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Use of three-dimensional laser scanning for the mapping of dimensional errors generated during the manufacturing process of investment casting

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ABSTRACT
Today, the jewelry sector still makes use of traditional design and manufacturing methods. However, jewelry manufacturers now have a much wider variety of tools at hand. CNC milling machine is a great tool for making jewelry wax models. To obtain the final jewelry pieces, the investment casting process is still considered the most suitable. The present study analyzed the materials and processes used in jewelry production aiming to map the dimensional errors generated during the manufacturing steps through a case study. A three-dimensional laser scanner was used in this analysis. The results obtained showed that the major point of dimensional loss occurred during the processes of making silicone rubber molds and wax injection.
Keywords - Investment casting, jewelry manufacturing, three-dimensional laser scanning

I. Introduction

Several areas of product manufacturing have positive returns with the use of technological advances. The jewelry sector still makes use of traditional design and manufacturing methods. However, evolving technologies, such as 3D modeling software, have brought additional knowledge to jewelry professionals [1-3]. To make these resources more accessible to small businesses, some technical improvements in obtaining molds are being made, especially in machining equipment [4,5].

CNC milling machine is a 3D tool commonly used to obtain wax models. This is a material removal process, which can create a variety of features on a piece by cutting away the unwanted material. To obtain the final pieces, the combination of both processes is still considered more appropriate, as it allows total freedom to create the desired shape. In addition, these processes enable the optimization of large-scale jewelry production, because they reduce the rework rate, material loss and ensure higher quality and productivity while maintaining the formal expressiveness of the original part [6-9].

This study aimed to analyze the materials and processes used to produce jewelry. The main focus was to map the dimensional errors generated during each production step through a case study.

For this purpose, a comparative analysis of the steps involved in the large-scale production of jewelry was performed using three-dimensional scanning.

II. Materials and Methods

For the analysis of reproducibility of metal pieces, the production process was divided into four steps, as shown in Fig. 1: (i) CNC machining of the wax model; (ii) investment casting to obtain the pilot brass piece; (iii) production of silicone mold and wax injection; and (iv) investment casting (2) to obtain the final brass piece.

A three-dimensional laser scanner (Digimill 3D, Tecnodrill®) was used for comparison of the four steps. This is a hybrid system with a laser emitter head attached to a CNC machine. Its output power is 1 mW at 655 nm wavelength. There is also the possibility of acquiring up to 1000 points per second, and accuracy depends on the lens used. The scan was equipped with a 50 mm lens, and accuracy of 0.006 mm.

In this case study, the reference model used was the *Hombre Murciélago* (Fig. 2a). The original piece is part of the collection of the Gold Museum located in Bogota, Colombia. A copy of the model

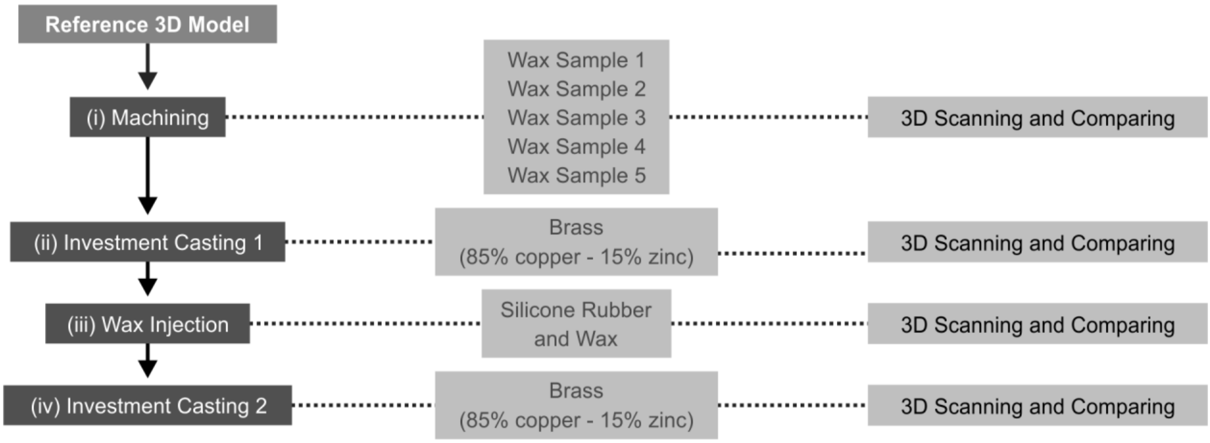

Fig. 1 Sequence of steps performed in this study.

was digitized with a layer thickness of 0.05 mm to acquire a virtual three-dimensional model (Fig. 2b), which was used for programming of machining strategy.

