vacuum casting system, the moulds used are produced of silicone rubber. The type of mould is reusable to make several castings. The reusable type is a two-faced mould with patterns on both parts, and each part is properly aligned and keyed to each other for producing three-dimensional casting. The form used for OneCent Africa has been highly tested over time for fitness to produce moulds with high exactness of duplication from the original models. Gas or air that might be included during mixing can cause deformations that differ in result at different steps, including deformations of the final product. The mixture was degassed under a vacuum before the mould was formed for best results.

3.4.1 Step 1: *Preparing the Mould for Casting*

The master pattern is a OneCent Africa piece created through rapid manufacturing techniques of 3d printing technology. The piece created through 3d printing was produced using stereolithography techniques for creating the prototype [8]. A precaution was taken to ensure that the master model piece has accurate proportions so that the final casting piece has the wanted proportions. To achieve an impression with optima definition with the reused mould, the model is replaced in the mould cavity, the mould parts pressed together again, and the mould section was carefully separated to remove the model.

3.4.2 Step 2: *Creating the master model*

Firstly, a master model is created. The master pattern is cautiously prepared before it is duplicated. The master pattern is a OneCent Africa piece created through rapid manufacturing techniques of 3d printing technology. The piece created through 3d printing was produced using stereolithography techniques for creating the prototype. A precaution was taken to ensure that the master model piece has accurate proportions so that the final casting piece has the wanted proportions too.

3.4.3 Step 3: *A mould frame was set up to mount the master model.*

For this research, figure 3 describes a manually created mould frame with measurements of 70mm height, 40mm length, and 20mm width made from a smooth surfaced glass frame secured together with an office clip.

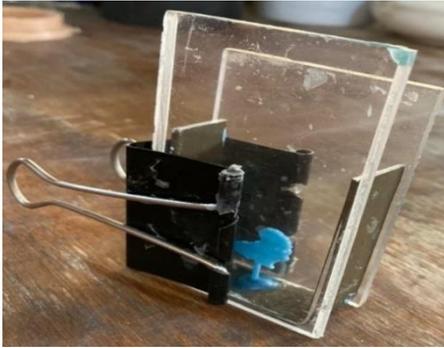


Figure 3: Mould casting frame

3.4.4 Step 4 : Measuring and mixing the silicone rubber.

When the prepared master pattern is ready, the next step is to position it in the mould frame. The frame is filled with liquid silicone and will be left for curing. The curing process will take about six hours until it solidifies. For this study, a foodsil two-part with a high tear strength of cure at room temperature with minor shrinkage was used as a flexible silicone mould rubber compound. This silicone is preferred as a mould material because it is appropriate for rapid prototyping, wax casting and various other casting material [9]. The mixing of the silicone rubber is done through the following steps below. To calculate the quantity of Silicon needed for this study, the Volume of the mould frame was multiplied by the specific gravity of foodsil 40, which is 1.1.

Length x Breadth x Height = Volume of the mould frame

$40 \times 20 \times 70 = 56,000$

The Volume of Silicon needed = Volume of the mould frame x
Specific gravity

$56,000 \times 1.1 = 61,600$

The Volume of Silicon required = 61.6g

3.4.1a Step 4.1: Processing

The process starts by measuring the two components, Part A and Part B, separately. The 35gram of Part A and 35grams of Part B were measured in a mixing container. For the components to be thoroughly mixed, it was mixed for about 3 minutes with care not to beat and whip the material throughout the mixing process to avoid introducing air bubbles. Calculating the amount of silicon rubber: Volume of the mould box x specific gravity (SG) of Silicon

3.4.1b Step 4.2: De-gas

Figure 4 demonstrates that the silicone rubber was placed in a vacuum chamber for 2 minutes to degas by evacuating the air bubbles. The silicone rubber expanded about three times in Volume, the operation is cautiously watched until primary degassing

is accomplished, i.e., when the level of the rinsing liquid in the mixing bowl has collapsed.



Figure 4: Vacuum Investment Chamber Machine

3.4.1c Step 4.3: Pouring

Figure 5 shows the silicone rubber is poured steadily and slowly to the lowest part of the mould frame in a thin stream at a single spot to allow material to flow around the model at self-level. The model was covered up to 10 mm. Cautious care to cleanliness is considered because the vacuum casting technique reproduces exactly every



blemish and imperfection of the mould. The quality of the mould directly affects productivity.

Figure 5: Silicon poured in mould casting frame

3.4.1d Step 4.4: De-gas

Further secondary degassing is performed by returning the rubber to the vacuum chamber following the same process and time for primary degassing above to evacuate the trapped air bubbles.

3.4.1e Step 4.5: Curing

the silicone rubber is allowed to cure for about 6 hours at room temperature (23°C) to solidify before demoulding.

3.4.1f Step 4.6: De-moulding

After curing, the mould frame is separated from the mould, which is cautiously cut lengthways at a predetermined ridge line with a scalpel to take out the pattern. The mould used for this research is a complex, and detailed, hence the part matching the undercut is done in a way that it can be easily removed without damaging the wax pattern [6]. Hence, the mould is acquired as a detailed piece with perfect product quality and reducing the effort of finishing. The cut is purposefully rough to key the mould halves when putting together. Afterwards, the finished process leaves a replica cavity of the original 3D printed pattern, as shown in figure 6 below.



