Surface characterisation and comparison of polymeric additive manufacturing features for an XCT test object

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Abstract. Additive manufacturing (AM) has experimented a huge development in recent years, improving the physical properties of parts produced by these technologies to the level of being capable of fabricating end-use functional products. High performance metals are widely used and studied; however, the reduction in material costs of polymers and their acceptable properties makes them suitable for common AM purposes. The intrinsic surface roughness of AM, as a consequence of the layer-by-layer technology, remains a challenge and its characterisation is necessary for quality control. X-Ray computed tomography (XCT), as a newly adapted evaluation technology for industrial applications, sets an opportunity for the dimensional measurement of AM parts, due to its capability of characterising the complex geometries that is possible to create with this manufacturing technologies. In this paper, a first approach to a surface characterisation of polymeric AM parts is presented. Several individual objects have been designed and manufactured using various polymeric AM technologies with different manufacturing principles (FDM, Polyjet, SLS) to build ramps with a range of surface roughness created by two main parameters (angle of inclination and layer thickness). Measurements have been carried out by an optical device (focal variation microscope, FVM), and a comparison with theoretical roughness values calculated following predictive models has been made, with the objective of analysing the behaviour of each surface. Results show that the influence of the angle of inclination is higher than the influence of layer thickness; post-processing, also, affects to the trueness of the real roughness comparing to the predicted one obtaining more unpredictable results.

Introduction

Additive manufacturing (AM) has become one of the most important manufacturing technologies in recent years in the industrial production [1,2]. The main reason is the higher design freedom that it provides [3,4] comparing to traditional processes, as machining, turning, moulding, etc, which have more physical limitations. AM technologies are capable of producing features which were almost impossible before, as freeform surfaces, lattice structures or internal cavities; it is even possible to manufacture macro and micro geometries in one print. All of this with a significant reduction in material usage.

Its higher interest as an industrial technology in recent years comes from the development of its general capacities [5]. When AM was invented, parts produced with these types of technologies had functional limitations and were used mostly for formal prototypes (rapid prototyping). However, as a consequence of the potential of AM technologies, they have been developed to the point of being now able to produce final and functional products with good mechanical, thermal and electrical properties.

With this AM development, and therefore, the appearance of new complex designs, dimensional quality requirements created the need of an improvement on metrological devices, which should be capable of measuring internal cavities, or lattice structures without sectioning the parts. For this purpose, the application of X-ray computed tomography (XCT) to the measurement of industrial parts (technique traditionally used for medical imaging) offers a suitable opportunity to cover those new metrological requirements [6–8]. XCT is based on the reconstruction of a 3D volume of the part using several 2D X-Ray images obtained by rotating the object 360º. This image acquisition allows not only to characterise the external surface of the part, but also the inner geometries. Thus, internal features can be evaluated, even porosity [9].

Surface quality remains as one of the weak points of the AM technologies, due to their intrinsic layer-by-layer manufacturing process which can only be eliminated with non-automated post processes, thus, risking the dimensional accuracy. XCT should be able to characterise surface roughness, depending on the voxel size achieved with a good geometrical magnification and the nominal roughness value of the part. XCT performance in the evaluation of metallic AM parts has been previously studied [10–12] due to the quality of parts produced with high-performance metal alloys; however, there are less studies for polymers [13], which are also commonly used and have less production cost. In addition, as density is one of the parameters which determines the X-Ray penetration, the evaluation of a less dense material suggests a variation of XCT parameters, and thus, the results extracted for metallic parts may not be translatable to polymeric parts.

On the other hand, AM process is a factor that influences the topography of the surface, even for AM parts made by the same material. Also, layer thickness and print angle of inclination of the feature play an important role on surface roughness, making it possible even to predict the theoretical roughness of the features [14,15]. As a first approach to XCT performance in polymeric AM surface evaluation, this study is focused on the characterisation of a wide range of polymeric AM features by a reference calibrated device; in this case, a focal variation microscope (FVM). This is necessary due to the difficulties on the traceability on XCT results; therefore, measurements with a calibrated device with good traceability are used as a reference to compare with XCT evaluation.

Three polymeric AM technologies are selected for the manufacturing of the parts: Fused Deposition Modelling (FDM), Polyjet and Selective Laser Sintering (SLS), and previously mentioned manufacturing parameters (layer thickness and angle of inclination) are used to design the objects of study. Measurements with the reference device have been compared with the theoretical models, applying existing normative [16] to extract roughness parameters.