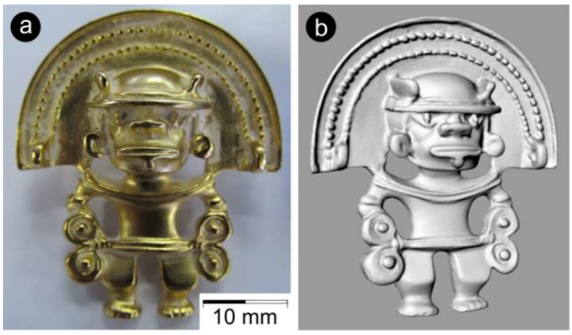

Fig. 2 Physical (a) and virtual (b) reference models of the *Hombre Murciélago* were used for machining assessment.

Five wax samples from the Ferris® File-A-Wax® line of carving waxes (Freeman) were used to obtain the machining parts. These materials are identified by their color and present different hardness grades. Hardness is one of the most important properties in machining operations. Thinning was performed using a 1.5 mm spherical tip milling cutter with a 30° cutting angle and 20% penetration. Finish was carried out with a conical milling cutter with 18° angle, two cutting edges and straight tip of 0.2 mm; a 1% penetration was used to reproduce the details. The cutting feed rate for each wax piece was determined by Pohlmann and collaborators [10], considering the assessment of the best surface finish (Table 1).

In Investment Casting 1, the waxed machined models were connected to one another to form a tree-like configuration. To obtain a ceramic model, the "tree" was then suspended inside a refractory ceramic fiber material (Master, Pasom®) and filled with plaster slurry (60% water and 40% plaster). After partially cured, the material was dewaxed in an electric oven. The plaster mold was pulled from the oven and the brass was poured in (85% brass and 15% zinc). The metal was casted using a gas forge at temperatures as high as 1100 °C. The brass was pulled from the oven and placed in the vacuum chamber and the pump was turned on at pressure of 700 mmHg (slightly below the atmospheric pressure). Finally, the casted parts were discarded, revealing the metallic parts.

	S 1	S 2	S 3	S 4	S 5
Hardness*	52	55	55	58	63
Color	Blue	Purple	Green	Yellow	Orange
FR**	700	1000	600	600	500

Table 1 Characteristics of waxes used in this study
Notes: *Shore D Hardness obtained from the manufacturer; **Feed rate values are given in mm/min.
Abbreviations: FR, feed rate; S, sample.

The pieces obtained were taken from the gate and then polished to be used as models for the production of silicone molds. Silicone rubber sheets (Nicem ®) with a hardness of 40 Shore A were applied around the model. The rubber was inserted in the vulcanizing unit where it remained for 1 hour at a temperature of 150°C. Subsequently, the rubber pattern was released from the cavity using a scalpel. The following step was the injection of red wax (Pasom®), with a pressure of 0.7 kgf/cm^2 and a mold temperature of 60 ºC. After completing this process, the pieces were cleaned and the tree assembled. Finally, to obtain the final pieces via investment casting (also known as the lost wax process), the casting tree was placed inside a cylinder and then dipped into a vat of ceramic to be coated with the metal in liquid state. The equipment, materials and parameters of this step were the same used for the production of the pilot piece. In order to determine the accuracy of details - compared to the original model - a 3D printing of the piece surfaces corresponding to each step of the production process was obtained.

Data analysis was performed using Geomagic Qualify™ software. This automation platform verifies the accuracy of molds, details, and dies as they are created.

For an accurate graphical comparison between the digital models, a virtual piece (Fig. 2b) was used as reference and data sets were aligned to the respective model of each step (i, ii, iii and iv) to be evaluated. The software calculates maximum and mean positive and negative deviations from the virtual model.