Figure 6: Mould of 3D Printed pattern

3.5 Stage 5: Injection Waxes

The waxes used in the injection wax model have the characteristic of forming a model for one-time reproduction by lost investment casting. The wax has both flexibility and hardness. The wax used for this study has the following characteristics: (i) it runs efficiently at a moderate temperature so that its properties are not damaged by overheating, (ii) it does not adhere to the mould, and (iii) it is flexible when warm to easily release it from the mould, (iv) desirable casting qualities of low thermal expansion, ease in-flow and (v) ability to burn out entirely after investment. All these are crucial in accomplishing a good casting. When melted, this is injected into the mould tool to create the wax pattern by solidifying inside it. The wax used is in a flake's form, which makes it easier to be melted in the wax injector tank [10]. An appropriate amount is poured into the injector machine according to its capacity.

Therefore, the mould cavity dimensions are higher than the nominal data to cover the shrinkages of casting metal and wax. Also, the wax shrinkage is determined by the wax solidification rate and the thermal conductivity of the mould. The shrinkage of casting metal was calculated using the casting design handbook [11]. Flexi blue-R34WF of the GRS premium is used for this research because it is the most flexible wax with high plasticity and exceptional memory and durability. Table 1 below describes the characteristics of the Flexi blue-R34WF. The flexibility allows easy removal from complex moulds and can withstand rough handling. It has an injection temperature of 80⁰C/176F, making it the highest quality and best for jewellery manufacturing.

Table 1: Wax technical data for Flexi Blue R34WF

Flow (cPs)	Nozzle	Barrel	Hardness (N)	Flexibility (N)	Solidification Point (°C)	Linear shrinkage (%)	Injection Temp (°C)
375	62	58	171	394	61	1.7	70

3.5.1 Wax injection process

When injecting wax, the mould casting frames were used to hold the rubber mould with hands. For this research casting frame was designed to create more comfort and efficiency for the hand and to produce more consistent injections. Figure 7 shows the wax model with the sprue end to attach them to the sprue tree. The injection time was set at 10s injection setting parameters, with freezing time at the 30s. Successively running different injections led to good scenery, producing approximately 50 wax models per hour.



Figure 7: Wax model with sprue attachment.

The result from this research identifies some characteristics of the waxing process with the following results:

- i. Good reproduction capacity with thorough rubber mould details
- ii. Minute metal loss with excellent finishing surface
- iii. High-quality property of material allows easy removal of the prototype from mould
- iv. The prototype is highly flexible and prone to cracking.
- v. Reduced effect of ash content, therefore, lowering residue during casting.

3.5.2 Melting wax

Figure 8 describes how the wax injection machine is operated manually in which the injection pump is pressed down while the mould is held against the nozzle. By manual hydraulic ram action, molten wax immediately fills the mould cavity. The wax capacity for the wax pot is 0.45kg operating at a room temperature of 90°C. The machine has thermostatic control, an insulated tank with a capacity of one quart of molten wax, and a built-in thermometer that shows temperatures up to 220°F (104.4°C). After the wax was poured into the tank, the researchers waited for 2 hours for the temperature to rise to work heat before injection started.



Figure 8: wax injection machine

3.5.3 Wax Injection

The injection nozzle is placed at the top of the tank. The nozzle is the exact shape of the sprue opening in the rubber mould. There is a tight fit to ensure maximum pressure on the wax when it is injected. The nozzle is mounted on a spring, and when the mould is pressed against it, a valve opens and allows the hot wax to be injected into the mould by manual hydraulic pressure. When the mould is removed, pressure on the spring in the valve is released and cuts off wax flow. At proper wax-melting temperature, the nozzles should not leak, nor should the wax freeze, but should readily fill the mould cavity at the working temperature for the wax was 80C (176F). The wax is not made hotter to not develop air bubbles that will make the result useless by gathering themselves to the mould surface.

3.6 STAGE 6: SPRUEING

It is economical in repeat production to use a large flask as viable and cast as many replicas as possible in the same flask at once. For this research, a tree sprueing system was used. This is used because several smaller-sized models are cast in a single flask. The models are arranged around one sprue stem, which is vertically and centrally positioned wax sprue fitted in a solid wax position in the centre. The end of each model runs in an upward and outwards direction from the central wax stem, and joined to the stem beginning from the bottom, then progressing upward. When preparing a sprue tree, it is important to visualise the positioning of each wax pattern in opposition to the building orientation, hence anything facing upwards during the “building phase” will be facing downwards during the casting phase.

A space of 3/16 is the thinnest distance allowed between the waxes. The [6] described the sprue as the passage through which molten metal can flow into the mould in an invested casting after the wax has been removed. For this study, the sprue is made from wax. The sprue process was done by surrounding the wax pattern with a heat resistance investment material mould. The role of the sprue is to: (i) avoid distortion by holding wax patten, (ii) form a channel to allow the heated wax to flow out of the mould (iii) allow the molten metal to flow into the mould space formerly filled with the wax pattern

3.6.1 Sprue requirement

It is recommended that the sprue have a relatively large diameter because this increases the flow of molten metal into the mould [12] [13]. In this case of this research, the sprue is 2.0mm in diameter. However, the sprue is attached to the non-critical part of the pattern and away from obstructing the original design. The sprue attachment was positioned at an angle (about 45 degrees), allowing the incoming molten metal to flow freely to all parts of the mould.