The objective of this first approach is to perform a first characterisation with a calibrated reference device to have a better knowledge of the expected topography of the surfaces. As future work, the objective will be to design an object for XCT evaluation, including features of the three technologies; the assembly should be compact enough to achieve a good geometrical magnification but with dimensions as similar as possible to a real functional part (maximum dimensions around 50 mm). Also, the trueness of the measurement results comparing to the theoretical models is a relevant output for this experiment because this way the errors occurred during manufacturing process could be identified and separated from the deviations found in the future XCT experiments.

State of the art

Other works about surface characterisation of relevant AM test objects have investigated. A brief summary of the state of the art is presented in Table 1.

Table 1.- Summary of previously designed objects of study for surface characterisation.

Research group	Material	Geometries evaluated	AM Technology
University of Huddersfield [17]	Ti6Al4V	Horizontal and inclined flat surfaces (L ≈ 25 mm). Sa ≈ 7 – 9 µm.	EBM, SLM
		Sinusoidal profiles with different amplitudes (L ≈ 25 mm). Sa ≈ 90 – 300 µm.	EBM, SLM
KU Leuven [18]	Steel 300 powder	Various inclined profiles (L ≈ 15 mm). Ra ≈ 10 – 25 µm.	LPBF
University of Huddersfield [10]	Ti6Al4 alloy	Flat surfaces (L ≈ 14 mm). Ra ≈ 15 – 25 µm.	EBM

Objects listed are designed specifically for AM production, and the materials used are high quality AM metals. AMSA artefacts used in [17] are a series of AM objects designed with different features not only for XCT characterisation, but also for AM print resolution and capability tests. Artefacts have a squared-shape base of 30 mm × 30 mm with 10-mm height; several features are included in them: AMSA1 is composed by 10 cylinders of 2 mm diameter, a flat surface and an inclined ramp, while AMSA 4 has different wavelength sinusoidal profiles. In this experiment, AMSA1 surfaces and AMSA4 sinusoidal profiles were relevant. Length of evaluated features are around 25 mm.

In the rest of experiments listed, only flat surfaces are used for roughness evaluation. In [18], various inclinations are used to create stair-stepped ramps with a range of roughness values. Meanwhile, flat vertical faces are measured in [10]. Length of profiles evaluated in those studies are approximately 14-15 mm.

In general, objects of study are designed as compact as possible, not only for material saving, but also as an optimization for the measurement of the features. In XCT, better geometrical magnifications (therefore, smaller voxel size and higher resolution), are achieved with smaller parts, while for the evaluation in other types of roughness measuring devices (FVM, profilometer), it is recommendable to use small areas due to their low measurement range.

Methodology

In this section, a description of the theoretical models employed for roughness prediction, the design of the test artefacts and the measurement process is presented.

Theoretical average roughness prediction

Layer-by-layer technology of AM creates a staircase effect in the inclined surfaces produced, previous investigations have stablished models for the prediction of the obtained roughness in these inclined surfaces. First model used for this experiment is Ahn model [14], in which the evaluated roughness parameter is average roughness Ra. Calculation of the theoretical Ra according to the Ahn model has been done following Eq. 1:

$$Ra = \frac{1000t}{2}\left|\frac{\cos((90-\theta)-\emptyset)}{\cos\emptyset}\right| \quad (1)$$

Where t is the layer thickness, θ is the angle of inclination, and Ø is the angle deviation of the vertical walls. Considering a theoretical scenario where Ø = 0, the two main parameters are layer thickness and angle of inclination.

For FDM parts, in [15] an alternative method for roughness prediction is presented, considering the roundness of the filament. In Fig. 1, comparison between theoretical stepped stairs with and without rounding is displayed:

