

Investigations on the accuracy of additive and conventional manufacturing

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Abstract. Thirty years into its development, additive manufacturing has become a mainstream manufacturing process. Additive manufacturing build up parts by adding materials one layer at a time based on a computerized 3D solid model. It does not require the use of fixtures, cutting tools, coolants, and other auxiliary resources. Additive manufacturing (AM), also known as rapid prototyping (RP), is a powerful tool that offers the necessary competitiveness to worldwide companies. AM comprises the use of layer-by-layer manufacturing in order to build a part by addition of material. During this study a test piece was designed in order to compare the conventional, milling manufacturing process with additive manufacturing from the viewpoint of geometrical accuracy and the quality of surface roughness. The aim is to develop a test piece design and produce this work piece by milling technology and polyjet additive manufacturing method. The dimensional measurements of these workpieces will show the accuracy of the different technologies.

1. Introduction

Additive manufacturing (AM), also known as rapid prototyping (RP), is a powerful tool that offers the necessary competitiveness to worldwide companies. AM comprises the use of layer-by-layer manufacturing in order to build a part by addition of material. Fabrication is performed directly from the 3D CAD model, which is sliced into layers that are printed one upon the other.

Popular applications of these techniques in the early phases included visual aids, form evaluation. After intensive research and development in the areas of materials, processes, software and equipment, rapid tooling applications have been developed by directly or indirectly employing AM technology in the fabrication of tools, dies and moulds [1]. AM also has been used to produce prototype parts with desired material properties for evaluation and testing, as well as to manufacture small or medium quantities of end-use products. Currently, the direct fabrication of functional end-use products has become the main trend of AM technology [2-4].

Although AM techniques have progressed greatly, many challenges remain to be addressed. These challenges include the limited materials that can be used in AM processes, relatively poor part accuracy caused by the “stair-stepping” effect [5], poor repeatability and consistency of the produced parts, and lack of standards for AM processes.

Within this report one type of AM technology is examined, the PolyJet Direct 3D Printing. This was developed by Objet Geometries, Ltd (Israel). In the process, layers of an acrylic based photopolymer are selectively jetted onto a build-tray via inkjet printing [6]. As the material is deposited, two ultraviolet lamps cure the photopolymer in multiple passes. Each subsequent layer is



jetted on top of the previous one. The PolyJet process offers a high resolution print, with a layer thickness of 16–30 μm and an in-plane resolution of 42 μm . This performance could compete with milling therefore our purpose is to examine the accuracy of this AM technology related to the traditional, milling process.

During this study a test piece was designed in order to compare the conventional, milling manufacturing process with additive manufacturing from the viewpoint of geometrical accuracy. Several researchers deal with the determination of differences between the above mentioned cases but from economical [7], environmental [8] aspects.

The quality of a conventional or additive manufactured part could be described by surface roughness measurements [9-12]. During the research the surface roughness of the conventionally and additive machined parts are determined to examine the quality of the surface.

The aim is to develop a test piece design and produce this work piece by milling technology and polyjet additive manufacturing method. The dimensional measurements of these workpieces will show the accuracy of the different technologies.

2. Materials and methods

2.1. Design of test workpiece

The design of the test piece is in Figure 1. The overall size of this part is 45 mm x 45 mm x 45 mm. The numbered characteristics are measured during this research. The distances are as follows: from 1 ... 4 and 11, 15 planes to base C; from 5 ... 8 and 12, 14 planes to base B; from 9, 13 planes to base A and the diameter is measured on the 10. hole. The nominal values are in Table 1, the numbers of the measured distances are identical with the numbers of the characteristics, i.e. 1. distance is the distance between the 1. flat and the base C, 10. measurement is the diameter of the 10. hole.