3.6.2 Reserves

Also, an additional wax of a small quantity was added to the sprue former 1mm below the wax pattern to cover up for the shrinkage that happens during casting solidification.

3.6.3 Length and venting

The Length of the sprue former was positioned by keeping the wax pattern about 6mm apart from the casting ring length to give enough investment to withstand force. Also, the pattern was placed much closer to the centre ring to allow the escape of gases from the end of the mould. A small vent was provided to improve the casting pattern and help with; (i) the gas escape during casting and (ii) allowing shrinkage during solidification.

3.6.4 Crucible former

This is made of rubber with a diameter of 62mm and a height of 22mm, which serves as a base to which the sprue is attached and is placed in the casting flask during investing. The sprueing technique used is direct, in which the flow of molten metal is directly straight from the casting crucible into the pattern. Figure 9 shows the three crucibles used for different metal casting, i.e., silver, copper, and bronze. Both crucibles for the silver and bronze have a single sprue while the copper has multiple



sprues. For identification, each crucible is marked C= Copper, B= Bronze, and S=Silver.

Figure 9: Crucible former with attached sprue trees

3.6.5 Attaching the wax pattern to the crucible Former

The sprue former in the form of a small-diameter (2 mm diameter) tube made of wax is used for the patterns. One end of the sprue former is bonded to the crucible former (a conical rubber base), and the other end to the wax pattern. After the investment has solidified, the crucible former is detached from the flask base, allowing a funnel-shaped passage for the mould. [14] describes the sprue as the passage allowed by the sprue former after burnout provides an inlet funnel through which the metal will be poured into the mould.

The sprue former was large enough and not too tinny or elongated on each pattern. This is to avoid possible solidification of the metal in the sprue before it arrives at the bigger cavity formed by the wax pattern and sufficiently fills it. The sprue former was attached to the biggest portion of the wax pattern at an angle to allow the incoming metal to flow to all parts of the mould freely. The sprue was fixed at a right angle to ensure even distribution of heat and metal flow.

The wax stem was selected and well positioned with the correct measurement in the crucible former and casting flask. The sprue former was adequately long for the peak point on the wax pattern, which was 5.0mm from the end of the ring. The sprue former was removed from the crucible former and reduced with a knife. Also, the hole in the crucible former was too big to grip the sprue former firmly, and the hole was filled with soft wax. Also, an additional wax of a small quantity was added to the sprue former 1mm below the wax pattern to cover up for the shrinkage that happens during casting solidification [15].

3.7 Stage 7: Investing

Perfect reproduction has been the highest interest of the lost wax investment casting techniques to jewellers. In this regard, every detail and feature invented with wax can be transformed into metal and reproduced. As a result, it has been widely adopted for the past seven decades by many jewellery manufacturers and independent jewellers. Investing is defined as filling the wax pattern surroundings with a heat-resistant material mould that can exactly replicate the pattern and structural features of the wax pattern after burning out the wax pattern to obtain a mould. This research adopted the investment method to

1. provide an accurate reproduction of the structural form of the wax pattern,
2. provide enough intensity to resist the heat of the burnout process and the casting of the real molten metal,
3. give a chance for proper expansion equivalent to the shrinkage and solidification of the metal.

As a result, the mould cavity was made bigger than the wax pattern and escaped the restoration to be reduced from the original wax pattern. This study used locally made apparatus such as crucible former, burnout oven, vacuum chamber, wax injection machine, casting flask, and the investment material to complete the investing process.

3.7.1 Casting flask

A metal casting flask was used to contain the investment material in position during its setting and to control its expansion. Figure 10 below shows the casting flask made of stainless steel with an internal diameter of 52mm greater than the measurement of the pattern and 70mm Height. The casting flask encloses the investment fluid around the wax pattern while the investment cures. It also permitted the solidified investment

to be carefully handled throughout casting and burnout. Hold the investment to the flask fast and avoid tripping the entire mass throughout the casting procedure. The significant benefits of the ring flask for this process are to increase the mould cavity by covering for solidification shrinkage of the metal it provides a space for flexibility of material; it makes removal of the investment more accessible, together with secured casting from the ring after the burnout procedure; during the casting procedure, it serves as an insulator against loss of heat.



Figure 10: Metal casting flask

3.7.2 Crucible Former

See description in section 3.7.4. The aims of using conical metal-based crucible former are to

1. Acquire accuracy of the wax pattern position within the casting ring,
2. Form a conical passage for easy flow of the molten metal, and
3. To create a reservoir for the molten metal from which the solidifying metal can draw additional material towards shrinkage.

3.7.3 Vacuum Chamber

A vacuum investing machine is highly recommended for vacuum mixing of investment materials for consistent results in investing and casting with minimal surface defects, mainly when a gypsum-bonded investment is used. The remaining air bubbles in the mix, and even in vacuum mixing, can be trapped on flat surfaces that are not adapted for air evacuation. Tilting the flask slightly helps in releasing the bubbles to rise to the surface. Too much vibration was prevented not to make solids in the investment settle and led to the accumulation of water adjacent to the wax pattern, causing surface roughness. Too much vibration can also displace small patterns from the sprue former, causing a miscast.