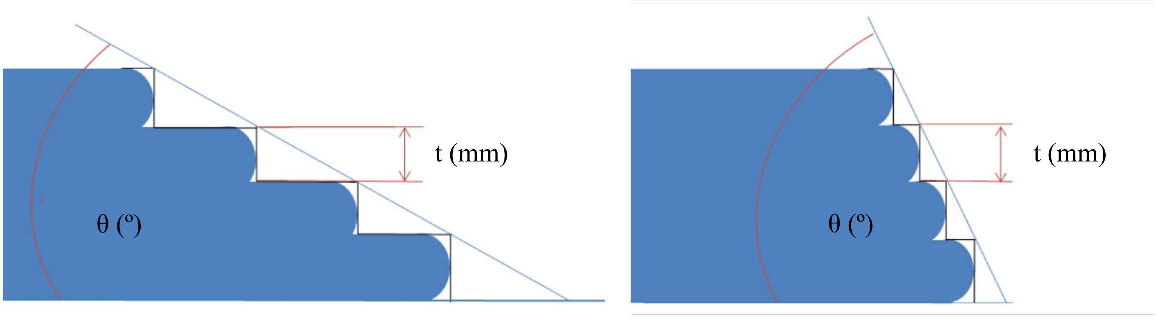


Fig. 1.- Comparison between stairs with and without rounding effect for two different build angles

This round effect of the filaments on the roughness varies depending on the layer thickness, but mostly, the angle of inclination. In this method, two consecutive filaments are considered for roughness evaluation. A cross section of the profile obtained is shown in Fig. 2:

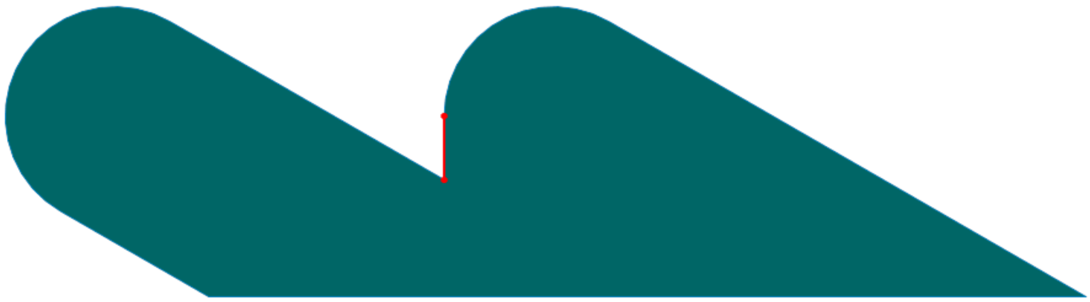


Fig. 2.- Cross section of FDM external profile (based on [15]).

Vertical red line is inserted in order to avoid negative values in the roughness theoretical calculations. In Fig. 3, an approximation model in SolidWorks is shown, used as a reference for the calculations:

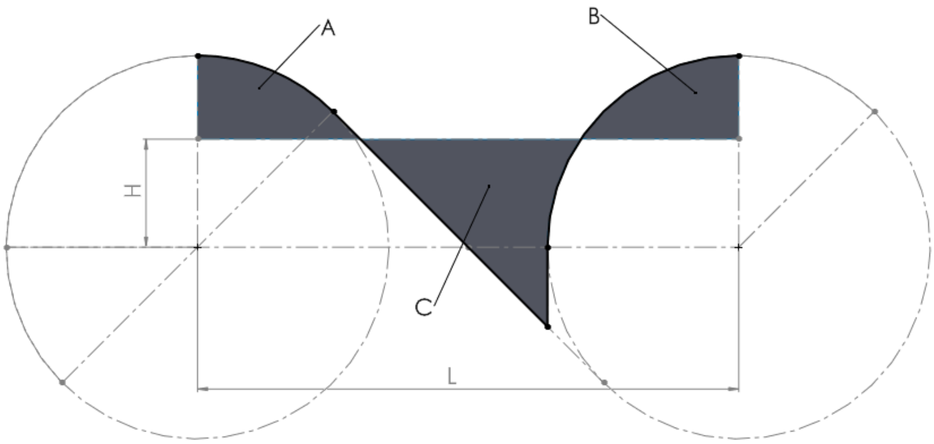


Fig. 3.- SolidWorks model for calculations.

Here, inclined line corresponds to angle of inclination of the surface, radius of the circles is equal to layer thickness and height of the horizontal line is calculated in order to obtain an equal area above (marked as A and B) and below (marked as C) it in the grey areas. Roughness parameter Ra calculation is made following Eq. 2:

$$Ra = \frac{1}{L} \int_0^L |f(x)|\, dx \tag{2}$$

Where L is the horizontal length and f(x) is the function determined by the profile (highlighted in black, see Fig. 3).

