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Quality Assurance of Reference Specimens Manufactured by Continuous Liquid Interface Production Using Coordinate Metrology

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Abstract
Continuous Liquid Interface Production (CLIP) is an additive manufacturing (AM) method developed as an evolution of the Digital Light Processing (DLP) principle. Utilizing an oxygen-permeable window below the ultraviolet image projection plane, the step-wise motion of the DLP printer can be avoided by maintaining a persistent liquid interface, thus allowing for a continuous growth of the printed specimen. To investigate the capabilities of this new process, a state-of-the-art CLIP AM machine was utilized to manufacture a series of reference specimens developed following the design of existing metrological transfer standards. The reference specimens were measured by a tactile coordinate measuring machine (CMM) to assess the manufacturing capability of the CLIP printer. Measurands included dimensions of 1D, 2D and 3D geometrical features as well as form errors (flatness, roundness, sphericity). Specifically, a flat hole-plate containing a grid of 25 evenly spaced holes (nominal diameter 5.5 mm, nominal pitch 25 mm) was used to assess the in-plane printing accuracy and precision of the holes' centres. Additionally, a ball-plate specimen containing 4 spheres (nominal diameter 22 mm) was produced measured to characterise the sphericity, as well as the printing accuracy and precision of the spheres' centres. The metrological characterization of the two reference specimens by CMM metrology allowed to determine the production capability of the used CLIP machine, and to highlight advantages and limitations of the CLIP method. The traceability of the CMM measurements was established by performing an uncertainty assessment using the calibrated artefacts corresponding to the two additively manufactured CLIP specimens. Eventually, the data collected will enable adjustments for improving the manufacturing accuracy of the CLIP machine and for paving the way towards the quality assurance of production based on the CLIP technique.

Continuous Liquid Interface Production, Additive Manufacturing, Quality Assurance

1. Introduction

In recent years the field of additive manufacturing has evolved rapidly and the amount of available manufacturing methods and variations thereof are increasing at a rapid pace [1]. The characterization of new evolving additive technologies is an important tool when quantify the developments and the direction being pursued, both on an industrial application as well as technological research level.

Figure 1. Picture showing the Optomechanical hole plate and the CLIP fabricated replicate used for the investigation. The large champfered corners are facing the CLIP machine operator during fabrication.

Continuous Liquid Interface Production (CLIP) additive manufacturing is a method developed as an evolution of the Digital Light Processing (DLP) principle by J. R. Tumbleston [2]. By utilizing an oxygen-permeable window below a ultraviolet image projection plane, the step-wise motion of the common DLP printer can be avoided by maintaining a persistent liquid interface, a so called "dead-zone", thus allowing for continuous growth of a printed specimen.

This research investigates the capabilities of CLIP by manufacturing of specimens replicating existing metrological transfer standards. Using tactile coordinate machine measurements, the quality assessment of the manufactured parts is performed investigating measurands including dimensions of 1D, 2D and 3D geometrical features as well as form errors.

2. Experiments

2.1. Specimen design

The fabricated specimens where designed as replicates of two existing metrological transfer standards. The first, developed at Technical University of Denmark for the task of characterization of tactile and optical coordinate measurement machines (CMM) is shown in Figure 1. It consists of a thin plate with 25 equidistantly placed identical holes of diameter Ø5.5mm and 25mm inbetween centers. The calibrated value being the inter-hole center position (x,y), obtained through a specific measurement acquisition pattern [3].

The second specimen, a ball plate design by obtained through RETTER Automation + Messtechnik Gmbh, containing 25 equidistantly placed identical cheramic spheres of diameter Ø22mm and 83mm inbetween centers, with the calibrated value being the inter-sphere center positon (x, y, z).

Due to build volume restrictions of the utilized CLIP machine only 4 spheres in a square pattern could be manufactured replicated the ball plate, while a full scale replicate of the Optomechanical Hole Plate was possible.

2.2. Specimen fabrication

The specimens where manufactured using a Carbon3D M2 machine mounted with CarbonResin RPU 70. The parametric model was loaded in the software and the specimens where placed directly on the buildplate. With the hole plate being a 2.5D structure the slicing height was not important. However for the ball plate specimen two different slicing heights where used: Specimen #1 with h_1=100 µm and specimen #2 with h_2=50 µm. A sphere from each of the two specimens is shown in Figure 2.

Following a fabrication procedure prescribed by the machine manufacturer, 3 units of the hole plate and 2 units of the ball plate with each h_1 and h_2 slicing heights where manufactured.