3.7.4 Investment material

A gypsum-bonded investment material with a binder that contains calcium sulphate hemihydrate was used. Gypsum-bonded investment is commonly used in silver and

gold casting. A calcium sulphate dihydrate (gypsum) is formed when the calcium sulphate hemihydrate reacts with water to which successfully binds together the refractory silica. [16] states that this can cause several defects such as gas porosity from the decomposition of gypsum. Other authors [17] [18] [19] [20] in their studies finds that the decomposition of calcium sulphate occurs at a high temperature resulting in the discharge of sulphur dioxide gas into the mould and causing gas porosity at the surface of the metal.

3.7.5 Measuring and mixing investment material

Inside the investment, a space was created as the mould cavity, which was filled by the sprue, wax pattern, and crucible former after the burnout procedure. The HK-1000 jewellery investment powder, which exhibits a higher thermal resistance at high casting temperatures, was used for this research. The investment compositions used with the mixing water to powder ratios (L/Kg) are provided in table 2 below.

Table 2: investment compositions

Model:	HK-1000
Water/Powder Ratio:	40:100
Working Time:	11 min
Initial Set Time:	15 min
Thermal Expansion @725°C:	0.76%
Setting Expansion @ 1hrs.:	0.58%
Thermal Compressive strength (725°C×1hrs):	0.60 MPa
Setting Compressive strength (1hrs.):	1.18 MPa
Max.Burnout Temp.:	715°C(1,315°F)

To guarantee that the bubbles are totally evacuated, mixing the investment was completed with a vacuum chamber. The investment process is completed through the following:

3.7.5a Step 1: Mixing

Investment is made by measuring 450gram of investment and 180 mm of distilled water. A spatula was manually used to pre-mix and pour the investment into a mixing bowl. In order to avoid any air bubbles from the components, it was thoroughly mixed with care for about 8 minutes.

3.7.5b Step 2: Pouring

The investment process is completed by pouring the degassed mixture around the model. The mixture is made to be thin enough to pour into the flask suitably. The investment is poured into the flask by slowly filling it down from the bottom to surround all details of the wax pattern and not directly over the pattern (this is not to knock down the model out of alignment).

3.7.5c Step 3: De-gas

When the investment materials were mixed, then air bubbles became trapped within the mixture. If the air bubbles are not removed before the material solidifies, the bubbles will cause defects such as balls ((metal filled air bubbles) in the finished cast. The investment was placed in a vacuum chamber for 3 minutes to degas and evacuate the air bubbles. When the bubbles start to reach the surface and burst, the bubbles

decrease after a short time, and the valve is opened again. The vacuum chamber process was repeated to evacuate the trapped air completely. The investment expanded during the degassing process to about four times the initial Volume. The container with sufficient Volume was essentially used. The expansion decreases as the bubbles surge to the surface. The process takes about 4 minutes due to: (i) the viscosity of the material, (ii) the Volume of the vacuum chamber, and (iii) the speed of the vacuum pump.

3.7.5d Step 4: Pouring

The investment is steadily and slowly poured to the lowest part of the casting flask in a thin stream at a single spot to allow material to flow around the model at self-level. The model was covered up to 10 mm. Cautious care to cleanliness is considered because the vacuum casting technique reproduces exactly every blemish and imperfection of the mould. The quality of the mould directly affects productivity.

3.7.5e Step 5: De-gas

Figure 11 depicts further secondary degassing is performed by returning the investment flask to the vacuum chamber following the same process and time for primary degassing above to evacuate the trapped air bubbles.



Figure 11: Vacuum chamber de-gassing process

3.7.5f Step 6: Curing

After the investment is poured and degassed, the casting ring was set aside and remain undisturbed for the full cure period of the investment. For this study, figure 12 shows the investment was allowed to cure for about 1 hour at room temperature (23°C) to solidify before putting in the Kiln for the burnout process. This data is based on the specific flask size and the amount of investment used for this research. However, for best practice this study followed the cure times supplied on the data sheet that accompanies the investment, which can vary from supplier to supplier.

For this study, figure 12 shows the investment was allowed to cure for about 1 hour at room temperature (23°C) to solidify before putting in the Kiln for the burnout process.



Figure 12: Investment cured for burnout process.

3.8 Stage 8: The Burnout

The casting rings are placed into the kiln with the mold mouth facing downwards to allow the escape of molted wax in the initial stages of the burnout. The invested pattern was heated at high temperatures after the material was cured. The wax was burnt away from the pattern until all fragments were removed. After burnout, a replica of the wax pattern is achieved for the molten metal to be cast into the mould through the casting sprues. Burnouts involve placing the investment in a thermostatically controlled furnace and heating it until all the wax traces have oxidised to CO₂ gas. When the furnace reached the desired casting temperature, the casting rings was soaked at a stable set temperature for at least 1 hour to ensure a uniform temperature through the whole casting ring. Inadequate burnout time or temperature can result in casting defects caused by wax residues, the results of negative chemical reactions between both the investment material, the metal, and said residues. The researcher makes sure that the full required heat cycle was achieved. Overheating of investment material (above 740⁰c) can also result in the decomposition of crystal bonds of the medium, resulting in loss of detail to the final piece. When the investment has cured, the top of the ring is marked (C= Copper, S= Silver, and B= Bronze) to differentiate between he three metals to be cast.)