III. Results and Discussion

The wax models created using a CNC milling machine (step i) were subjected to the investment casting process (step ii). Generally, the pieces obtained exhibited good finish quality despite the damages caused during the mold removal. The details were reproduced, as well as the marks left by the tool on the surface of the models (Fig. 3).

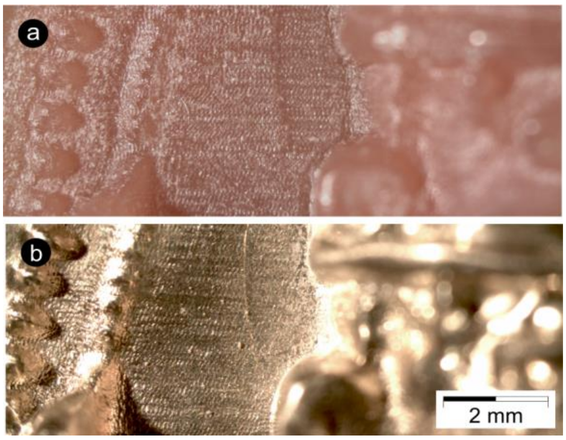

Fig. 3 Evaluation of results obtained with the pilot pieces for the surface finish: (a) the tool marks on the waxed models were reproduced in the metallic version (b) of the *Hombre Murciélago*.

The models obtained by injection of wax (step iii) in silicone mold were smaller than the pattern. In addition, these models showed loss of details, appearance of bubble-like cavities and distorted format.

It should be observed that the dimensional errors that occurred in this step, as well as in the subsequent step, were not related to the different materials applied, since the molds were obtained from models of the same materials: brass and wax. The final pieces produced by investment casting process (step iv) presented similar results to those of the pilot pieces, especially with the use of multiple gates.

Data generated by a 3D laser scanner enabled the analysis of the results obtained during the production of the pieces. The dimensional errors that occurred in each of the four steps are presented in Fig. 4 to 7. Cold tones (bluish) indicate points located below and the warm tones (reddish), the points above the surface. The green color defined the areas where there was no significant dimensional error. The models of the *Hombre Murciélago* (Fig. 4) obtained using the CNC machining (step i) showed that there were no significant dimensional errors when compared to the virtual reference model (Figure 2b).

The dimensional analysis of the models in this step pointed out a mean error lower than 0.1 mm. Greater alteration occurred in the region around the head due to its vertical format, where the tool with 18° angle (inclination) could not reach. As a result of the production of pilot pieces, no significant differences were expected between the pieces of a same model, since the best parameters were used in CNC machining operations of each modeling wax.

The investment casting (step ii) of the *Hombre Murciélago* pilot pieces did not show significant dimensional errors, with a mean value of 0.1 mm (Fig. 5). In the previous step, it seemed that the errors were replicated in the portion of the head. In addition, there was a decrease in height in the face (in blue), in which the maximum value was 0.5 mm. The portions in yellow were predominantly in portion of the head ornament and the legs. These dimensional deviations were caused by warping, probably as a result of the contraction of the metal during the cooling cycle.

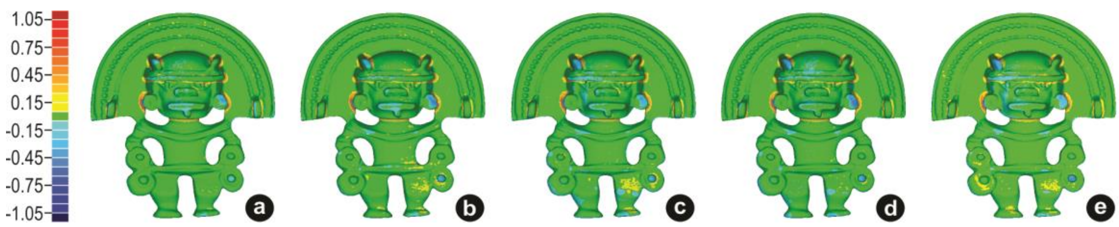

Fig. 4 Dimensional analysis of *Hombre Murciélago* models obtained by CNC machining. Results of the comparison between the virtual reference model and the CNC machining of Sample 1 (a), Sample 2 (b), Sample 3 (c), Sample 4 (d) and Sample 5 (e).