2.3. Dimensional measurements

The hole plate specimen was measured following the procedure stated in the calibration certificate for the respective metrology transfer standard. However instead of using 4 point measurements of a hole, a scanning measurement was used with a scanning speed of *v*=2.5 mm/s and a total of 500 acquired points. The position of all holes relative to hole 1 was measured.

The ball plate replicate was measured using scanning measurements with a total of 12 semi-sphere paths across the top surface of each element. The diameter and form of each of the four spheres in the two specimens was measured.

All measurements are presented with their respective expanded uncertainty value evaluated according to ISO 15530-3:2011 with a coverage factor *k*=2 similar to previous study [4].

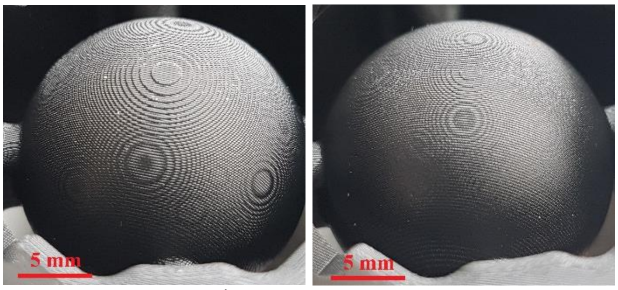

Figure 2. Manufactured Ø22mm spheres: sphere #1 with slicing layer height h_1 to the left and sphere #2 with h_2 to the right.

All measurements where performed in a temperature and humidity controlled environment using a Zeiss Prismo CMM with a VAST XT Gold scanning head fitted and a synthetic ruby probe of diameter Ø3 mm. A total of 5 repetitions of all presented measurements where acquired.

3. Results and Analysis

3.1. Hole plate center positions

The deviations of the hole positions for the 25 equidistant holes from their nominal positions are shown in Figure 3. It can be seen that a skewing of the full plate is experienced in the negative x-direction whereas little or no diviation is present in the y-direction. The average absolute x- and y-deviation and standard deviation (STD) for the top horizontal row of holes shown in Figure 3 is -213 µm (STD = 43 µm) and +11 µm (STD = 15 µm) respectively.

3.2. Hole plate inter-hole center distances

The distances between the center positions of the holes in the hole plate has the same nominal value. Therefore a measurement and comparison of these distances will provide 25 equal distances within the same part and thus provide information about the process accuracy as well as the process repeatability. The obtained average measurements for each of the 3 hole plates are shown in Table 1. While the dimensions in y-direction does not deviate significantly from the nominal value, the deviations in x-direction are much more significant.

Table 1 Average values of inter-hole center distances with respective expanded uncertainty budgets, all values in [mm].

Part ID	X-distance	Y-distance
#1	19.973 ± 0.047	20.004 ± 0.021
#2	19.971 ± 0.019	20.007 ± 0.024
#3	19.979 ± 0.019	20.003 ± 0.017
Average	19.974 ± 0.028	20.005 ± 0.021

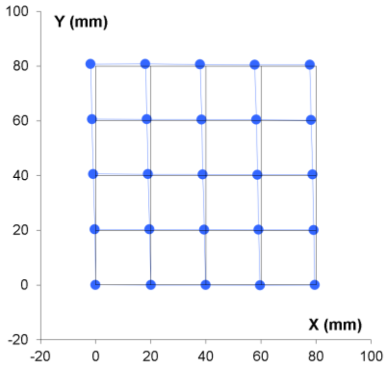

Figure 3. Schematic magnified error (100x) of the average position for each of the 25 measured holes of the CLIP manufactured specimens.

3.3. Sphere plate diameter and form

The average measured diameters and roundness along with expanded uncertainty values of the spheres for part #1 and #2 with different slicing heights are shown in Table 2.

Table 2 Average values of sphere diameter and roundness with respective expanded uncertaint. All values in [mm].

Part ID	Diameter	Roundness
#1 (h1)	21.842 ± 0.026	0.081 ± 0.013
#2 (h2)	21.938 ± 0.023	0.064 ± 0.024

4. Conclusion

The investigation presented differences of the obtained dimensional accuracy between x and y direction of the build orientation in a CLIP AM process. With the used manufacturing parameters and process conditions, additional compensation would be needed particularly in the x-direction to obtain improved results. The measured variation might however be due to various factors in the processing parameters and post process or material shrinkage. From the 3D measurands, it was found that the diameter and roundness both vary depending on the slicing height used. Better accuracy of both the diameter and the roundness is found with the smaller slicing height (50 µm).

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