3.8.1 Burnout Kiln

The burnout kiln used for this study is heated electrically. It has a vent that allows fumes produced in the process to emerge and is adequately ventilated to avoid health hazards. The kiln chamber is large enough to accommodate the three flasks. The chamber has a built-in pyrometer which correctly shows the temperature and a switch that controls power which controls the temperature at any time within the maximum. The flasks are placed towards

the centre of the chamber with the sprue opening facing down where it is hottest. To cumulate the molten moisture and wax that may begin from the flask, a wax collection sand is placed on the chamber floor to protect the furnace floor. On it is placed triangular sectioned refractory sticks in a spot spreading equally away from a centre. The flask was placed on these and raised above the sandy floor, allowing air access



and wax drainage space. Ceramic pottery props cut to size are also put in place.

Figure 13: Electrical burnout kiln

3.8.2 Burnout circle

A furnace with an automatic temperature control device for the phases, as illustrated in figure 13 below. Opening the door of the furnace was avoided during the circle to prevent the inside temperature from dropping or might cause a temperature shock, thereby causing the investment to crack.

3.8.2a Phase 1

The mould was subjected to a slow heating process from level A to B, as shown in figure 13. To drain the wax and cause all the free moisture in the investment to be eliminated as steam from the flask, the furnace is heated within 1 hour to 300⁰C (572⁰F), higher than the melting temperature of waxes. This initial temperature level was increased slowly to 300⁰C and remained constant for 2 hours. The excessive pressure from the expanded wax and steam pressure will trigger the investment to crack if this stage is accelerated. However, not to allow the mould to crack due to flask metal contraction, the temperature was not allowed to drop below 450⁰F (232⁰C) during burnout.

3.8.2b Phase 2

As the furnace increased to 732⁰C from levels C and D, the remaining wax which has not flowed out was turned to Carbon. The Carbon combined with oxygen at 600–732⁰C from the air formed carbon dioxide and carbon monoxide gases, thus removing all carbon residues in the mould. Hereafter, the burnout cycle continues slowly at 200⁰C per hour and the temperature gains a speedy increase as the highest expansion of both wax and investment occurs between the temperatures of 300-732⁰C (572-1350⁰F) for 5hours 16munites. The investments expand till they get to a temperature of 732⁰C (1350⁰F), after which there is no appreciable change.

3.8.2c Phase 3

To eradicate any traces of Carbon in the mould, it was further heated at 732⁰C, as illustrated in levels D to E, referred to as burnout temperature. At approximately 7 hours, Carbon was eliminated from the mould at this high temperature. The burnout process had completed by creating clean mould cavities without a trace of Carbon at approximately 8 hours. At the average maximum of 732⁰C (1350⁰F), when all chemical and carbon mixed moisture is eliminated, the temperature is quickly brought to normal. This was kept stable for a period of 2 hours, as depicted in D to E. The investment was never heated further than this maximum after 7 hours of this cycle so that its characteristics would not change, thereby causing a rough-surfaced and brittle casting.

3.8.2d Phase 4

Finally, at the casting temperature, the mould was allowed to cool down. This process took about 40 minutes, and the ramp of points E to F shows the gradual drop of the mould temperature of 430⁰C per hour to the desired mould temperature for the pouring process of Copper, Brass and Silver, that is 560⁰C. At this phase, the burnout was completed as shown at levels F to G, and the temperature was allowed to fall to adapt the mould to the temperature appropriate for casting the metals and assure it is being able to enter the mould cavity without undue resistance from gases.

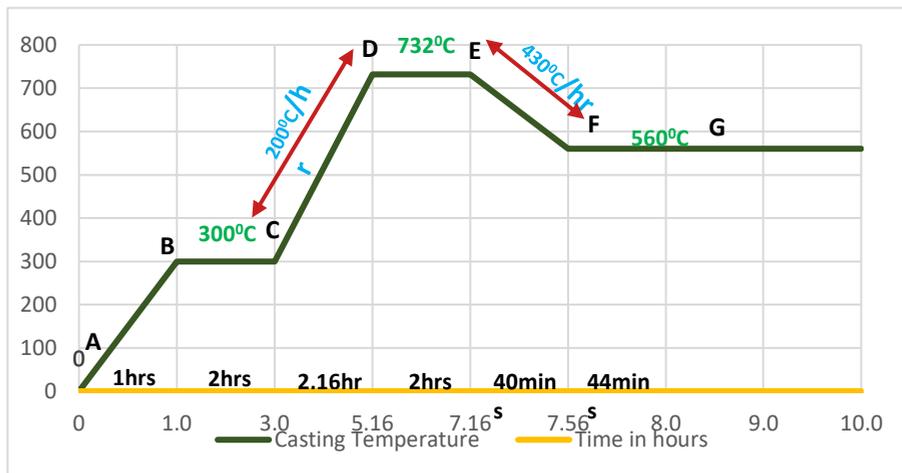


Figure 14: Burnout cycle of the Kiln

3.9 Stage 9: Casting the Metal

The metal is heated to a higher temperature than its melting point to become fluid, but not more than 100 degrees tolerance is allowed, as overheating of metal can result in bubbling, turbulence, loss of alloy ratios and an array of casting defects attached. The casting process is obtained by pouring molten metal into the open investment cavity, the shape of which was determined by the wax placement in investment medium, to obtain a metallic duplicate of the wax pattern and sprue through the casting channel. Casting is when something is cast in a mould to form an object by solidifying a fluid poured or injected into a refractory mould. This is done in the vacuum chamber to (i) degas trap air and (ii) assist with the flow of metal into all areas of the wax pattern in a short time.