Notes: the blue tones correspond to points located below the middle surface; the red tones represent points above; the green color green indicates portions without significant dimensional errors. Units expressed in mm.

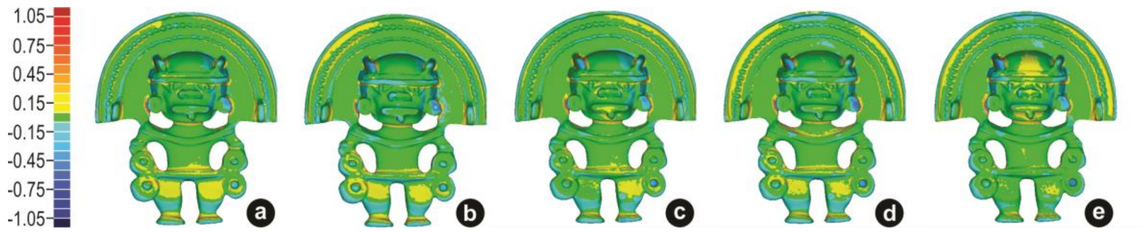

Fig. 5 Dimensional analysis of *Hombre Murciélago* pilot pieces obtained by investment casting. Results of the comparison between the virtual reference model and the investment casting of Sample 1 (a), Sample 2 (b), Sample 3 (c), Sample 4 (d) and Sample 5 (e). Units expressed in mm.

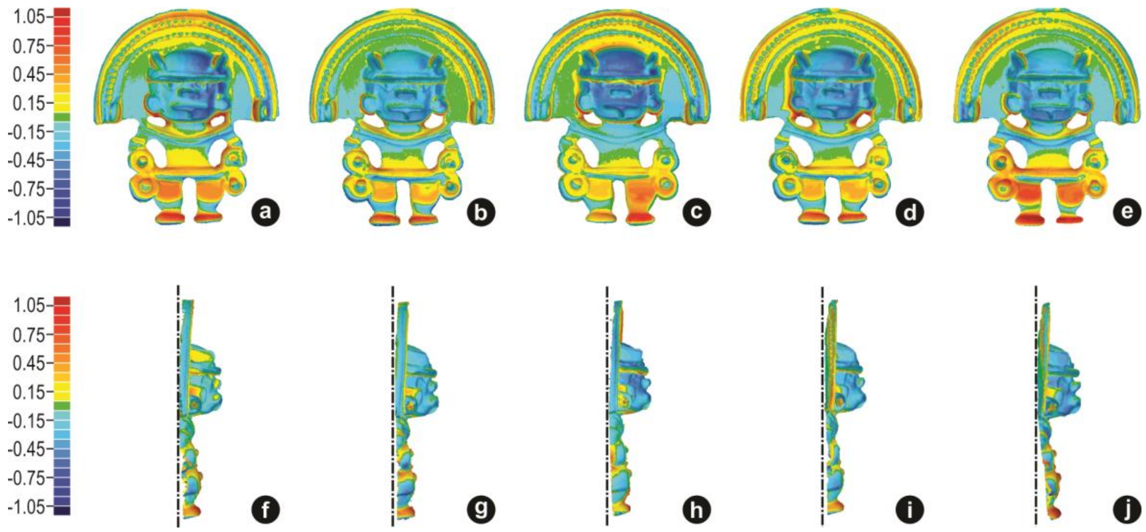

Fig. 6 Dimensional analysis of wax injection to obtain the *Hombre Murciélago* models. Results of the comparison between the virtual reference model and the wax-injected pieces of Sample 1 (a,f), Sample 2 (b,g), Sample 3 (c,h), Sample 4 (d,i) and Sample 5 (e,j). Units expressed in mm.

