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Dimensional accuracy assessment in Rapid Investment Casting: Evaluating metal components with Additive Manufacturing wax patterns

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Abstract

Rapid Investment Casting (RIC) is an advanced manufacturing technique that combines the capabilities of Additive Manufacturing (AM) technologies to fabricate complex metal parts through the creation of wax models for investment casting. The success of this process relies heavily on the dimensional quality and precision of the initial wax patterns. The growing adoption of Material Jetting Technology (MJT), a type of AM process, for crafting these wax patterns necessitates a thorough investigation of dimensional properties imparted by this approach.

The analysis involves a direct comparison of the final 3D scanned metal parts with the corresponding CAD model, offering insights into the accuracy of the MJT-generated wax patterns. A structured light projection 3D optical scanner was utilized to capture the 3D models of casted parts, and Geomagic Control X was utilized to point out the dimensional discrepancies between the scanned and CAD models. Additionally, the research provides a comparative analysis between MJT and Vat-photopolymerization (VPP) methods in RIC processes, contributing to the understanding of the impact of Additive Manufacturing (AM) on dimensional precision. The findings aim to enhance the knowledge surrounding the efficacy of MJT in RIC, paving the way for advancements in precision casting.

Rapid Investment Casting, Additive Manufacturing, Material Jetting Technology, Vat-photopolymerization, Dimensional Accuracy, Precision Metrology.

1. Introduction

The pursuit of enhanced precision in metal component manufacturing has led to the integration of innovative processes such as Rapid Investment Casting (RIC) [1]. RIC is a casting process in which the lost-wax molds are produced using Additive Manufacturing (AM) technology, making it possible to produce complex geometrical designs. The RIC method offers shorter lead times, enhanced design flexibility, and reduced material waste, making it one of the most reliable methods for producing complex metal components. This process finds its applications in various fields such as aerospace, medical, and dental sectors and, most commonly, jewelry applications [2]. However, the success of this process mainly depends on the accuracy and precision of the AM-produced wax components.

Several research has been conducted to optimize the dimensional accuracy and surface roughness of AM wax patterns for the RIC process [3, 4, 5]. Most of the research has been based on the Stereolithography (SLA) technology, which is the Vat-photopolymerization (VPP) AM method. In this method, the wax patterns are fabricated layer-by-layer by selectively curing the liquid polymer wax resin by exposing it to UV radiation [6].

However, this present study focuses on using another type of AM process, namely, Material Jetting Technology (MJT), to produce these wax patterns required for the RIC process. This study aims to understand the dimensional accuracy of the produced wax pattern by evaluating metal components produced through the RIC process, emphasizing the role of AM technology in wax pattern production. MJT is central to this investigation, offering a unique approach to generating wax patterns. MJT is similar to an ink-jet printer, where several tiny nozzles selectively spray the material layer-by-layer to build the part [6]. Figure 1 displays a wax pattern produced by the MJT method using a 3Dialog CeraCaster® printer. Figure 2 presents some examples of cast metal components through this technology.

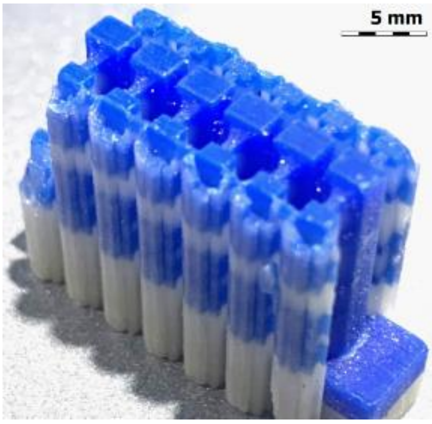

Figure 1. Example of the wax pattern produced by 3Dialog CeraCaster® MJT technology. The build material is represented by blue, and the support material by white paraffin wax.

The objective of the study is to conduct a direct comparison between the final metal parts and their CAD models, shedding light on the accuracy of MJT-produced wax patterns. Additionally, a comparative analysis with Vat-photopolymerization (VPP) [6] contributes valuable insights into the evolving landscape of AM techniques. Through this exploration, the research aims to advance precision casting methods, setting the stage for the integration of cutting-edge technologies into traditional manufacturing practices.