3.9.1 Step 1: Metal measurement

In preparation for the melting process, the exact amount of metals (Bronze, Brass and Silver) needed was calculated to fill the investment mould adequately. The formula for the calculation is Wax weight x Specific gram = Total gram required.

Table 3: Quantity of metal needed for casting

Metal	Wax weight (g)	Specific gravity	Total grams required (g)
Silver	1.1	10.4	11.4
Bronze	3.5	9	31.5
Brass	1.1	8.5	9.35

3.9.2 Step 2: Casting crucibles

The melting of metal requires a crucible to act as a platform on which the heat can be applied to the metal. The crucible was a traditional clay crucible which provided a clean and good surface on which the metal could be melted and was used for this study. This crucible was chosen because it prevents metal contamination with oxidised residuals that may be present in the crucible. Separate crucibles were used for each of the three metals. This is to avoid contamination and guarantee metal quality.

3.9.1 Step 3: Melting metal in the crucible

A gas air casting touch is used to melt the metals. The flame is directed unto metal with the nozzle of the touch at 6.35mm away from the metal. A complete fluid was obtained within 2munites, at which point the metal was poured into the mould. The actual production of flame was achieved by adjusting the pressure and flow of specific gases (oxygen and LPG gas). The crucible was prepared by coating it with a thin layer of flux to prevent metal from sticking and reacting with the ceramic crucible medium., and the film of flux formed on the surface of the molten metal to prevent oxidation. Excess heat was avoided not to distil the lower melting component and gases to dissolve in the casting, causing porosity. The best results are obtained when the flame is used at a distance of 10cm between the face of the blow torch nozzle and the base of the crucible. When the reducing zone of the flame is in contact, the surface of the metals is bright and mirror-like. The three metals are melted in the shortest possible time. The table 4 shows metal casting temperature varying slightly with the individual metal. The brass, bronze and silver metal used in this casting do not have a liquid metal temperature differential of more than 100⁰C. Hence, it is possible for these three metals to be cast at the same casting temperature. The metals are heated above their liquid temperature. The flask temperature only showed slight differences.

Table 4: Casting temperature for the metals

Metal	Metal casting temperature		Flask casting temperature	
	⁰ F	⁰ C	⁰ F	⁰ C
Sterling silver	1756	958.1	1040	560
Bronze	1926	1052.3	1040	560
Copper	1878	1025.5	1040	560

When the metal is in contact with the oxidising portion of the flame, there is a glossy film develops over the surface. The metal is melted in a separate crucible and cast into the mould with the help of a vacuum chamber. It is essential to know that the temperature of the gas air is determined by the nature of the gas and the proportion of air and gas in the mixture. With the casting couch, two types of flames were obtained, and when the air supply for the lower flame was excessive, incomplete combustion and the lower temperature were observed [21]. However, the flame torch was adjusted adequately for maximum temperature and efficiency.

The first emanating long cone directly from the nozzle is the zone in which the gas and air are mixed up before combustion, and in this region, there is no heat present. The cone that follows is called the "combustion zone", which is green and immediately surrounds the inner cone. This zone oxidised and was immediately removed from the molten metal during fusion. The zone that followed is dimly blue, located just ahead of the tip of the green combustion zone, called the "reducing zone". This was kept constantly on the metal during melting as it is the hottest part of the flame. The zone in which combustion occurs with the oxygen in the air is the outer cone and is called the "oxidising zone" [22]. This portion of flame could not be used to melt the metal under any conditions because this temperature is lower than the reducing zone and also oxidises the metal

3.9.4 Step 4: Casting the metal into the mould

The hot flask investment mould was removed from the Kiln at 560⁰C and placed on the vacuum table. A rubber seal was placed between the vacuum chamber table and the flask to ensure an adequate tight seal. During the torch melting process of metal granules in the melting crucible the transition of phases of matter was observed. At first the metal granules discoloured with the introduction of heat, then slowly small globules appear, showing a "wet or glossy look" as they begin to melt. After sufficiently heated and correctly melted the liquid metal forms a spheroidal shape in the crucible, with a very pronounced meniscus. At this stage, the molten metal appeared light orange at the right casting temperature and followed the flame when the latter was slightly moved. The metal was about 100⁰C above its liquid temperature. A gentle swirling action of the crucible revealed unmelted pieces (often found underneath the molten mass) and ensure a homogeneous mix in the metal. Once the melt is declared sufficient the vacuum pump is switched on, and the drawn pressure is allowed to reach 100Kpa. As soon as the gauge indicates the correct degree of vacuum pressure, the crucible is lifted with a tong, and the molten metal is quickly and steadily poured directly into the sprue gate of the flask. To inhibit the introduction of oxygen to the molten metal, a reducing flame from the torch is held over the molten metal throughout the pouring process [23]. The casting was made immediately when this right temperature was achieved. After pouring, the torch flame was placed on the sprue button for a few seconds. Because the atmospheric pressure on the closed end of the mould is reduced by the vacuum, the lowered pressure causes a quicker escape for air and other gases that might otherwise resist the passage of the metal through the pores of investment. Gravity, aided by the vacuum, immediately draws the molten metal into the mould cavity [24]. The torch is removed, and the vacuum is switched off. The flask is allowed to cool for 5 minutes until the button surface freezes and becomes dark, and then the flask is removed from the casting table