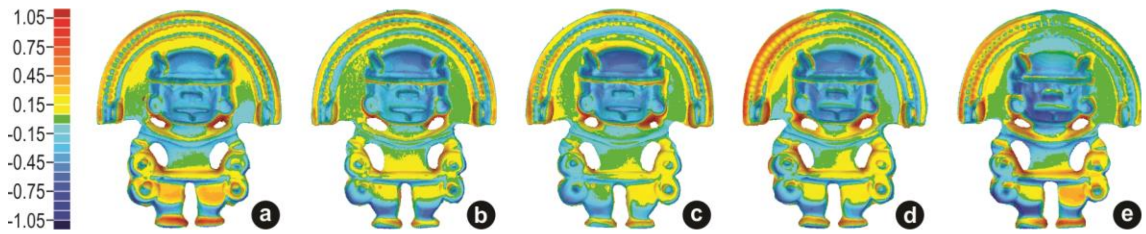

Fig. 7 Dimensional analysis of the final pieces of the *Hombre Murciélago* obtained by investment casting. Results of the comparison between the virtual reference model and the final pieces of Sample 1 (a), Sample 2 (b), Sample 3 (c), Sample 4 (d) and Sample 5 (e). Units expressed in mm.

The production of silicone rubber molds were made from metal models. The assessment of the 3D scanning surface acquisition showed reduced mold size of the *Hombre Murciélago.* The dimension alterations were even more noticeable when the injected wax parts derived from the silicone rubber molds (step iii) were evaluated. After the means were calculated for the sample dimensions, a decrease of 6% in size was observed.

The images generated for the evaluation of the models produced by injection of wax into silicone rubber molds indicate greater discrepancy in the dimensions obtained between the production steps (Fig. 6). Note that the portions in yellow-as shown in the investment casting process of the pilot pieces-are now represented by reddish tones (Fig. 6a, b, c, d, e). This color change indicates that there has been an increase in the degree of warping (Fig. 6f, g, h, i, j), this time due to the contraction of the wax injected.

The final pieces of the *Hombre Murciélago* created by means of investment casting (step iv) showed virtually the same standard deviation value obtained from the previous step. Warping caused by the contraction of materials seemed to be homogeneous; however, with no criteria for this process to occur. It was still predominant in the head ornament and legs of the model, however, it alternated between the central and the lateral portions (Fig. 7).

Table 2 displays the dimensional errors generated by 3D printing technology employed to manufacture the copies of the *Hombre Murciélago*. Higher standard deviation (SD) values revealed that the maximum errors were significantly higher than the average values obtained.

		i	ii	iii	iv
S 1	Mean	0,07	0,09	0,43	0,41
	SD	0,09	0,08	0,28	0,28
S 2	Mean	0,07	0,10	0,34	0,41
	SD	0,09	0,09	0,22	0,26
S 3	Mean	0,08	0,10	0,44	0,47
	SD	0,09	0,09	0,28	0,30
S 4	Mean	0,08	0,11	0,39	0,45
	SD	0,09	0,09	0,25	0,29
S 5	Mean	0,08	0,10	0,44	0,46
	SD	0,10	0,09	0,29	0,30

Table 2 Mean and standard deviation values of the different three-dimensional scanning obtained at each step of the production of the *Hombre Murciélago* models (units in mm).

Notes: i, refers to step of CNC Machining; ii, refers to step of Investment Casting 1; iii, refers to step of Wax Injection; iv, refers to step of Investment Casting 2.
Abreviations: S, sample; SD, standard deviation.

Fig. 8 shows the graph as the result of the comparison between the dimensional error means obtained during the reproduction process of the *Hombre Murciélago*. Note that the different values obtained between the first steps (Machining and Investment Casting 1) and the last ones (Wax Injection and Investment Casting 2) are negligible. It is noteworthy that dimensional discrepancies occurred during the processes of making silicone rubber molds (wax injection) and were responsible for approximately 70% of the dimensional losses in the reproduction of the object details.

IV. Conclusions

As result of the three-dimensional scanning analysis, we can affirm that the CNC machining step (i) and the investment casting processes 1 and 2 (ii and iv) did not generate significant dimensional errors. Greater discrepancies occurred in areas rich of details or in angles the tool could not reproduce.

The injection step (iii) was the most critical one among those evaluated in this study. In the models produced by wax injection, some air bubbles appeared on the surface, the shape was distorted (mainly in the longitudinal edges) and the pieces were 6% smaller.