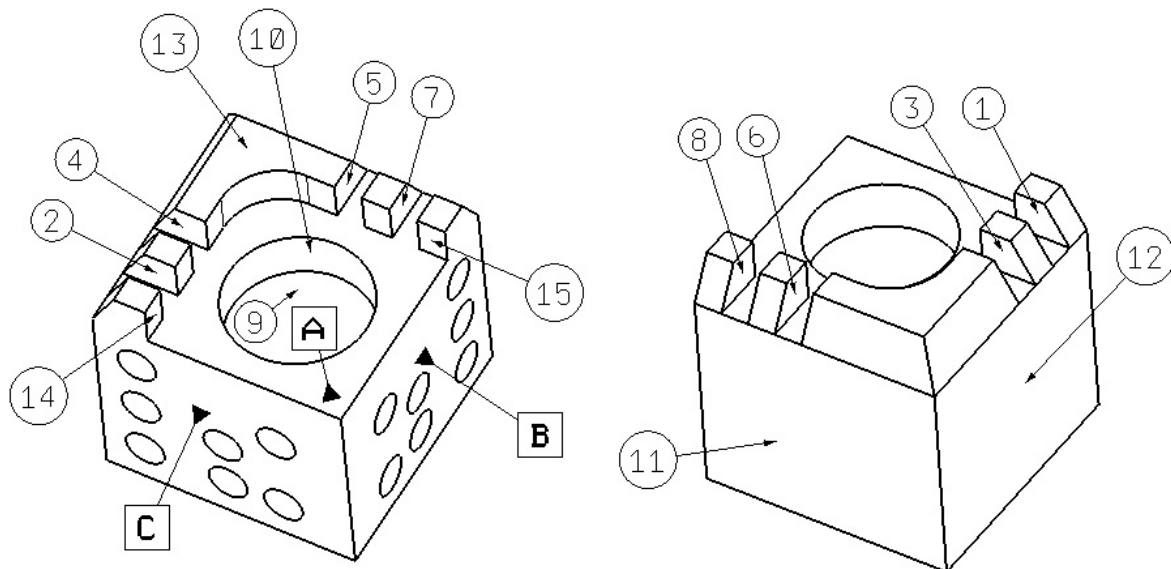


Figure 1. Design of the test piece and measured geometries (overall size of this part is 45 mm x 45 mm x 45 mm).

2.2. The materials, devices/equipment used

Three parts were produced from different materials and with different manufacturing method. The first test piece was prepared by polyjet procedure with Objet500 Connex3 3D printer. The material was RGD720 which is a translucent, multi-purpose PolyJet photopolymer (PolyJet 3DP).

The purpose of this research is to compare the accuracy of the 3D printing with the accuracy of conventional manufacturing methods. For this comparison such materials were chosen which

characteristics are similar to the RGD720 photopolymer and are able to cut. Two materials were chosen: polyoxymethylene (POM) and Necuron 1001 (Necuron) technical plastics. The manufacturing processes were prepared by MAZAK Nexus Vertical Center 410A-II machining center. Therefore two test pieces were manufactured by conventional methods: POM and Necuron, and one test piece by additive manufacturing.

The measurements were made by Mitutoyo Crysta-Apex C544 3D coordinate measurement machine. The measurement strategy was as follows: the A, B and C bases were determined by 12, equally distributed points for each; the flat surfaces (No. 1 to 8, 9,11-15) were determined by 4 points and the diameter of the cylinder (No. 10) was determined by 40 equally distributed points. The distances between the surfaces and the related base were calculated with average values (point-base flat distances) by Gauss fitting method.

Surface roughness was measured with a Surftest SJ301 surface tester (measuring setup: $\lambda=8$ - cutoff length, $N = 5$ - number of sampling length) with 4 repetitions.

3. Results and discussion

The measurement results are in Table 1. The differences are the errors, i.e. measured size minus the nominal value. There are differences in the geometries among the two cut test piece and the additive test piece. The mean differences for the whole measured characteristics are 0.0426 mm for POM, 0.0420 mm for Necuron and 0.0745 mm for PolyJet 3DP. It is seen from the measurement results the measured geometries of the Polyjet 3DP are the more inaccurate comparing to the CAD model.