Figure 15: Molten metal casting into the mould

3.9.5 Step 5 De-investing

After the metal had been cast and it had solidified, the investment flask was taken for quenching in water as soon as the button exhibited no glow. As soon as the hot investment had contact with water, a fierce reaction occurred, causing the investment material to rapidly release from the casting ring and the cast metal tree, as the bonds of the ceramic were broken down by thermal shock. The casting was shaken out of the flask in room temperature water. Figure 16 shows the investment later placed into a warm solution of 100g alum and 1 litre of water to remove stubborn investment further. [25] attests that the casting is advantageous because it puts the metal in an annealed form for further working off, as well as easier cutting of castings from the main stem of the tree by use of a sprue cutter rather than a hand saw.



Figure 16: Quenching the solidified metal in water

3.10 Stage 10: Cutting the Sprue

The sprue was cut by moving a separating cutter back and forth with very little pressure and as adjacent as possible to the precise contour of the casting. After cutting off the sprue, the sprue region was filed, sanded, and cleaned up with a rubber wheel using a jeweller's hanging motor to create an accurate shape surface. As shown in figure 17a, the tarnish and oxides caused the surface of the casting to appear dark, and the surface film was removed by the process called "pickling". Figure 17b below shows the hole at the top of the pendant re-drilled to get a perfectly round opening for the link through which the chain passes. This stage is followed by smoothing the cut surface.

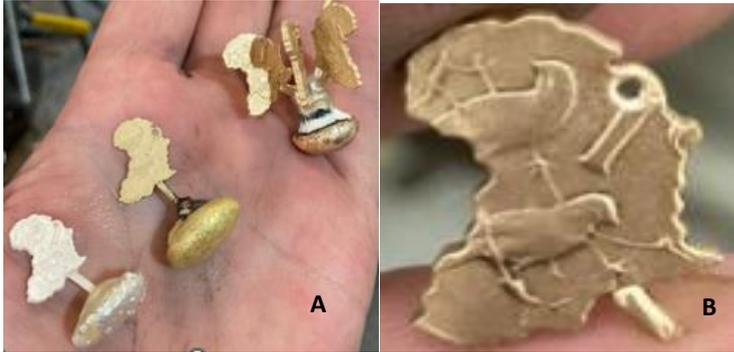


Figure 17: Complete investment jewellery cast

3.11 Stage 11: Finishing and Polishing

Figure 18 displays the final step in polishing using a polish motor machine, soft cotton mop, and UNIPOL polish. The diameter of the casted pendant is Length on pendant: 26mm, and the thickness is 1.2mm. The UNIPOL polish was applied to the polish mop. The polish motor machine was switched on, and the pendant was firmly held against the rotating polish mop to achieve the desired shine on the entire metal surface.



Figure 18: Finishing

4 Discussion

The rapid wax injection equipment was effectively tested, and the results showed a successful technique. Detailed edges and images on the OneCent African jewellery have been very well replicated on the wax model. This is especially highlighted compared with traditional tooling, which requires special attention while machining sharp corners [26]. For instance, during making with traditional tools, the tool is slow and takes time, which requires additional processes to trim and file jewellery's sharp corners. Any other process means more skills are required, probably losing accuracy as well [6]. During the loss wax investment production process, despite the rapid variance in heat conductivity coefficient between foodsil two-part resins and the three metals used for this research, the heat of wax melt was conducted well in the electric induction furnace, and the loss wax time had a significant change compared traditional method. Temperature data regarding the barrel and nozzle during the injection process is given in table 1.

Regarding the injection setting parameters, injection time was set at 10s and freeze time at the 30s. The casting mould bearing a temperature of 715°C (1,315°F) with higher thermal shock resistance is given in table 2. The casting mould ensures quick and direct temperature rising for the mould cavity not to be fractured. This applies to casting silver, bronze, and copper lower melting temperature jewellery parts. Regarding the production rate, the equipment has produced 100 shots in an hour, which appears acceptable. As revealed in the several stages in the figure 19 below, it is possible to improve the production rate using multi-cavity equipment, making rapid prototyping for jewellery manufacturing options further suitable and economical for quick production.