With regard to the dimensional errors as a result of the materials used, higher values were expected due to metal contraction during cooling. However, it was observed that the use of these materials allowed reproducing greater details of the model with negligible errors. Finally, the higher dimensional differences as a consequence of the contraction of the material were from parts produced by wax injection in silicone rubber molds.

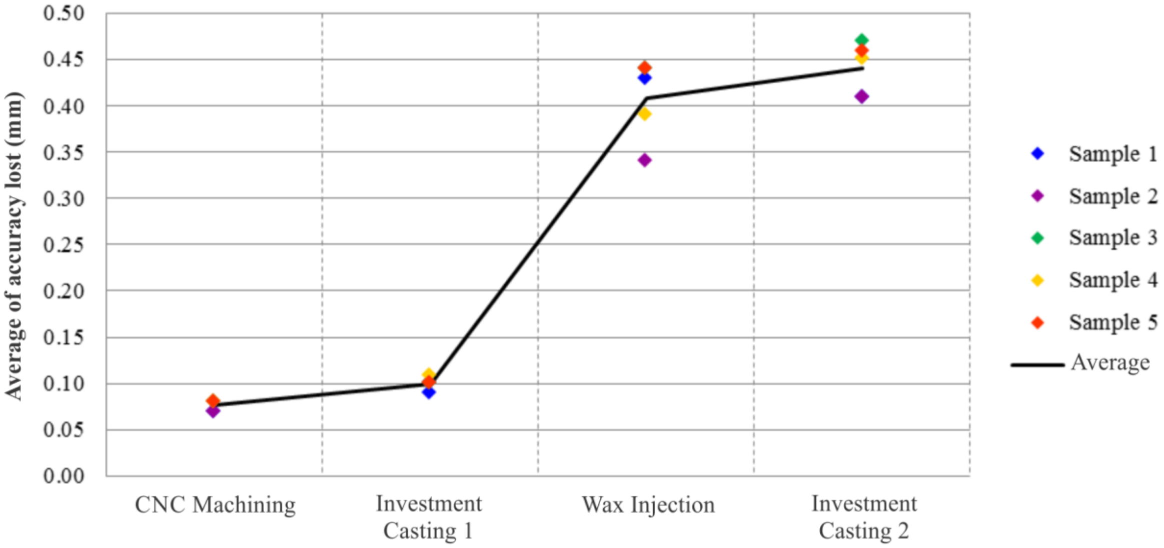

Fig. 8 Mean dimensional errors that occurred during the production processes of the *Hombre Murciélago* models.

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References

[1]. F Cooper, Current best practices in the use of various Rapid Prototyping systems. (Jewellery Industry Innovation, Birmingham, UK. Jewelry Technology Forum, 2005).
[2]. U Hohkravt, Rapid prototyping and jewelry design. Annals of DAAAM & Proceedings, Vienna, 2010.
[3]. DS Ghag, JJ Dange, Adoptability of CAD/CAM for jewellery making industry using method comparison technique. International Journal of Latest Trends in Engineering and Technology. 3(1), 2013, 44-58.
[4]. NSB Hashim, Design of mini CNC machine. (Universiti Malaysia Pahang, 2012).
[5]. W Qin, Design and analysis of a small-scale cost-effective CNC milling machine, thesis. University of Illinois at Urbana-Champaign, 2013.
[6]. M Grimwade, Introduction to precious metals: metallurgy for jewelers and silversmith. (London: A&C Black Publishers, 2009).
[7]. J Campbell, Complete Casting Handbook: Metal Casting Processes, Techniques and Design. Elsevier, (2), 2011, 939–1011.
[8]. S Pattnaik, DB Karunakar, PK Jha, Developments in investment casting process—A review, Journal of Materials Processing Technology (212), 2012, 2332–2348.
[9]. P Kapranos, C Carney, A Pola, M Jolly, Advanced Casting Methodologies: Investment Casting, Centrifugal Casting, Squeeze Casting, Metal Spinning, and Batch Casting, Comprehensive Materials Processing, 2014, 39–67.
[10]. M Pohlmann, FP Silva, W Kindlein Júnior, LC Duarte, Influência da velocidade de avanço no acabamento de ceras para modelagem de joias via fresamento CNC. 7th Brazilian Congress on *Manufacturing Engineering*, 2013.