Artefact design

Several parts have been designed and manufactured for the experiment considering the objects of study investigated in the section “State of the art”. Inclined ramps have been selected for roughness evaluation, because, as detailed in subsection “Theoretical average roughness prediction”, the aim is to make a comparison of the measured average roughness with theoretical average roughness according to predictive models.

Parameters used for the design of the parts have been AM technology (FDM, Polyjet, SLS), layer thickness (0.1 – 0.15 – 0.2 mm) and angle of inclination (30º – 45º – 60º – 75º). Polyjet 3D printer nominal layer thickness is between 16 – 48 µm, which creates surfaces with very low roughness (theoretical Ra around 1-2 µm according to calculations made by theoretical models) which are out of the minimum measuring resolution of future XCT measurements. Therefore, an approximation has been made with artificial steps of 0.098 mm and 0.196 mm in the measurand ramps, multiples of nominal layer thickness and similar values to the other AM technologies, with the objective of achieving comparable results with the rest of the parts. To create this artificial steps, CAD files were modified substituting plain ramps by stairs with the desired dimensions.

Two different morphologies have been created for the parts: two-faced, with complementary angles (30º – 60º and 45º – 75º, dimensions shown in Fig. 4) and four-faced (30º – 45º – 60º – 75º, dimensions shown in Fig. 5). Measurand ramps dimensions are designed in order to obtain at least 15 mm profiles, to have a sufficient evaluation length for roughness evaluation. The opposite face of each measurand ramp is printed with the same angle, in order to ease the evaluation and fixture in the measurement devices (allowing to place the measurand geometries in a perpendicular position to the FVM beam).

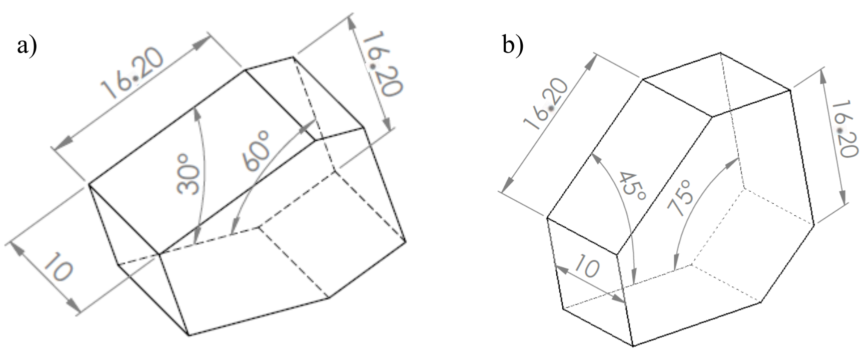


Fig. 4.- Dimensions of two-faced parts. a) 30º - 60º. b) 45º - 75º.

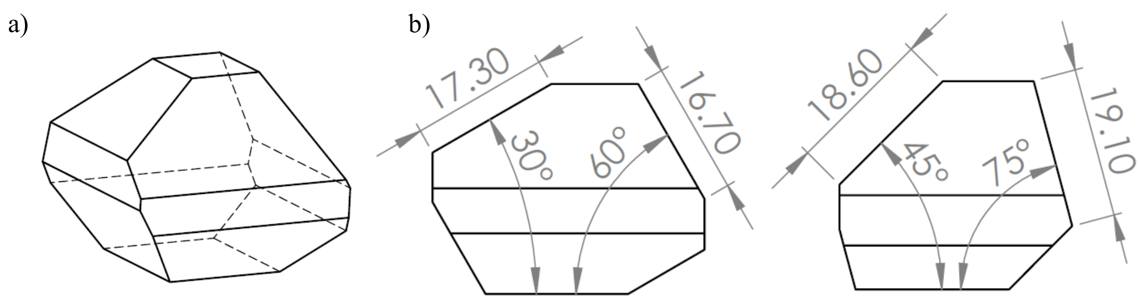


Fig. 5.- Four-faced parts. a) General view. b) Dimensions.

Manufacturing and measurement process

Various parts of each type (at least 3 replicas) have been printed and visually evaluated to detect possible manufacturing defects. Manufacturing parameters (layer thickness, ramp angle of inclination) were used to create a range of parts to be evaluated. Most suitable objects with none or few defects have been selected for each type of geometry. Post processing has consisted in the cleaning of the parts by pressurized water (for Polyjet parts) and by compressed air (for SLS parts). No post processing was necessary for FDM parts.

