DTU Library

Additive manufacturing with vat polymerization method for precision polymer micro components production

Davoudinejad, Ali; Péreza, Lucia C. Díaz ; Quagliotti, Danilo; Pedersen, David Bue; Garcíaa, José A. Albajez ; Yagüe-Fabra, José A.; Tosello, Guido

Published in:
Procedia CIRP

Link to article, DOI:
10.1016/j.procir.2018.04.049

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 75 (2018) 98–102
www.elsevier.com/locate/procedia

15th CIRP Conference on Computer Aided Tolerancing – CIRP CAT 2018

Additive manufacturing with vat polymerization method for precision polymer micro components production

Ali Davoudinejad*[a], Lucia C. Diaz-Perez[b], Danilo Quagliotti[a], David Bue Pedersen[a], José A. Albajez-García[b], José A. Yagüe-Fabra[b],Guido Tosello[a]

[a]Department of Mechanical Engineering, Technical Univ. of Denmark, Building 427A, Produktionstorvet, 2800 Kgs. Lyngby, Denmark
[b]Aragón Institute for Engineering Research, I3A - Universidad de Zaragoza, María de Luna, 3, 50018, Zaragoza, Spain

*Corresponding author. Tel.: +45-254897; fax: +45 45 25 19 61. E-mail address: alidav@mek.dtu.dk

Abstract

The direct fabrication of miniaturized polymer components by Additive Manufacturing (AM) processes is a remarkable method at the micro dimensional scale. However, the measurement of complex micro products and the evaluation of the related uncertainty are still particularly challenging and necessary in the micro AM field. In the DTU, a proprietary Vat Photopolymerization machine able to produce micro features has been designed, built and validated. This study evaluates the capability of the machine in terms of printed dimensions and the corresponding uncertainty assessment. For this purpose, two test parts with micro features of different geometries and dimensions have been designed and five samples of each test part have been printed. The dimensions of the micro features have been evaluated for quality control capability assessment and to stablish procedures for verification of AM machines.

Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.

Keywords: Additive manufacturing; Micro precision manufacturing; Polymer components;

1. Introduction

The group of technologies addressed as Additive Manufacturing (AM) technologies differentiate for being able to produce parts directly from a 3D CAD model, by building them layer by layer. Recent improvements in AM materials and technologies resulted in a rapid growth of AM processes in the industry, not only for rapid prototyping but also for the production of final parts. One of the biggest advantages of AM technologies is that they are able to produce complex geometries without the need of tooling. This allows decoupling the part manufacturing cost from the complexity of its geometries [1] and to provide customized products with short development cycles [2].

Nevertheless, the AM relevance in the industry is limited by the processes accuracy, repeatability and reproducibility. Communicating and assessing the dimensional and geometric accuracy of an AM machine is challenging, mainly in micro scale features. The study presented in [3] proposes a new approach by combining current tolerancing practices with an enriched voxel-based volumetric representation of AM machine to conquer the boundaries of standard methods. Another study [4] focuses on geometrical quality assessment of AM product. In contrast, the work presented in this article studies the capability and performance of the AM machine when printing micro features.

The AM technologies can be divided into seven groups: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization [5]. From them, Vat Polymerization (VP) methods are considered scalable methods, because they can be applied in normal-size and micro-size manufacturing [6]. The AM machine subject of this study is a proprietary VP machine able to produce features in the micrometer range. In this work, the performance and capability of the machine is evaluated by

2212-8271 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.
10.1016/j.procir.2018.04.049

producing, measuring and characterizing two test parts, having features with different geometries and sizes.

In this article, firstly, the VP machine subject of the study is introduced, as well as the printing and post processing procedure. Then, the design of the test parts is described, the measurement procedure and the uncertainty calculations are explained. Afterward, the results are presented. Finally, conclusions are deduced.

