Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 79 (2019) 119–124

www.elsevier.com/locate/procedia

12th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 18-20 July 2018, Gulf of Naples, Italy

Investigation of additive manufacturing processes to fabricate small components with mezzo features

Krassimir Dotchev[a,*], Mariana Dotcheva[a]

[a]*University of Portsmouth, School of Engineering, Anglesea Building, Anglesea Road, Portsmouth PO1 3DJ, United Kingdom*

* Corresponding author. Tel.: +44 (0)23 9284 2345. *E-mail address:* Krassimir.Dotchev@port.ac.uk

Abstract

This study investigates the capabilities of two Additive Manufacturing (AM) processes, ProJet 5500X and EnvisionTec Aureus, to fabricate small components with mezzo features (dimensions below 1mm). Benchmark parts for accuracy and strength evaluation have been designed, manufactured and tested. The results demonstrate the achievable dimensional and geometric accuracy, surface finish, tensile and flexural strength of parts made by these two high resolution processes. Their capabilities and limitations in fabrication of small parts with mezzo features have been discussed. This investigation provides metrics for the selection of the most appropriate AM process for a specific application.

© 2019 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 12th CIRP Conference on Intelligent Computation in Manufacturing Engineering.

Keywords: Additive Manufacturing, Dimensional and Geometric Accuracy, Tensile and Flexural Strength, EnvisionTec Aureus, Projet5500

1. Introduction

The first Additive Manufacturing (AM) technologies, also known as 3D Printing, have been introduced more than 30 years ago mostly as machines for rapid prototyping. They were able to fabricate physical objects directly from 3d computer aided design data in a very short time ranging from one to several hours. Due to the very high investment costs AM was mostly available in larger industries such as aerospace, automotive and defense. Since then a variety of technologically new and improved 3d printers and materials have emerged and matured, the prices have dropped, and many companies (even the SMEs) have discovered the advantages of AM to directly manufacture variety of end use products and not just to prototype a new product. Also, in the last 5 years many of the patents protecting the exclusive rights of the machine manufactures have expired and now there is a real boom in the development and sale of new AM machines at much lower prices. That allowed many smaller enterprises to look at the advantages of AM such as: design freedom, less manufacturing constrains, direct production of small quantities, reduced investment cost, compressed time to market, high level of customization, and production of custom fit products and adopt these technologies in their business models. Also, the short supply chains and delivery times of AM are very attractive in the production of spare parts for industries where the waiting time can generate huge losses (packaging and food industries, unique machines for mass production, etc.). Still there are many obstacles to fully embrace the AM as a reliable manufacturing technology because of the layer wise nature of AM to fabricate parts, insufficient resolution and accuracy, and limited variety of materials and corresponding mechanical properties.

Currently, there is a huge variety of different AM machines available on the market and it is often unclear for the user what are the opportunities and limitations of a specific AM process in relation to product design and eventual manufacture.

2212-8271 © 2019 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 12th CIRP Conference on Intelligent Computation in Manufacturing Engineering.
10.1016/j.procir.2019.02.024

The main characteristics that define 3D printed parts quality [1] which are taken into account in the design process are:

- Surface characteristics - surface texture and colour, appearance, surface roughness;
- Geometric characteristics - dimensional accuracy (deviation from size and tolerances) and geometrical accuracy (deviation in shape and position);
- Mechanical properties - tensile strength, flexural modulus, flexural strength, hardness, etc.

This paper investigates two of the most promising high resolution AM technologies: Multi Jet 3d printing with Projet 5500 [2] and Photo Mask printing with Envisiontec Aureus [3]. The main focus is their capability to produce components of high quality, accuracy, and resolution with feature size below 1mm. Both technologies employ Ultra Violet (UV) light sensitive liquid resins which after solidification exhibit properties similar to the properties of molded plastics such as Polyamide, Polycarbonate or ABS.