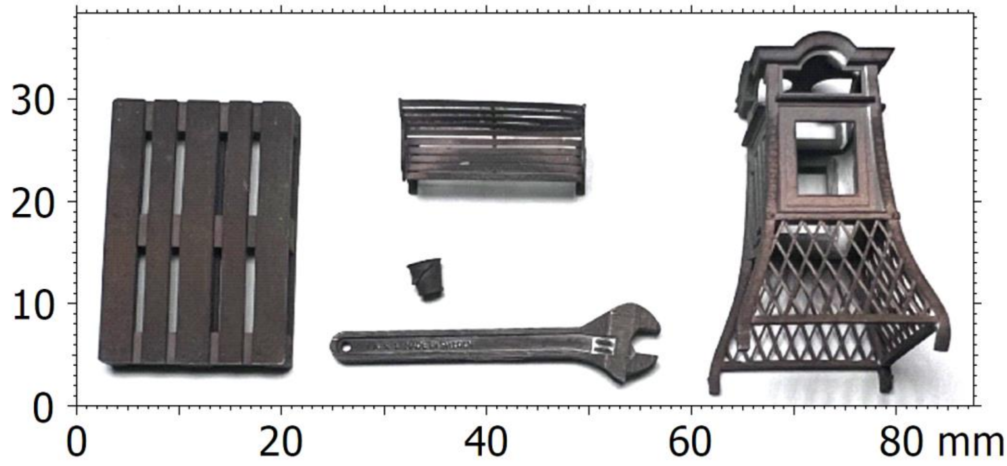

Figure 2. Examples of metal components produced by the RIC process using MJT wax patterns.

2. Material and Methods

The wax patterns required for the RIC process were produced using 3Dialog CeraCaster®, based on the Material Jetting Technology (MJT) 3D printing process. The metal sample examined in this paper was created using a wax pattern printed using draft settings, with a print resolution of 720 dpi, corresponding to a layer thickness of 35 µm. It is worth noting that the CeraCaster® in its latest version can print at 2540 dpi, resulting in a layer thickness of 10 µm, which can significantly improve the dimensional quality compared to the findings in this paper. The produced wax patterns were then utilized to create gypsum molds, during this phase, the wax melts and gets recycled. The molten metal was then poured into hollow gypsum molds in a vacuum environment and further pressurized with inert gas to ensure the fill in the cavities, consequently improving the casting quality and minimizing the porosity.

From the sustainability perspective, the wax patterns utilized for mold-making get recycled, while the recycling of gypsum molds comes with limitations related to purity, moisture, processing capabilities, cost, and quality.

The casted metal component was scanned using a Shining 3D AutoScan Inspec optical scanner (see Fig. 3). This scanner is based on the structured light 3D scanning principle with a resolution of less than 10 µm.

Figure 3. Shining 3D AutoScan Inspec 3D optical scanner.

Before actual measurements, the instrument was calibrated as per the specifications provided by the manufacturer. In order to establish a sense of fidelity of scanned measurements, it is crucial to note the accuracy and repeatability and thereby understand the uncertainty of the measurements. The ISO/IEC 98-3 Guide to the expression of uncertainty in measurement (GUM) [7] provides general rules for expressing measurement certainty. It states that the uncertainty of a measurement is usually a complex expression consisting of several variables, namely, environmental conditions (temperature variations), limited instrument resolution, human errors, and so on [7]. Generally, the easiest way to estimate uncertainty is to calculate the standard uncertainty of the measuring instrument, which is expressed as a standard deviation of several repeated measurements taken on standard gauge blocks. Hence, the repeatability test was performed by measuring a standard dimensional gauge block of 10 mm in width, which was scanned repeatedly five times, and the dimensional variation was noted.