Table 1. Measurement results of the numbered characteristics (in [mm]).

No.	Nom.	POM		Necuron		PolyJet 3DP	
		Meas. size	Diff.	Meas. size	Diff.	Meas. size	Diff.
1.	5	5.0745	0.0745	5.0660	0.0660	5.2023	0.2023
2.	10	10.0680	0.0680	10.0760	0.0760	10.0025	0.0025
3.	15	15.0713	0.0713	15.0628	0.0628	15.2575	0.2575
4.	20	20.0703	0.0703	20.0715	0.0715	20.0278	0.0278
5.	20	19.9790	-0.0210	20.0110	0.0110	19.9315	-0.0685
6.	15	14.9808	-0.0192	14.9878	-0.0122	15.3135	0.3135
7.	10	10.0087	0.0087	10.0243	0.0243	9.9023	-0.0977
8.	5	4.9845	-0.0155	4.9878	-0.0122	5.2885	0.2885
9.	9	8.9800	-0.0200	9.0018	0.0017	9.0008	0.0008
10.	25	24.4280	0.0810	24.8900	-0.1100	24.7910	-0.2090
11.	45	44.9905	-0.0095	44.9945	-0.0055	45.2323	0.2323
12.	45	45.0795	0.0795	45.0600	0.0600	45.1975	0.1975
13.	7.5	7.5573	0.0573	7.5530	0.0530	7.5335	0.0335
14.	35	34.7397	-0.2603	34.8340	-0.1660	4.9695	-0.0305
15.	35	34.8283	-0.1718	34.8773	-0.1227	35.0030	0.0030

The largest positive differences are in case of 1,3,6,8, 11, 12 for PolyJet 3DP, the value of the differences is about 0.2 mm. The 10. measured size (the diameter of the cylinder) has the largest negative error in case of additive manufacturing (approx. -0.2 mm). It is interesting that this diameter error is 0.081 mm in case of POM and -0.11 mm in case of Necuron. The errors (measured size minus the nominal value) are seen in Figure 2. Among the points Necuron errors fits most closer to the 0 line, the next is POM technical polymer. There are characteristics (such as 2,4,9,13,14,15) where the 3D printed, additive manufactured part show the best results in the value of error.

Not only is the geometrical accuracy the major element for the further use of the machined parts. It could be as important the quality of the produced surface, the roughness values.