Several measurements have been taken with an optical focal variation microscope (FVM) InfiniteFocusSL of Alicona. FVM results have been evaluated by software IfMeasure.

All profiles were extracted and filtered according to ISO 21920-3 [16], selecting a λc filter cutoff of λc = 8 mm and a λs filter of λs = 25 µm. Ra parameter has been calculated.

Results and discussion

In this section, results obtained with the measurements of the metrological device (FVM) and a comparison with calculated theoretical predicted roughness is presented.

Theoretical Ra

Results of the predicted Ra values for both models evaluated – Ahn [14] and FDM optimised [15] are presented in Table 2, divided by layer thickness (t) and angle of inclination (θ).

Table 2.- Theoretical Ra values calculated by predictive models.

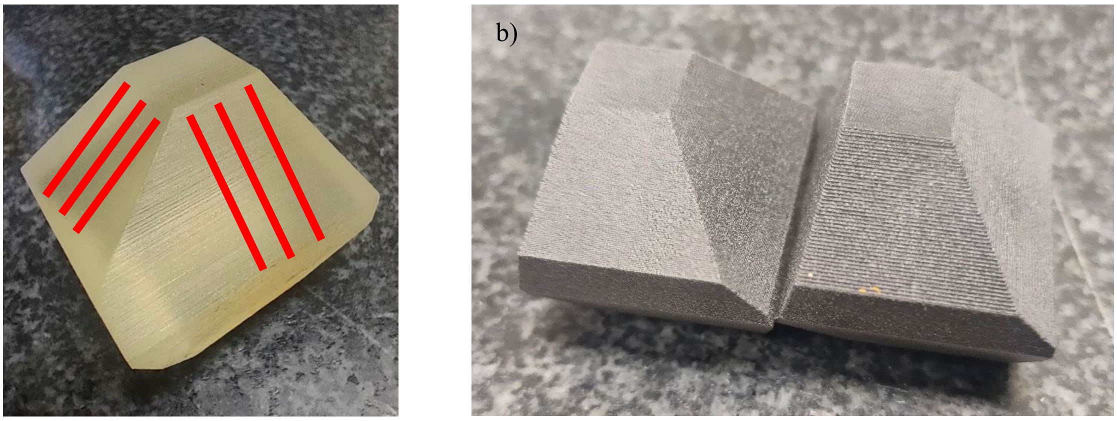
	t = 0.1 mm		t = 0.15 mm		t = 0.2 mm	
	Ra [µm] (Ahn)	Ra [µm] (FDM opt.)	Ra [µm] (Ahn)	Ra [µm] (FDM opt.)	Ra [µm] (Ahn)	Ra [µm] (FDM opt.)
θ = 75º	6.47	10.37	9.70	15.56	12.94	20.75
θ = 60º	12.50	13.86	18.75	20.80	25.00	27.73
θ = 45º	17.67	17.98	26.51	26.98	35.35	35.97
θ = 30º	21.65	21.22	32.47	31.84	43.30	42.45

Calculations show similar results for both models when the angle of inclination decreases; for values of θ = 75º, Ra calculated by FDM optimized model [15] is considerably higher. Bigger layer thickness is, as expected, also correlated with higher theoretical Ra values.

Measurement results and comparison

Surfaces of the ramps have been characterised (see Fig. 6b), and individual profiles have been extracted and filtered according to ISO 21920-3 [16], as stated in section "Manufacturing and measurement process".

a) b)