For performing the dimensional analysis, the scanned STL model of the metal component was imported into the Geomagic® Control X™ metrology software, where it was superimposed on the reference CAD model for comparison. Figure 4 shows the 3D comparison between the reference CAD (grey) and the scanned model (blue). These models were aligned by using the "best-fit" method in the software, which is based on a Rigid Registration through point-to-point Iterative Closest Point (ICP) algorithm [8]. The alignment minimizes the mesh distance between each corresponding data point based on the least-squares principle. Rigid registration through the ICP algorithm does not explicitly designate any single point or surface as the datum or reference throughout its process. Instead, it continually updates the correspondence between points on the scanned model and the closest points on the CAD model, minimizing the overall distance between these pairs through iterative adjustments [9].

Figure 4. The scanned model in blue is superimposed on the reference CAD model in grey.

This paper is a form of a pre-study presenting an initial assessment of the dimensional accuracy of the parts produced by MJT for the RIC process. The methodology employed in this paper is mainly based on a direct comparison between the CAD model and the scanned metal object based on one example. This perhaps illustrates the capability and feasibility of CeraCaster® in producing wax patterns for the RIC process. As a next step, a comprehensive analysis involving dimensional test artifacts with detailed statistical analysis will follow to assess the quality of the casted metal components firmly.

3. Results and Discussion

As mentioned earlier, to reduce the measurement uncertainty, the 3D scanner was calibrated, and uncertainty was calculated by performing the repeatability tests using the standard gauge block, noting the standard deviation in measurements. The standard uncertainty of the 3D optical scanner was found to be less than 0.2% measured on a 10mm width gauge block. This establishes a sense of understanding regarding variation in actual measurements.

Figure 5 illustrates the discrepancies between the reference CAD model and the scanned 3D model of a wrench. The discrepancies are in the form of a color map demonstrating the dimensional accuracy of the manufactured sample. The tolerance of ±0.01mm was set, and the regions corresponding to the green color on the wrench marked the area where the differences between the two models are within tolerance. It must be noted that the tolerance set is an arbitrary value and highly depends on the application where the sample will be used. In this example, a tolerance of ±0.01mm is irrelevant, and it is mainly utilized for illustration purposes to bring out the discrepancies between the models.

It may be seen from Figure 5 and also from generated data shown in Tables 1 & 2 that a maximum of ±0.27mm was observed with an overall average deviation of 0.02mm was observed between the models. Table 1 also illustrates that nearly 23% of the total volume of the wrench is within the tolerance limits of ±0.01mm, and the volume increases considerably and achieves almost 90% for the tolerance limit of ±0.08mm. These results reveal that the MJT exhibited notable advantages in achieving superior dimensional accuracy.