To evaluate the above listed characteristics in the context of 3d printing of “small components with mezzo features” a number of bench mark parts have been designed, produced, measured, tested, and evaluated as it will be described in next sections of this paper. All surface and dimensional measurements have been performed using Mititoyo Coordinate Measuring Machine (CMM), Quick Vision APEX, and CV500 surface roughness tester. The mechanical properties were evaluated by tensile testing and 3-point bending using Zwick Roell z030 tensile testing machine.

2. Multi Jet 3D printing with ProJet 5500X

Projet 5500X (Fig. 1) is manufactured by 3D Systems Corporation [2]. This 3D printer employs multi jet printing technology using UV light curable resins [4]. A print head with a multi jet matrix delivers micro droplets of build material that are selectively deposited to form a layer of the part being build.

The machine can print simultaneously flexible and rigid photopolymers layer-by-layer (0.013mm to 0.029mm thickness) with X-Y voxel resolution of 0.034mm. The machine can blend these two materials during the building process and fabricate areas within the part that exhibit gradually different properties. A third, wax-like photopolymer is used as melt-away support structure.

Fig. 1. ProJet 5500X multi material 3D printer.

This printer has an impressive build capacity of 518mm in X axis, 380mm in Y axis and 300mm in Z axis [2]. The UV light exposure and curing of the resin droplets and hardening from liquid to solid take place immediately after the jet printing and while the head moves at high speed across part layer which reduces the build time. The building speed, depends on the selected resolution mode and layer thickness, however, compared to other 3d printing technologies is relatively fast. This is the only machine capable to print parts with areas of different or graded materials. However, the post processing – wax support removal and cleaning is a time consuming job that could compromise part quality.

2.1. Bench Mark Parts (BMP)

Several types of BMP shown in Fig.2 and Fig. 3 were designed using Creo Parametric CAD software and printed by Projet in Ultra High Definition mode with resolution of 34µm (in X and Y axes), and 29µm layer thickness (Z axis). The resins used were: VisiJet® CR-WT as main material, which after solidification exhibit ABS-like properties; VisiJet S500 wax polymer as support material.

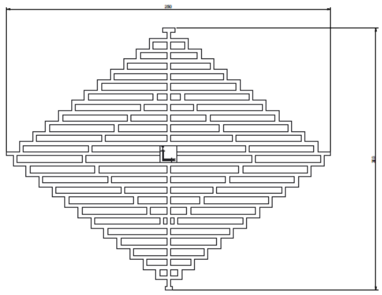
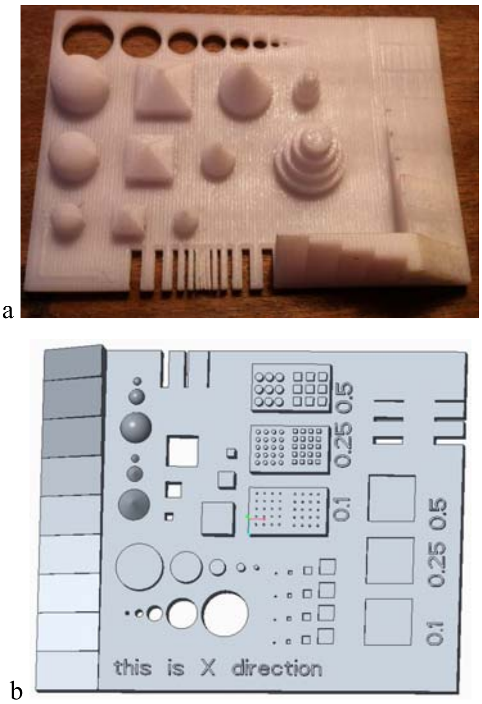


Fig. 2. BMP for dimensional accuracy (250mm x 203mm).

a



b

Fig. 3. a) BMP with small geometrical features (overall size: 75mm x 54mm x 15mm); b) BMP with mezzo features (overall size: 27mm x 22mm x 3mm).