2. Digital Light Processing 3D Printing Method and Post Processing Procedure

The principle of vat photopolymerization is that of a liquid photopolymer resin contained in a shallow vat and, by mask projection in the ultraviolet spectrum, geometries and features are fabricated through selective photo-initiated crosslinking of the resin [7] [8] to form solid matter, following a layered fabrication method [9] [10]. The applied method employs a Digital Light Processing (DLP) based video projector that contains a micro-opto-electro-mechanical mirror array and a Digital Micromirror Device (DMD), to modulate a collimated UV light source, which is subsequently focused to an imaging plane placed on the bottom surface of a transparent vat. The light engine of the machine tool is based on a LUXBEAM RS WQ *WQXGA* projector and equipped Projection Lens LRS-10 P/N 6501980 with x1 magnification. This projector has a DMD with a 2560x1600px array and an image plane size 20.736 x 11.664 mm (7.56 µm pitch). The printing area for this machine was about 20 × 11 mm^2. The vertical stage of the machine tool are based upon GTen spindles with zero backlash couplings and an error of e300 = ±8 µm. The machine employs ISEL LFS-12-10 precision steel shaft guide rails with pillow blocks and the vertical stage assembly is resolved into 0.4 µm increments at the encoded positioning accuracy limit. Fig. 1 shows the experimental setup used in this work. The desired geometry is built up layer by layer by modulating image masks corresponding to a sliced representation of the fabricated geometry as the vertical stage of the machine moves upwards, and thus, the workpiece is created layer by layer. This method of vat photopolymerization is an evolution of stereolithography [9] which allows for more control on the process. Consequently, uniform layer thickness is achieved [11] [12].

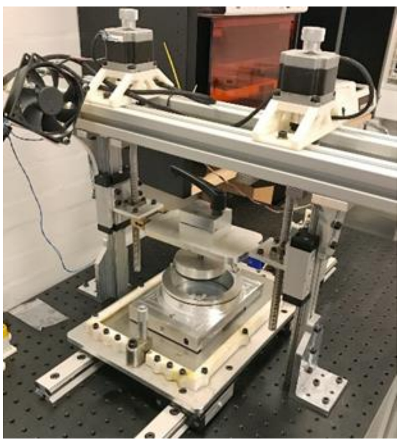

Fig. 1. Experimental set-up DLP 3D printer.

The machine subject of this study is a proprietary machine that allows the user to choose some machine settings like, exposure time, light intensity and the resin type. In the previous work [13] [14], influence of printing parameters settings was evaluated. The parts were produced with an industrial photopolymer that maintained its structural integrity while exposed to very low (-45 °C) and high (225 °C) temperatures. The printing range of the machine allows printing just one test part at a time and the printing time of each of the test parts proposed in this study is about thirty minutes. The selected parameters for this study are listed in Table 1.

Once the printing process is finished, the part is adhered to the build plate. It is necessary to unscrew the build plate from the machine in order to safely remove the part using a scraper. At this point, the sample is covered by the remaining liquid resin, and, thus, it must be cleaned with isopropyl alcohol (IPA). Then, the part is dried with pressurized air and placed in a light oven with a diffuse UV light with an irradiant flux density of 300 W/m^2 for about 80 minutes, to complete the curing of the photopolymer.

Table 1. Experimental conditions.

Parameter / unit	Selected value
Layer thickness / µm	25
Light intensity / mW	1.75
Photopolymer resin	FTD red resin
Printing resin temperature / °C	23

3. Micro features design

In order to find out the replication of the 3D printing micro features, in terms of dimensional accuracy of the parts, two test parts (Fig. 2) were designed to cover different geometries in the micro scale. The two test parts are similar, differing only in the features geometry; each test part has only one type of geometry: box or cylinder. The features are organized in a matrix of 20×6. All the elements in the same column are equivalent and in the rows the features are ordered in decreased size from left (1.5 mm in diameter—width) to right (6 µm in diameter—width). Therefore, in each sample, there are 20 batches of features of each size and each batch (column) has six equivalent features. All the features have the same height, 500 µm, and they are placed in a base of 12 mm × 12 mm × 2 mm^3.