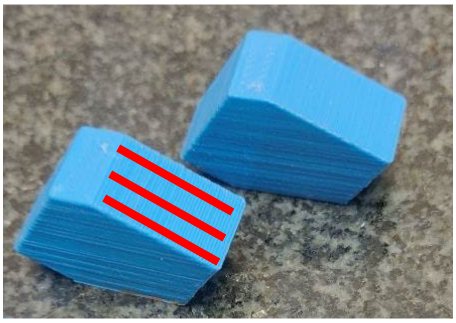
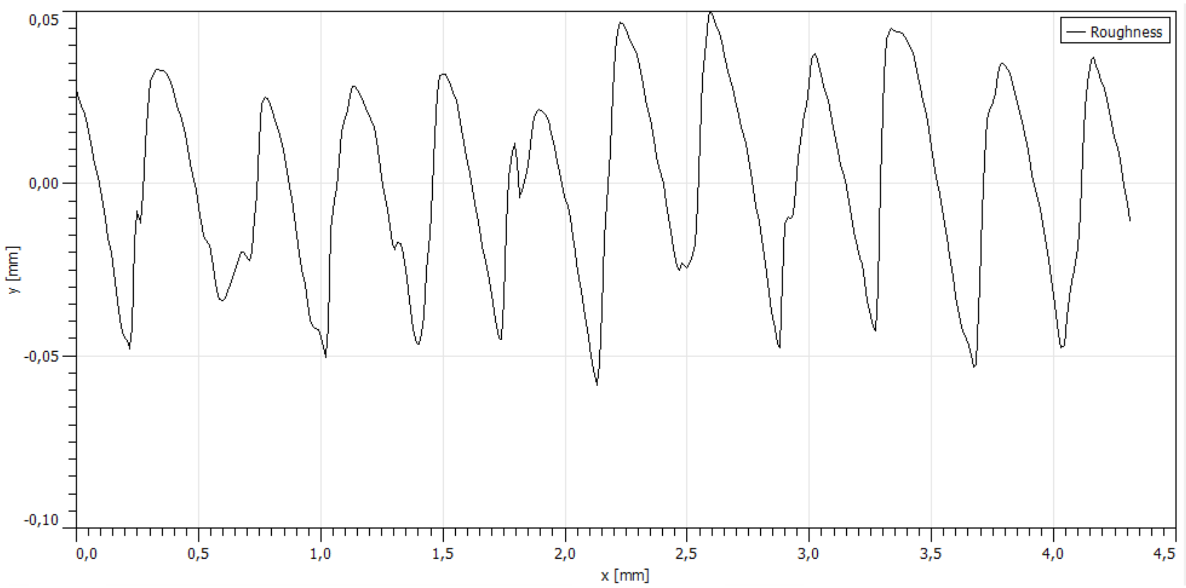
c)  d) 

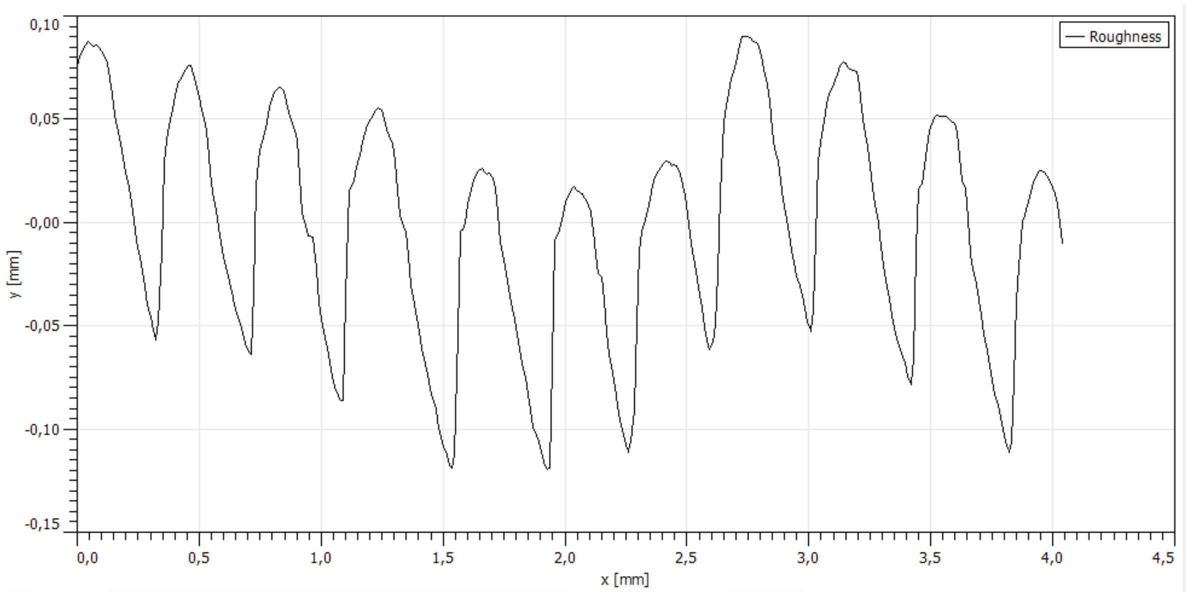
Fig. 6.- a) Printed four-faced Polyjet part b) Printed four-faced SLS part c) Printed two-faced FDM parts d) Example of surface extracted by Alicona.