2.2. Surface, Geometric and Mechanical requirements

Surface Texture and Appearance

Thanks to the high resolution, all parts had crisp appearance and invisible layer marks on slanted surfaces. Some horizontal surfaces experienced visible texture, caused by the print head motion (Fig. 3a). There was a slight bow at the corners, due to material post build shrinkage.

All AM technologies build parts in layers with a fixed thickness and all angled surfaces experience stair-stepping effect and distinctive surface texture. In order to investigate the surface roughness, the BMP shown in Figs. 3a and 3b have several surfaces sloped at angles from 0° to 45°. The surface profiles were measured and calculations performed for the mean roughness (Ra), ten-point height (Rz), and root mean squared (Rq). The results are shown in Fig. 4.

Mezzo features

The BMP, Fig 3b has arrays of mezzo features (cuboids, cylinders, holes, slots) with sizes of 0.1mm, 0.25mm, 0.5mm and 1mm. The majority of features below 0.5mm failed to be produced. Fig. 5a shows 0.5mm cuboids and Fig. 5b - 0.5mm and 0.25mm slots. All cuboids, measured with Quick Vision APEX, are larger from their nominal by 50µm to 60µm in X and Y directions. Also, all slots are generally smaller by 60µm-70µm.

Fig. 6 shows the array of 0.5mm cylinders and 1mm hole. The actual measured dimensions of the cylinders and holes demonstrate similar dimensional accuracy trend: outer diameters are larger and inner diameters smaller by 50µm-60µm. All holes below 1mm and slots below 0.25mm were blocked with wax. The main reason for the failure of mezzo features below 250µm is the impossibility to clean smaller holes or slots from the wax support. Also, at the "resin-wax" interface the droplets of both materials mix and create debris seem in Figs. 5 and 6, which leave a rough surface finish. This demonstrates the limitations of the Projet process to fabricate mezzo features smaller than 0.5mm.

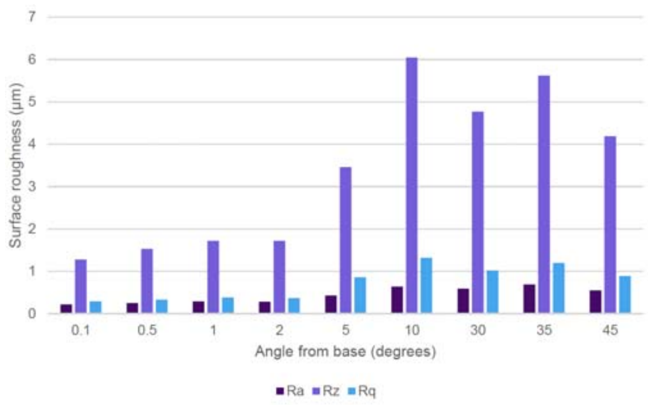


Fig. 4. Surface roughness against the surface angle.

a) b)

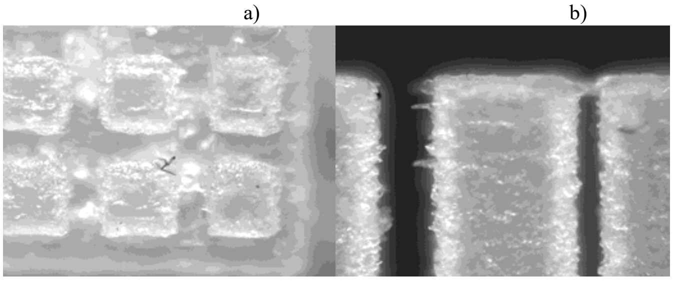


Fig. 5. a) Cuboids of 0.5mm; b) Slots of 0.5mm and 0.250mm.

Dimensional and Geometrical Accuracy

Dimensional accuracy (DA) and Geometrical accuracy (GA) of fabricated parts are crucial for the part quality and product functionality. DA and GA demonstrate the capability of each AM technology to fabricate high quality components. It is defined as a deviation of the produced geometry against ideal 3d CAD geometry and it is evaluated by means of manufacturing tolerances.