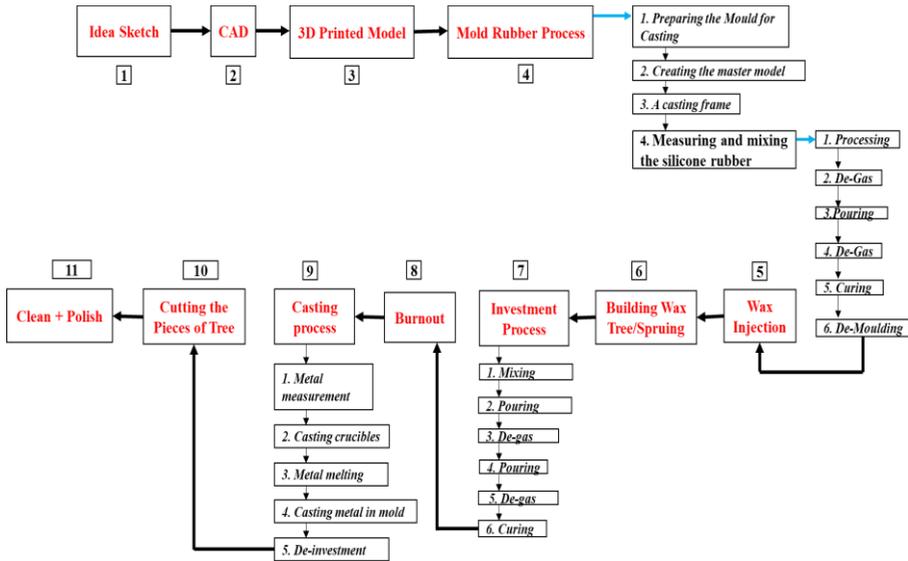


Figure 19: Stages of Investment Casting for Jewellery Production

5 Reasons For Porosity in Investment Casting

Controlling the solidification of the metal in the flask helped to get rid of many of the difficulties of "porosity", also known as metal shrinkage. Porosity is inaccuracy in cast metals caused by the presence of small holes, pores, or voids in the metal. Previous researchers [27] [28] [29] in their study provides the causes of porosity as the following:

1. Sprues' thickness and location can cause an inhibited metal flow into the mould resulting in turbulence that creates porosity.
2. Incomplete burnout shown by streak black or greyish colour in the investment is proof of carbon present in the mould cavity or investment. When the mould is filled, the Carbon penetrating the investment inhibits the evacuation of gases which become trapped in the metal.
3. Using an oxidising instead of a reducing flame or too hard air pressure from the torch flame during the melting of the metal may cause porosity by introducing oxygen in the melt.

4. Insufficient lack of flux applied during the melt leads to oxides that form being moved into the casting, creating porosity. If flux coating is used in the melt and old metal is not adequately cleaned, an excess flux is dissolved into the metal and added air [30].
5. A structural or compositional change in the metal causes overheating metal because the low-melting metals in the alloy are vapourised. The subsequent space remaining in these metals in the alloy structure permits the incorporation of oxygen into the melt.
6. Incorrect calculation results and an insufficient amount of metal for the casting due to a small or non-existent button which implies insufficient back pressure on the rest of the metal in the mould, creating expansion and porosity.
7. During shrinkage, trapped gas pits in the metal called "pinhole porosity" comprise a sprinkling of small holes in a casting. [31].
8. Uneven shrinkage cooling of the casting causes unequal shrinkage, which can cause porosity [32].

6 Future Research

Jewellery manufacturers are mostly constrained in their methods of production by the cost of equipment, which still gets obsolete during the life cycle of a production process. With the present conventional jewellery manufacturing process, there is an engineered relationship between the complication of the tooling components, manufacturing cost, timing, and repairs. This complexity can be significantly reduced with the use of innovative Additive Manufacturing (AM) processes. AM technologies have been broadly adopted by the jewellery industry manufacturers and designers because as more manufacturers acquire the skills to use the technologies, they become less expensive. With the gradual knowledge and understanding of the prospective design and manufacturing benefits of AM, jewellery manufacturers must be presented with the motivation and opportunity to consider adopting AM processes, as suitable to their enterprise's needs. Many high-value products are made in small volumes or require individual, personalised adaptations for each customer or application. The accessibility to toolless fabrication, along with the capability to deliver such modifications impacts the design, the quantity of products provided, and the design techniques. [33] in their study compared the conventional casting process with Selective Laser Melting (SLM) to identify when the direct printed patterns technique is more advantageous than traditional casting. Zito and Carlotto found from a qualitative point of view that jewellery production using SLM looks superior both in terms of internal porosity and surface macro defects. Previous researchers [34] [33] [26] [35] in their studies present results from gold alloy SLM process parameters performing the key role and use of powder chemical composition for producing quality precious metal jewellery. They demonstrated the impact of carefully chosen chemical elements to enhance laser radiation absorption and advance the melting of metallic particles. Therefore, innovative Design for AM (DfAM) approaches could be considered of significant importance for the future development of jewellery, contrary to the belief that the manufacture of well-designed exclusive products relies on an expensive, labour-intensive, and consumer-centred process [3].

7 Conclusion

The research aimed to investigate jewellery manufacturing processes using the design and production process of jewellery products of 'OneCent Africa' as a case study to describe rapid prototyping technology into the wax model production for the investment casting process. The success of this application was not only confirmed by the result but also proved great benefits with details on prototyping techniques. The results of this research show savings of 60% in cost and 50% in time compared to the traditional manufacturing process. The stages from design, putting-together and waxing casting operation took seven days to produce 100 jewellery pieces, compared to the traditional techniques which can take about two months.

Considering that as low as the wax melting temperature is 68°C and injection pressure of 0.60 MPa, the model cannot damage because of the pressure and thermal stresses, contributing to the mass production of wax models and jewellery products. Figure 1 affirms that the aim of delivering different stages of traditional jewellery production processes has been achieved by revealing eleven stages from the simple start of the design idea to eight following stages of ambiguous use of machines and equipment to follow several other steps.

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