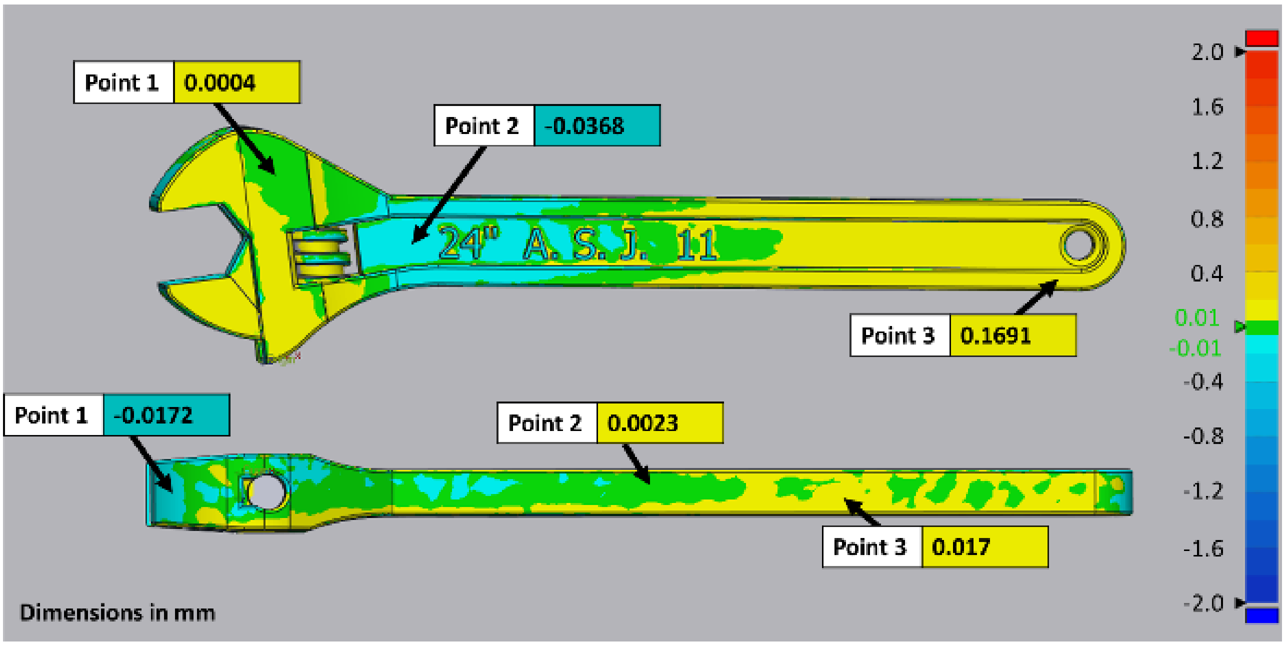

Figure 5. Dimensional deviations are represented as a color map

Table 1. The percentage volume of the wrench within the corresponding tolerance limits

Tolerance Limit in mm	Volume in %
± 0.01	23
± 0.02	42
± 0.04	67
± 0.08	90
± 0.16	99
± 0.27	100

Comprehensive research has been conducted using the Stereolithography (SLA) method for wax patterns for the RIC process, assessing dimensional accuracy [4, 5]. Results showed that a square artifact measuring the dimension of 6.5*4*2.5mm (X*Y*Z), when measured using CMM, the deviations between the CAD model and cast part in Z direction was 0.1% and in X-Y directions average deviations were observed to be 2.1%. This gives a slight understanding of where the MJT technology stands in comparison to the SLA method for the RIC process. However, to compare the two methods, further research is needed.

Table 2. Statistics of the measured dimensional deviation between reference and scanned models

Description	Value
Ovr. Avg.	0,0206
RMS	0,0491
Std. Dev.	0,0445
+Avg.	0,042
-Avg.	-0,0222

Furthermore, the SLA method typically uses acrylate photopolymer formulated with liquid wax, which, during the burn-out cycle, leaves behind traces of polymer ash that reduce the purity of the cast metal components, especially while casting gold in the jewelry-making process. In contrast, MJT technology does not encounter this issue since it utilizes pure paraffin wax for pattern production. Paraffin wax, with its low melting point, chemically inert nature, and ease of removal, serves as an effective sacrificial support material in casting applications. Its low melting point allows for easy removal without compromising the properties of the casted material. Additionally, its chemical inertness prevents the formation of residues that could compromise the quality of the final casted part [10].

These unique advantages over the SLA process positions the 3Dialog CeraCaster® as a promising technology for not only achieving stringent dimensional requirements in investment casting but also potentially reducing production costs and enhancing overall efficiency.

4. Conclusion and Future work

In conclusion, this study has demonstrated the promising feasibility of employing Material Jetting Technology (MJT) in investment casting, with a specific focus on achieving enhanced dimensional accuracy in the printed patterns. A systematic comparison between MJT and SLA processes is necessary to assess the capabilities of respective AM technologies. Nonetheless, the present study highlights the superior performance of MJT, which is attributed to its high precision due to its fine layer resolution and ability to produce intricate details.

Building upon these findings, future work should further investigate optimizing the MJT process parameters to enhance dimensional accuracy. Additionally, extending the study to include the evaluation of mechanical properties and surface finish of the casted parts produced using MJT patterns would offer a comprehensive understanding of the overall quality and performance. Furthermore, exploring the scalability of MJT for mass production and assessing its environmental sustainability aspects would be critical for a holistic evaluation of its potential in industrial applications.

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