The BMP design shown in Fig. 2 has bars along X and Y axes that increase in length which allows DA evaluation in each direction. Bars were measured with Mitutoyo digital Vernier calliper and deviations were calculated as differences between measured sizes and corresponding nominal (N). Fig. 7 shows the deviation graphs and best fit lines for X and Y directions. Deviations are negative due to resin shrinkage after UV light curing. All graphs show linear shrinkage trends. The X offset (0.19mm) is larger than Y offset (0.05mm). The best fit equations are calculated as follows:

Dev X = -0.0054 . N + 0.19 (in X axis);
Dev Y = -0.0054 . N + 0.05 (in Y axis);
Dev Ave = -0.0054 . N + 0.12 (average for X and Y).

a) b)

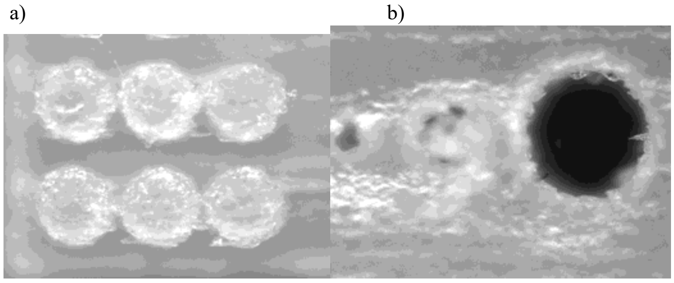


Fig. 6. a) Cylinders of 0.5mm; (b) Hole of 1mm.

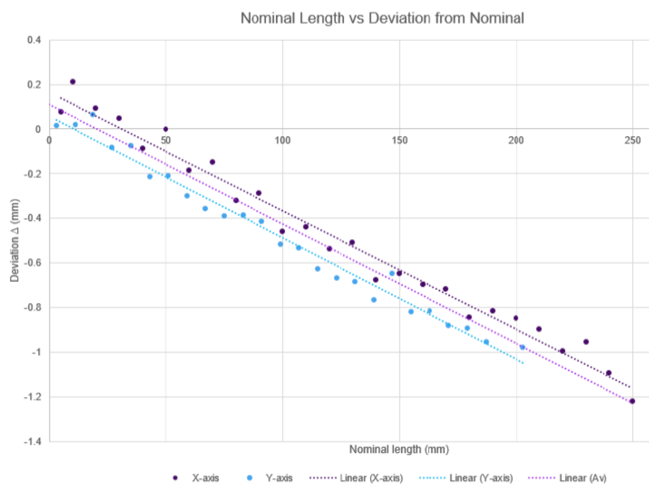


Fig. 7. Deviation from nominal in X and Y directions (Projet)

These deviations were compared to the IT tolerance grading system [6] in order to compile the process DA capability (see Table 1).

Fig. 8 shows the circularity of holes and raised domes (BMP in Fig. 3a). About 50% of points are within 0.030mm circularity, and 100% of points within 0.100mm.

Mechanical properties

Test specimens for tensile testing [5] (aka "dog bone") have been produced in horizontal (X-Y) and vertical (Y-Z) orientations.

The samples have been tested with Zwick Roell z030. The results are shown in Figs. 9 and 10 and then summarised in Table 2. Generally, the ultimate tensile strength is similar in all orientations with only 10% difference demonstrating very good bonding of subsequent layers. It shows that the Projet process can achieve almost isotropic properties of fabricated parts. This is atypical to most AM technologies which normally exhibit similar mechanical properties only in X-Y plane and inferior properties in the Z direction due to their layered nature of fabrication.

Table 1. Dimensional accuracy in X and Y axes (Projet5500X).