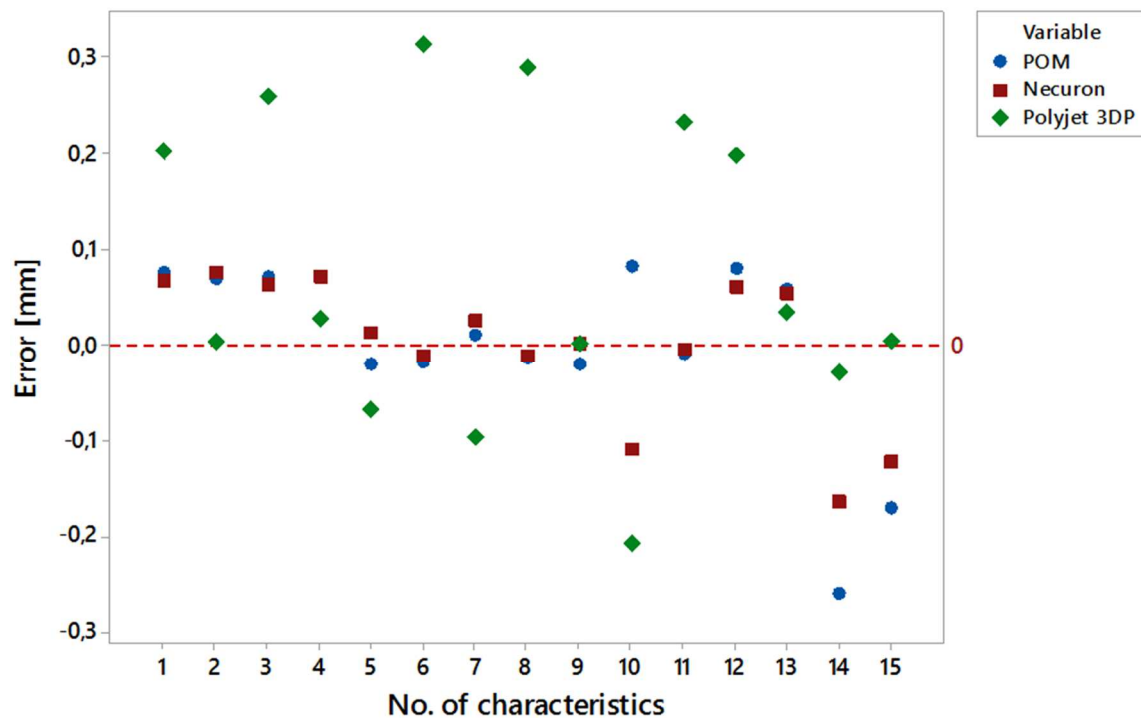


Figure 2. Errors of the measured characteristics.

The surface roughness values (R_a and R_z) for the Base A and B are in Table 2 for each test pieces. The good surface quality is essential for the future use of the parts. It is seen that the worst surface roughness value is in the case of PolyJet 3DP for Base B ($R_a=11.04 \mu\text{m}$). This flat is a vertical flat and this 3D printing technology has difficulties in having good vertical plains. The best surface roughness values can be found in case of POM manufacturing for both bases. In case of vertical flat (Base B) the difference between the two cut test piece surface roughness is not essential. The surface of the horizontal flat (Base A) is the best in case of POM, the second in case of PolyJet 3DP and the worst in case of Necuron.

Table 2. Surface roughness values of the test pieces.

	POM		Necuron		PolyJet 3DP	
	R_a [μm]	R_z [μm]	R_a [μm]	R_z [μm]	R_a [μm]	R_z [μm]
Base A	1.13	7.14	1.37	12.36	11.04	53.09
Base B	0.98	5.18	1.59	11.55	1.35	6.02

The R profiles for the measured surfaces are in Figure 3. The R profiles show that the Base A has lower roughness, the data are between $-4 \mu\text{m}$ to $5 \mu\text{m}$ for POM, $-12 \mu\text{m}$ to $6 \mu\text{m}$ for Necuron, and $-2 \mu\text{m}$ to $4 \mu\text{m}$ for PolyJet 3DP. The conventionally manufactured surfaces have similar pattern, the 3D printed surface shows different characteristics, this has the lowest density, lowest frequency.

The vertical flat (Base B) has larger surface roughness comparing to the Base A. The surface roughness data are between $-5 \mu\text{m}$ and $7 \mu\text{m}$ for POM, $-5 \mu\text{m}$ to $5 \mu\text{m}$ for Necuron with some outliers, and $-35 \mu\text{m}$ to $25 \mu\text{m}$ for PolyJet 3DP. It can be clearly seen the difference between the conventional and additive manufacturing methods. The surface roughness of the additive manufacturing process has large amplitudes periodically because of the building up 3D printed elements.



Figure 3. Surface roughness plots of the examined workpieces.

4. Conclusion

The results have met with the previous expectations. It has been determined that the accuracy of the machined parts is still greater than that of the additive manufacturing process. The largest difference is in vertical or related characteristics.

Comparing the two, conventionally manufactured POM and Necuron materials it is stated that Necuron 1001 has better cut properties, it was more accurate in all geometrical sizes.

The quality of the conventionally and additive manufactured surfaces show differences. The traditionally milled surfaces have much better surface quality than additive machined parts, especially in case of vertical surfaces, flats.

The current trend in 3D printing is not to increase accuracy, but rather to improve the appearance, with more and more colour staining and colours. Probably because it is most used for presenting, simulating, and future-selling the product, rather than manufacturing parts. So much is not expected in the near future in this area.

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