4. Measurement and uncertainty evaluation procedure

This investigation was carried out using a focus variation microscope (Alicona Infinite Focus), using a 5× magnification lens for visual inspection and a 10× magnification lens (pixel witdh 883 nm × 883 nm) to perform the measurements. The smallest printed features having the right shape and the smallest printed feature regardless of the shape have been evaluated by visual inspection. The boxes are considered to have the right shape when, despite of the rounded edges, orthogonal straight lines can be observed. Similarly, the cylinders are considered to have the right shape, when their roundness is higher than 0.8. The printed parts are opaque and of red colour. The measurand is the height of the pillars in the third column, with a nominal diameter (width) of 840 µm, as shown in Fig. 2. The microscope measuring settings were the following: 900 µs of exposure time, 25 % of contrast, 200 nm of vertical resolution and 3 µm of lateral resolution. The software used to post-process the data was SPIP [15].

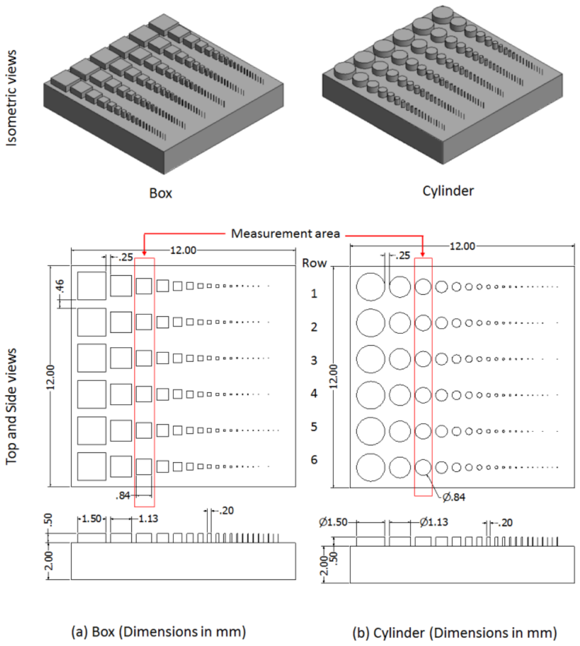

Fig. 2. Drawing of the test part (a) box and (b) cylinder

This study focuses exclusively on the analysis of the dimensions in Z-axis, that is, the height of the pillars. The reason for this is that the dimension is measured and calculated using exactly the same procedure for boxes and cylinders, regardless of the base geometry.

The expanded uncertainty of the measurements has been calculated, as well as the repeatability and reproducibility of the machine. The expanded uncertainty U has been calculated with a coverage factor k=2, which corresponds to an approximate confidence level of 95 % (see Equation 1). The uncertainty model was inspired in the ISO Standard 15530-3 [16].

$$U = k\sqrt{u_{cs}^2 + u_w^2} \ ; \qquad k = 2 \tag{1}$$

The contributor u_{cs} is the combined uncertainty, estimating the variability of the measurements due to the measurement instrument. It was evaluated on measurements of a calibrated standard as follows:

$$u_{cs} = \sqrt{u_c^2 + u_p^2 + u_b^2 + u_n^2} \tag{2}$$

where u_c is the uncertainty stated in the calibration certificates of the reference. u_p takes into account the random factors affecting the measurements and it is calculated by taking repeated measurements of the reference. u_b is the effect of the temperature on the references, in this case this term was negligible due to the fact that all the experiments were carried out in a metrology laboratory with low temperature variation (20-22 °C) and, in addition, the material of the reference had a very low thermal expansion coefficient. Finally, the contributor u_n is the measurement noise of the measuring instrument and it is calculated by the subtraction method [17].