From (mm)	To (mm)	Deviation (mm)	IT Grade
	3	-0.015	IT9
3	6	-0.077	IT12
6	10	N/a	N/a
10	18	-0.086	IT11
18	30	-0.072	IT10
30	50	0.111	IT11
50	80	0.273	IT12
80	120	0.466	IT13
120	180	0.733	IT14
180	250	0.973	IT14

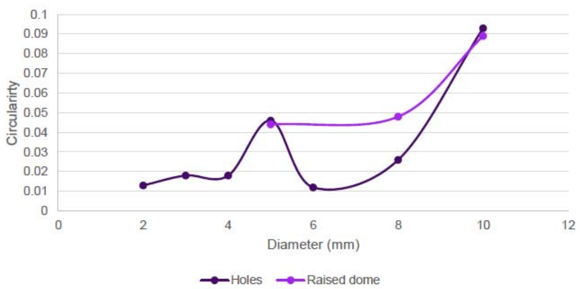


Fig. 8. Circularity (mm) of the holes and domes.

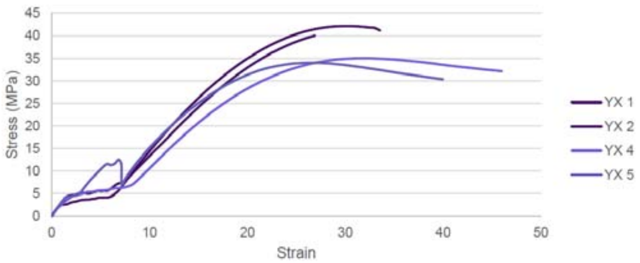


Fig. 9. Tensile stress-strain diagram in X-Y plane.

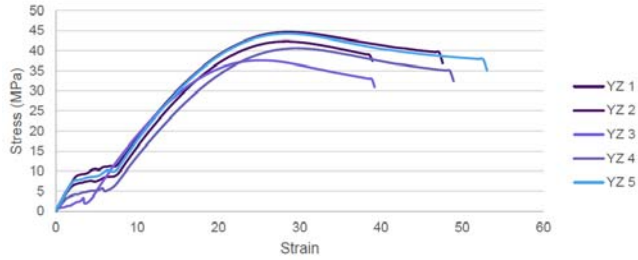


Fig. 10. Tensile stress-strain diagram in Y-Z plane.

Table 2. Tensile properties (Projet5500X, VisiJet® CR-WT material).

Orientation	Elongation at break (%)	Young's Modulus (MPa)	Ultimate Tensile Strength (MPa)
Horizontal (XY)	2.7-4.6	656-1070	34-42
Vertical (YZ)	3.9-5.3	690-1110	37.6-44.6
Horizontal average (XY)	3.7	870	37.7
Vertical average (YZ)	4.6	910	42

3. Photo mask printing with EnvisionTec Aureus

The second 3d printing technology – Aureus desktop, manufactured by EnvisionTec [3] is shown in Fig. 11. This is a similar to the Stereolithography apparatus technology that uses UV light curable resin. Instead of a laser, this technology employs "Digital Light Processing" device, developed by Texas Instruments in 1987, that contains a matrix of digital micro mirrors.

The part is suspended on a build platform that moves upwards. The platform creates a thin layer of resin at the bottom of a container with a transparent base. The whole layer as a bitmap mask is projected underneath onto the resin layer. This printer has relatively small building envelope of 60mm in X, 45mm in Y and 100mm in Z. The minimum layer thickness is 0.025mm with X-Y voxel resolution of 0.043mm. There is a variety of UV curable resins that can be used.

3.1. Bench Mark Parts (BMP)

Several types of BMP shown in Figs. 3b and 12 were designed and printed for this analysis. Two materials were


Fig. 11. EnvisionTec Aureus desktop 3d printer.

used in these experiments: HTM140v2 (green) - a high temperature (up to 140°) resistant material for parts or tooling for wax patterns used in jewelry; and Photosilver RCP130 grey [7] – a ceramic filled resin for end use parts.