Profiles extracted were located in the central part of the faces (see red lines in Fig. 6a and 6c). Three profiles along the central area of each ramp were extracted to obtain mean values for each geometry. Examples of roughness profiles of each technology (layer step ramps of 0.2 mm for FDM and SLS, 0.196 mm for Polyjet) extracted after filtration per ISO 21920-3 [16] are shown in Fig. 7.

a)



b)



c)

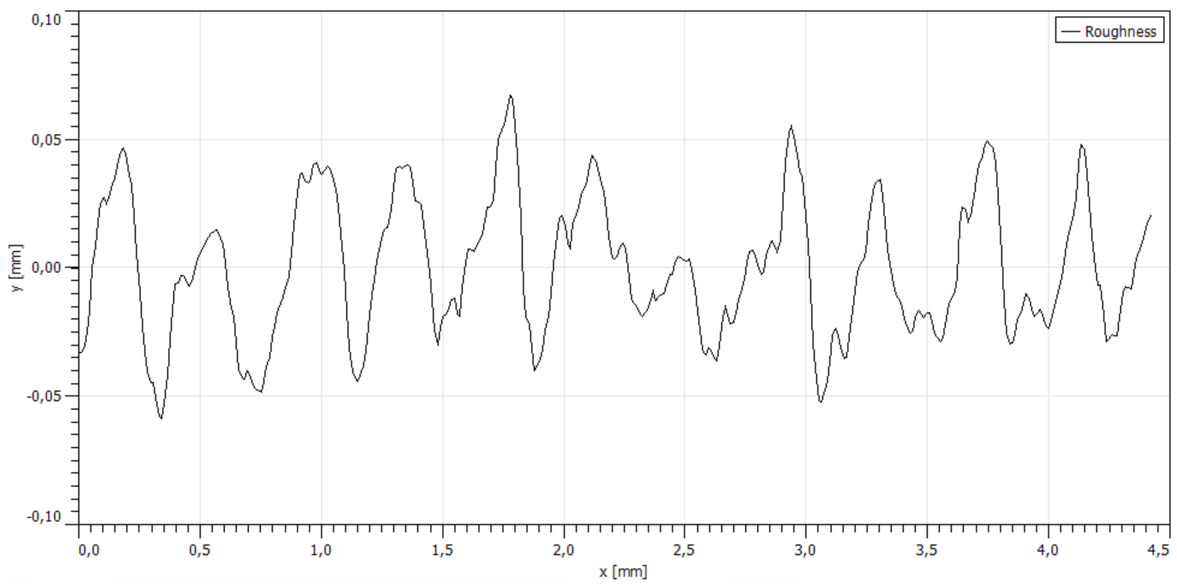


Fig. 7.- Examples of extracted profiles from 0.196-0.2 mm layer step ramps. a) Polyjet. b) FDM. c) SLS.

Graphics of measured Ra values compared to theoretical models are displayed in Fig. 8.