The contributor u_w is related to the components under investigation and has two contributors (see Equation 3): u_{repr} includes the variability of the manufacture of the DLP AM machine. u_{wt} takes into account the effect of the temperature on the parts, negligible in this case because all the processes have been carried out in a temperature-controlled laboratory.

$$u_w = \sqrt{u_{repr}^2 + u_{wt}^2} \tag{3}$$

Repeatability (u_{repeat}) and reproducibility (u_{repr}) of the process were inspected respectively in one batch and several batches of production. Then, a good estimation of this quantities can be obtained by 'quadratic' subtracting an estimation of the variability due to the measurement instrument u_{instr}, as shown in Equations 4 and 5 [18] [19].

$$u_{repeat} = \sqrt{u'^2_{repeat} - u^2_{instr}} \tag{4}$$

$$u_{repr} = \sqrt{u'^2_{repr} - u^2_{instr}} \tag{5}$$

The contribution of the measurement process, u_{instr}, is calculated by taking ten repeated measurements of the same dimension of the same feature and, then, calculating its standard deviation, considering a normal distribution. u'_{repeat} is calculated as the standard deviation of the measurements of the same dimension in different features of the same batch, considering a uniform distribution. Finally, u'_{repr} is calculated as the standard deviation of the measurements of the same dimension in different features of different batches. In order to evaluate the reproducibility, five samples of each test part have been produced in different printouts.

5. Results

The printed samples have been evaluated, firstly, by visual inspection in the microscope and, then, the height of the features in the third column has been measured. Fig. 3 shows the printed samples for both designs, on the left side the whole sample and on the right side the magnification of the selected area. As it can be observed, the number of printed features is the same in both test parts, being the 11th column the last column printed, with a nominal width/diameter of 84 µm. Regarding the test part with boxes, the box shape changes to a cylindrical shape from the 7th column (nominal width of 266 µm), due to the machine incapacity to print the right edges.