3.2. Surface, Geometric and Mechanical requirements

Surface Texture and Appearance

All test parts exhibit very smooth surface finish and crisp appearance of sharp corners. Their appearance is much better than test parts produced by Projet. The surface roughness on horizontal surfaces was measured and the average is Ra=0.7µm, Rz=2.4µm and Rq=1µm, similar to Projet results.

Mezzo features

The same BMP (Fig. 3b) used in the previous AM process have been produced by Aureus in RCP130 grey resin.

Figs. 13 and 14 show fragments of the BMP containing arrays of cuboids, slots, cylinders and holes similar to the previous Figs. 5 and 6. In this case the best feature definition of cuboids and cylinders achieved with Aureus was 0.25mm, compared to Projet 0.5mm features shown in Fig. 5. This was a surprise considering that Projet voxel size is smaller than Aureus voxel.

a

b

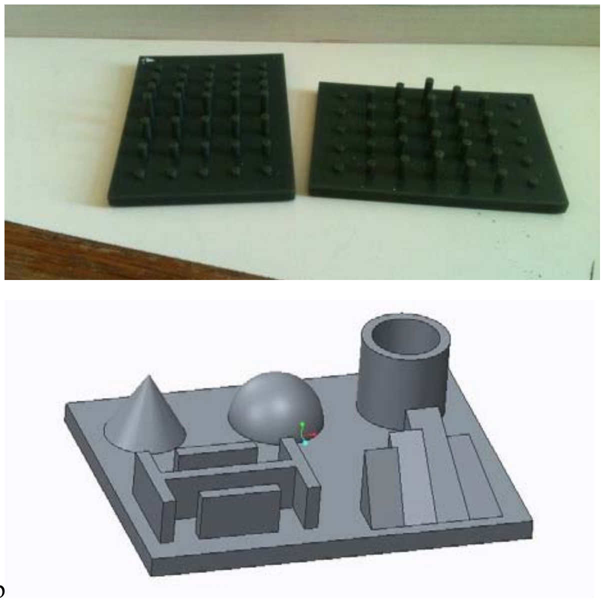


Fig. 12. BMP for geometrical accuracy: a) positional accuracy; b) geometrical shapes and surface roughness.

a) b)

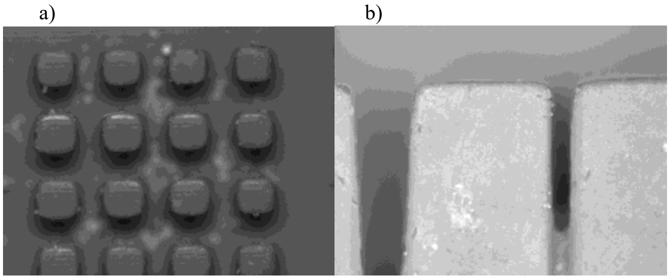


Fig. 13. a) Cuboids of 0.25mm; b) Slots of 0.5mm and 0.25mm.

a) b)

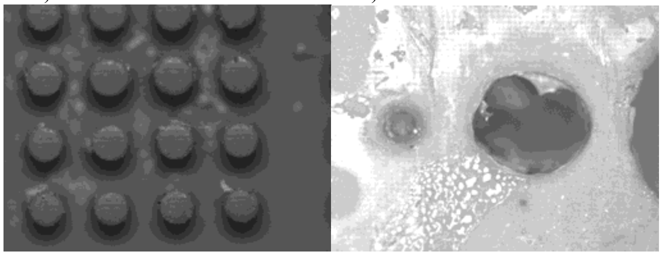


Fig. 14. Cylinders of 0.250mm; (b) Hole of 1mm.

All measured dimensions of the cubes, cylinders and holes demonstrate similar to Project dimensional accuracy trend: outer diameters are larger and inner diameters smaller. However, all mezzo features of BMP build by Aureus demonstrate better accuracy with smaller deviations of 10-30µm. Nevertheless, all holes below 1mm and slots below 0.25mm were blocked with resin. Among the reasons for the failure of mezzo features below 250µm could be: impossibility to clean cavities from uncured resin and also random errors from the mechanism that tilts and moves the platform during the recoating phase.