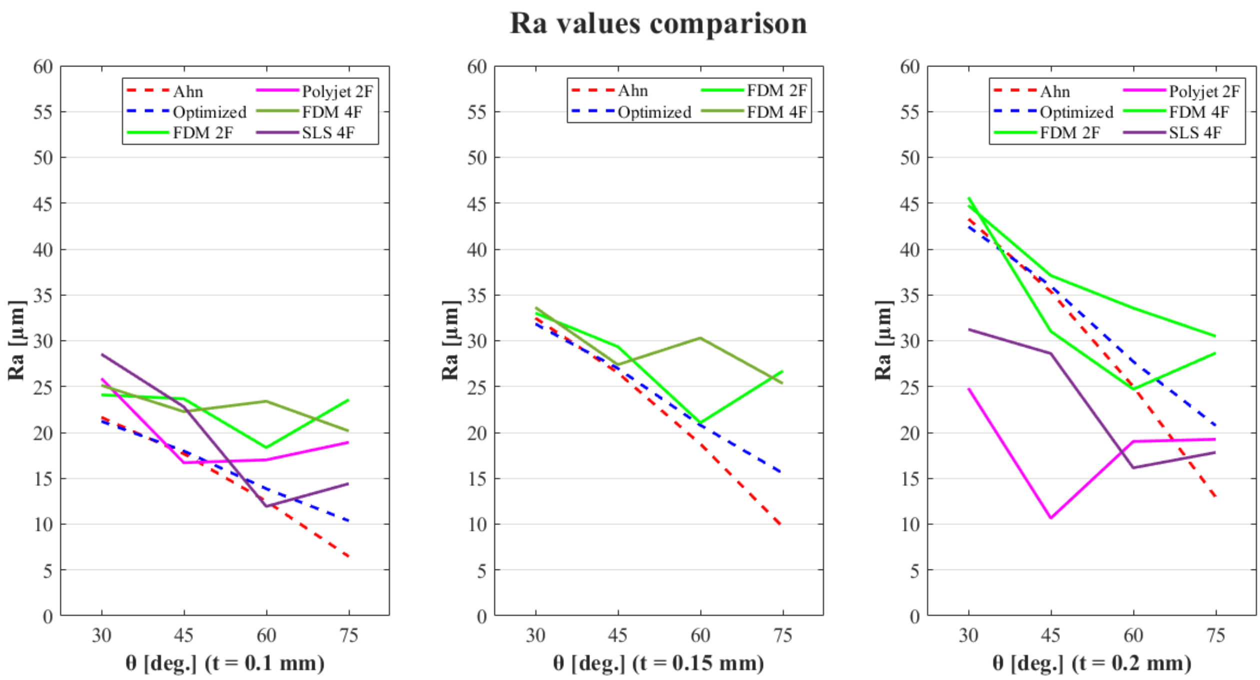


Fig. 8.- Comparison of measured and theoretical Ra values for each layer thickness (t).

Several measurements of each geometry have been done, and mean values are considered. As stated, results are grouped and compared according to the layer thickness of the geometry evaluated.

Discussion

Experimental results show in general, as expected, a difference with theoretical calculations, in both predictive models. For FDM parts, the bigger accuracy of the optimized model [15] than the Ahn general model [14] is demonstrated, mainly for angles of inclination of $\theta \geq 60^{o}$ where bigger deviations occur, not following the theoretical values' tendency. For this build angles, approximations have been made by some authors, as Pandey model [14].

As a consequence, nominal value of Ra plays an important role, because as it decreases, higher precision of AM devices is required and therefore better resolution for measurements is necessary. Layer thickness is, indeed, a parameter to consider, but its influence is not as big as the angle of inclination in terms of manufacturing precision. No tendency in the differences between results of two-faced and four-faced parts has been identified.

FDM results show in general clearer tendencies in the deviations than Polyjet and SLS values. The main reason is that no post processing was needed for FDM parts; Polyjet parts were affected by remaining resin trapped between stairs, same effect happens in SLS with unfused powder. As the post processing method is different for both technologies (pressurized water for Polyjet, compressed air for SLS), the effect caused in the results is also different and difficult to predict due to the non-automated cleaning process.

Profiles extracted confirm this tendency visually; in the images of Fig. 7, it is possible to see that most regular profiles are found in FDM parts. Both Polyjet and SLS parts show irregularities, being caused by the imperfect cleaning process. This effect is more patent in SLS parts where the unfused powder makes it difficult to distinguish correctly all the layers. Another aspect observed is the roundness in the peaks of the FDM parts, confirming that the approximation made by the optimised model [15] is funded.

Conclusions

In this paper, a metrological study of the topography of parts made by various polymeric AM technologies has been presented. A range of objects of study have been designed, manufactured and evaluated, with inclined ramps as a measurand created using relevant manufacturing parameters (layer thickness and angle of inclination). Parts have been designed with two different morphologies, as the future objective is to develop an object of study optimised for XCT characterisation Measurements have been carried out by a calibrated optical metrological device (FVM), and results have been compared to theoretical predictive models [14,15] using average linear roughness (Ra) as a parameter.

Results show higher influence of the angle of inclination over layer thickness in the accuracy of the real Ra values compared to theoretical values, being more evident when the angle of inclination increases over $\theta = 60^{\circ}$. For FDM parts, the optimised model shows better correlation to real values.

FDM results have a clearer tendency; technologies with a needed post process show more unpredictable values due to the remaining material in its surface, which is difficult to automate.

This experiment has planted the base for future work, which will be the design and evaluation by means of XCT of an object of study including features of the three AM technologies, to evaluate the XCT performance characterising polymeric AM micro geometries.

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