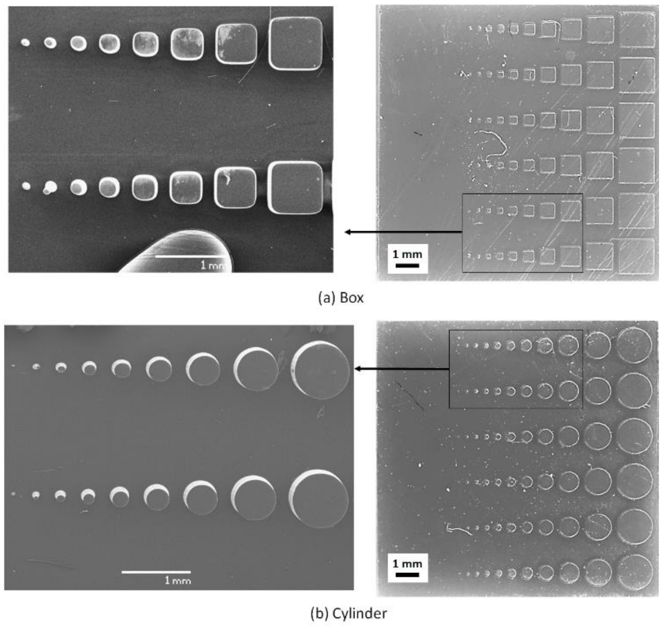

Fig. 3. Images of the printed features: (a) box (b) cylinder

The height of the features has been measured and the average value and the expanded uncertainty of the dimension have been calculated, as well as the repeatability and reproducibility of the machine. The nominal height of all the features is 500 μm (Fig. 2). Each sample contains six repetitions of the same feature in each column (one batch), to assess repeatability. Moreover, five samples of each test part have been printed in different printouts, to assess reproducibility. In Fig. 4(a) the average height of the boxes of each batch has been represented, the error bars represent the repeatability, being ±11 μm the highest one. Similarly, in Figure 4(b), the average height and repeatability of each batch has been represented for the cylinders, being ±5 μm the highest repeatability. The average height of the boxes, taking into account all the batches is 396 μm, with an expanded uncertainty (k=2) of ±27 μm and the reproducibility of the machine for this dimension is ±14 μm. Similarly, the average height of the cylinders is 437 μm, with an expanded uncertainty (k=2) of ±18 μm and the reproducibility of the machine for this dimension is ±9 μm. The calculation of the expanded uncertainties for the boxes and cylinders height and their contributors is described in Table 2. Because the dimension subject of this study is the height, the contributors have been evaluated only in Z-axis. Manufacturing by vat photopolymerization is a process chain that involves three main stages. The additive manufacture of geometry, the post-print cleaning of the geometry and the post-print curing of the geometry in order to ensure that no residual uncured resin is left on the manufactured components. Besides, each time prior to the printing the calibration and referencing was applied. Each stage might slightly affect fabrication of the features and batches were printed in different days. The variation of the size might be due to the printing procedure that involve in the manufacturing process.

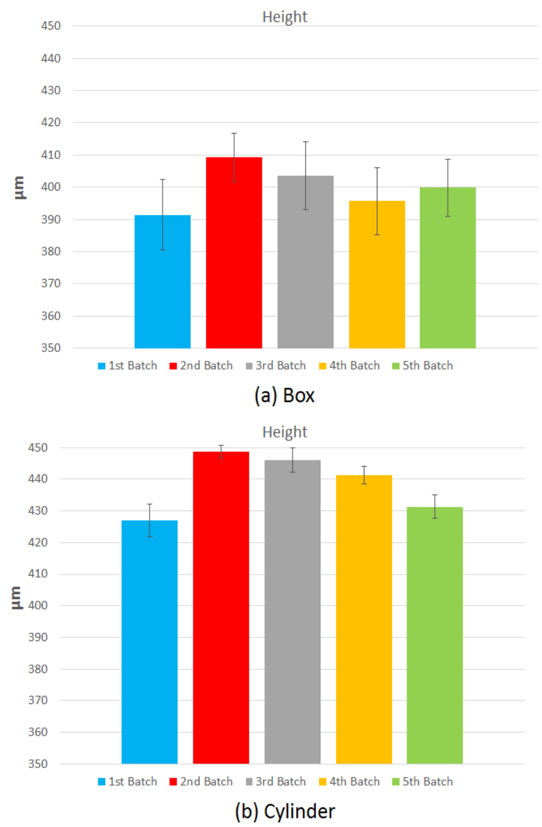

Fig. 4 Height measurement for (a) box and (b) cylinder

Table 2. Expanded uncertainty calculation for the height.

Uncertainty Source	Justification	Z-axis contribution [μm]	
Uncertainty of the reference (u_c)	According to the calibration certificate	0.1	
Instrument repeatability (u_p)	Ten repeated measurements of the reference	0.2	
Thermal variation on the reference (u_b)	Low CTE and controlled temperature	-	
Background noise of the instrument (u_n)	Experimentally measured according to [17]	0.015	
Calibrated standards (u_{cs})	According to Equation 2	0.45	
		Boxes	Cylinders
AM machine reproducibility (u_{repr})	Considering five different batches	13.72	9.21
Thermic variation on the sample (u_{wt})	Low CTE and controlled temperature	-	-
Sample (u_w)	According to Equation 3	13.72	9.21
Expanded Uncertainty k=2 (U)	According to Equation 1	27	18

6. Conclusion

In this study, the performance and capability of a proprietary DLP AM machine has been evaluated. For this purpose, two different test parts have been designed. Each test part has features of one geometry, boxes or cylinders, in different sizes, being the smallest feature 26 μm wide, while the nominal height of all features is 500 µm. Five samples of each test part have been printed, in order to evaluate the repeatability and reproducibility of the machine. For both geometries, the smallest printed feature has a nominal size of 84 µm and in the case of the boxes, the smallest feature having a square base has a width of 266 µm, then, the base becomes circular. The average height of the printed boxes is 396 µm, with an expanded uncertainty (k=2) of ±27 µm and the average height of the cylinders is 437 µm, with an expanded uncertainty (k=2) of ±18 µm, while the nominal height of both features is 500 µm.