Dimensional and Geometrical Accuracy

A smaller version of the BMP shown in Fig.2 and similar approach were used to estimate the DA in X and Y directions.

Fig. 15 shows the “deviation from nominal” graphs and best fit equations in X and Y directions. Similar to the previous process, they are negative due to the material shrinkage by about 0.7% of the nominals and the trend is linear. The offsets in X (0.037mm) and Y (0.033mm) are smaller than Project ones. This proves a better DA.

The X-Y positional accuracy of the pins in Fig. 12a have been measured using Mitutoio CMM. The results show a standard deviation of 0.011mm in X direction and 0.007mm in Y direction. It means that 68% (±2σ) of the features are within the boundaries of IT7-IT8 tolerance and 95% (±3σ) are within IT9 to IT10 (see Table 2). The diameters of these small pins and their heights were also measured and the results shown in Table 3.

To improve the DA of both Projet and Aureus parts, a scaling factor could be applied to the input models in order to compensate for the material shrinkage.

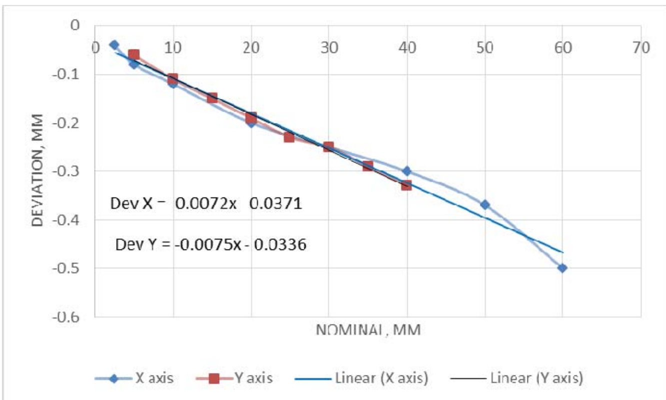


Fig. 15. Deviation from nominal in X and Y directions (Aureus).

Table 3. Dimensional accuracy in X and Y axes (EnvisionTec Aureus).

	Standard Deviation (mm)	IT Grade (68%)	IT Grade (95%)
Diameter	0.006	IT8	IT9
Height (Z)	0.012	IT9	IT10
X direction	0.011	IT8	IT10
Y direction	0.007	IT7	IT9

Mechanical properties

Taking into account the machine building envelope a scaled version of test specimen, "dog bone" type [5] for tensile testing have been designed. Test parts were then printed in horizontal (X-Y) and vertical (Y-Z) orientations. The samples have been tested with Zwick Roell z030 tensile testing machine. The loading speed was set to 1mm/min and a small pre-load of 10N applied to compensate any slack in clamping. The Young's (flexural) modulus, tensile strength, and elongation at break have been calculated from the tensile testing results and shown in Table 4.

The material flexural properties have been estimated by standard 3 point test using rectangular specimens 60mm long with cross section of 10mm by 4mm. A set of specimens produced in horizontal (X-Y) and vertical (Y-Z) directions have been tested in Mitutoyo universal testing machine. The force (in N) and deformation (in mm) at break were recorded, flexural modulus and flexural strength calculated and shown in Table 5.

4. Discussion and conclusions

Multijet (Projet 5500x) and Photo mask (Aureus) 3d printing and high resolution processes, capable to produce small components with mezzo features have been investigated. A number of BMP types have been designed, fabricated, measured, and analysed. Normally, the printing resolution or the smallest voxel (volumetric elements) size that can be created by these processes defines the appearance, accuracy and also the manufacturing tolerances achievable.

However, the results from this investigation demonstrate that the feature and part quality can vary and does not always correlate to the theoretical machine specification, voxel size or material properties. Various other factors such as the machine specifics and 3d printing settings, post processing method, environment (temperature, vibrations, etc.), and other random factors can influence the final part quality.

Table 4. Tensile properties (EnvisionTec Aureus, HTM140v2 resin).

Orientation	Elongation at break (%)	Young's Modulus (MPa)	Ultimate Tensile Strength (MPa)
Horizontal (XY)	0 - 0.1	1230	45.6
Vertical (YZ)	0.2	1280	52.4

Table 5. Flexural properties (EnvisionTec Aureus, HTM140v2 resin).

Orientation	Deformation at break (mm)	Flexural Modulus (MPa)	Flexural Strength (MPa)
Horizontal (XY)	1.2 -2.0	2200-2570	57.8
Vertical (YZ)	2.3-2.7	1930-2090	84.5

The voxel size in Projet is 34µm in X and Y, and 29µm in Z while Aureus has a voxel of 43µm in X and Y, and 25µm in Z. Surface roughness can vary from Ra 0.5-1µm (horizontal) to 3-5µm (angled) surfaces. Despite larger voxels, the appearance of the parts produced by Aureus is smoother and crisper compared to those produced by Projet. A main reason for this could be that Projet process uses wax support. The wax droplets mix and develop tiny deposits at the interface with the main material which could ultimately compromise the surface finish. The later could increase of the external dimensions by 50-60µm and decrease the internal dimensions by 50-60µm thus making the accuracy worse. In both processes small cavities (holes, slots) are filled with either wax or liquid resin during the build. If the cavity size is below a certain threshold, then the wax or resin deposits cannot be completely removed and mezzo features such as slots or holes will remain blocked and sharp corners rounded.

The dimensional and geometrical accuracies depend on the part in-build orientation, material shrinkage, post processing and some other random factors. The resin shrinkage could be compensated by applying a scaling factor of 0.5% (Projet) or 0.7% (Aureus) to input models. The best accuracy that could be achieved for macro features (above 1mm) is within IT9 to IT10 tolerance grades. Parts strength (tensile, flexural) depends mostly on the resin properties and in-build or post-build UV curing. Typically, the tensile strength is 35-40MPa (VisiJet CRWT) and 45-50MPa (HTM140) and the corresponding flexural strength is 30-35MPa (VisiJet CRWT) and 45-50MPa (HTM140). There is very little variation in mechanical strength due to part in-build orientation and the parts fabricated by these technologies exhibit isotropic properties.

Acknowledgements

The authors would like to thank Marco Curto, Alexis Arous, and George Akerman for their help in producing some of the test parts and measurements.

References

[1] British Standards Institute. BS EN ISO 17296-3:2016. Additive manufacturing. Part 3: Main characteristics and corresponding test methods. 2016; Available from https://bsol.bsigroup.com.
[2] 3D Systems. Projet5500X [Internet]. Technical Specification. 2017. Available from: http://uk.3dsystems.com/3d-printers/professional/projet-5500x.
[3] Envisiontec. Aureus Plus [Internet]. 2018. Available from: https://envisiontec.com/3d-printers/desktop-3d-printers/aureus-plus/.
[4] 3D Systems. Visijet CR-WT 200 [Internet]. Technical Specification. 2018. Available from: https://uk.3dsystems.com/materials/visijet-cr-wt-rigid-white-abs-material/tech-specs.
[5] British Standards Institute. BS EN ISO 20753:2014. Plastics. Test specimens. 2014; Available from https://bsol.bsigroup.com.
[6] British Standards Institute. BS EN ISO 286-1:2010. Geometrical product specifications (GPS). ISO code system for tolerances on linear sizes. Part 1: Basis of tolerances, deviations and fits. 2010; Available from https://bsol.bsigroup.com.
[7] Envisiontec. Photosilver [Internet]. 2018. Available from: https://envisiontec.com/3d-printing-materials/micro-materials/photosilver/