Acknowledgements

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement no. 609405 (COFUNDPostdocDTU) and the project DPI2015-69403-C3-1-R "MetroSurf". The authors would also like to acknowledge the FPU Program of the Ministry of Education, Culture and Sports of the Spanish Government and the Program Ibercaja-CAI for Research Stays, which sponsored the PhD student L. C. Diaz Perez

References

[1] Adam G, Zimmer D. Design for Additive Manufacturing—Element transitions and aggregated structures. CIRP Journal of Manufacturing Science and Technology 2014;7:20–28.
[2] Thompson MK, et al. Design for Additive Manufacturing: Trends, opportunities, considerations and constraints. CIRP Annals - Manufacturing Technology 2016;65:737-760.
[3] Moroni G, Petrò S, Polini W. Geometrical product specification and verification in additive manufacturing. CIRP Annals - Manufacturing Technology 2017;66:157-160.
[4] Dantan JY et al. Geometrical variations management for additive manufactured product. CIRP Annals - Manufacturing Technology 2017;66:161-164.
[5] 17296-2:2015 ISO-DIS, Additive Manufacturing – General Principles – Part 2 Overview of Process Categories and Feedstock. Standard, International Organization for Standardization.
[6] Vaezi M, Seitz H, Yang S. A review on 3D micro-additive manufacturing technologies, Int. J. Adv. Manuf. Technol. 2013;67:5:1721-1754.
[7] Gibson I, Rosen DW, Stucker B, Photopolymerization Processes, in Additive Manufacturing Technologies, Boston, MA: Springer US 2010:78–119.
[8] Decker C, Photoinitiated crosslinking polymerisation, Prog. Polym. Sci. 1996;21:4:593-650.
[9] 52900:2015 ISO/ASTM, Additive manufacturing -- General principles -- Terminology. Standard, International Organization for Standardization, p. 19.
[10] ASTM International, F2792-12a - Standard Terminology for Additive Manufacturing Technologies 2013.
[11] Jørgensen AR, Design and development of an improved direct light processing (DLP) platform for precision additive manufacturing. Technical university of denmark (DTU), 2015.
[12] Tyge E, Pallisgaard JJ, Lillethorup M, Hjaltalin NG, Thompson MK, Clemmensen LH, Characterizing Digital Light Processing (DLP) 3D Printed Primitives, in Image Analysis: 19th Scandinavian Conference, SCIA 2015, Copenhagen, Denmark, June 15-17, 2015. Proceedings, R. R. Paulsen and K. S. Pedersen, Eds. Cham: Springer International Publishing, 2015, p. 302–313.
[13] Davoudinejad A, Pedersen DB, Tosello G. Evaluation of polymer micro parts produced by additive manufacturing processes by using vat photopolymerization method. Dimensional Accuracy and Surface Finish in Additive Manufacturing, Joint Special Interest Group meeting between euspen and ASPE, KU Leuven, BE, 2017.
[14] Davoudinejad A, Ribo MM, Pedersen DB, Tosello G, Islam A. Biological features produced by additive manufacturing processes using vat photopolymerization method. Joint Special Interest Group meeting between euspen and ASPE Micro/Nano Manufacturing, Glasgow, UK, 2017
[15] "SPIP-www.imagemet.com."
[16] 15530-3:2011 ISO, Geometrical product specifications (GPS) -- Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement -- Part 3: Use of calibrated workpieces or measurement standards. Standard, International Organization for Standardization.
[17] Giusca C, et al. Calibration of the scales of areal surface topography-measuring instruments: part 1. Measurement noise and residual flatness. Meas. Sci. Technol. 2012;23.
[18] Quagliotti D. Multi scale micro and nano metrology for advanced precidion moulding technologies. PhD Thesis, DTU.
[19] Weckenmann A, Rinnagl M. Acceptance of processes: do we need decision rules. Precis. Eng. 2000;24:264-9