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Analysis of measurement problems of curvilinear profile specimen models produced by 3D printing

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Abstract: The development of modern manufacturing technologies requires the adaptation of measurement methods, which generates the problem of developing a new measurement strategy and an in-depth analysis of known measurement methods. The paper presents the results of an investigation into the measurement of the surface topography of models manufactured by Material Extrusion Technology (MEX). The measurement was carried out using three optical methods: - confocal, the interferometric, focus variation. The curved surface was analysed in its central part and in the rounded area, both concave and convex. The results showed significant differences in both measurement reliability and measurement errors. The results of the research showed that interferometry was the least effective method, characterised by the highest number of non-measured points regardless of the measurement location and sample shape. In contrast, the focus variation method showed the highest number of noise - spikes/ghost points located mainly at the edges of the measured area, which has a direct impact on the calculated value of the surface parameters. On average, the differences in the number of non-measured points for interferometric measurements were roughly four and a half times greater than for the confocal method and about one and a half times greater than for the focus variation method.

Keywords: surface metrology; 3D printing; MEX; non-measured points;

Nomenclature

MEX	Material extrusion
ST	Surface topography
NMP	Non-measured points

1. Introduction

The dynamic development of non-conventional technologies such as 3D printing requires the use of increasingly new measurement methods in accordance with current standards [1], where the author presented in detail the latest standards in the field of 3D printing and their industrial application. No references to measurement methodology were found in this publication. ISO/ASTM 52900 [2] presents a classification of measurement methods: binder jetting (BJT), directed energy deposition (DED), material extrusion (MEX), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL), vat photopolymerization (VPP). One of the most popular and widely used is the MEX method, which includes fused deposition

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modelling (FDM) and fused filament fabrication (FFF) technologies [3,4]. The increasing growth in the use of 3D printing methods in various industries determines the need for methods to measure their surface topography. The surface obtained by 3D printing varies depending on the technological parameters used and the 3D printing method, moreover, as shown in [5] the surface quality changing with the direction of printing has an impact on the wettability properties.

The measurement of the surface topography can be carried out using optical and contact measurement devices. ISO 25178-6 [6] provides a classification of methods for measuring spatial topography, including optical methods. However, optical methods have some disadvantages that can affect the final measurement result. In publication [7] for example, for the interferometric method, the authors pointed out the relatively small measurement area, long measurement time, and sensitivity to strong changes in surface contrast. In article [8] the authors pointed out measurement problems related to, among other things, multiple changes in standards related to surface topography, which makes it difficult to compare results. In addition, the paper pointed out that there are currently many different measurement methods and instruments, most of which allow only a few surface features to be measured. One disadvantage for optical methods is the phenomenon of non-measured points, the authors of the study pointed out, among other things, that even the smallest number of non-measured points falsifies the surface measurement in a certain way and has a direct impact on the final quality assessment of the final models. At the same time, the authors state in studies that the location of non-measured points on the surface vertices has a significant impact on the value of the determined roughness parameters.

The problem of non-measured points in optical measurement is extremely important as evidenced by ongoing research work by scientists from all over the world. The authors in paper [9] analysed the number of non-measured points for samples made with four additive technologies: PolyJet Matrix, fused deposition modelling, selective laser sintering, and selective laser melting), they used a Talysurf CCI device using an interferometric method for the measurement, the results show significant differences in the number of non-measured points and the samples produced with PolyJet Matrix technology had the lowest NMP regardless of the print orientation. The paper [10] analysed the influence of non-measured points on the measurement errors of the surface topography. The results show a significant effect on parameters such as Sv, Sal, Str, Sda, Sha, for example, but they concern conventional technologies and do not apply to 3D printed elements with a different surface structure. The effect of non-measured points for components made with additive technologies was addressed in [11] where they created a designed experiment for results related to this phenomenon. The researchers in [12] among other things, investigated the effect of the number of NMPs on the parameters: Sp, Sv, Sz, Spd and indicated their significant influence. The paper [13] describes the NMP phenomenon for the results of measurements obtained using three optical methods: FV - focus variation, CSI - scanning coherence interferometry, CM - confocal microscopy for the analysed parameters: Sa, Sq, Ssk, Sku, Sz. In the paper [14] a comparative analysis of contact and optical measurement methods was carried out for models produced with selective laser sintering (SLS) technology from the PBF group of methods, significant differences were found as to the number of non-measured points depending on the optical measurement method used and differences in the values of the parameters Sa, Sp, Sv, among others.

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An analysis of the current literature and publications in this field shows that there is no comprehensive description of the issue under study. There is no enough comparison of research methods in a comprehensive way for free-form surfaces, where there are many design limitations related to measurement. Most articles on determining surface topography parameters do not present the number of non-measured points, but only the results of the parameters. Articles [15–17] only present the measuring device and the determined surface topography parameters without specifying the number of measurement points.

Models manufactured using additive methods may have a more complex geometry than those made using conventional methods, so it is very important to develop guidelines (what is the reference gap) that give an indication of the best measurement method depending on the additive method used, as well as the material. Due to the development of manufacturing technology, more and more frequently used surfaces are so-called free-forms, which, due to the specificity of the rounded radius at the measurement point, cause problems with the measurement of the surface topography, where this problem is precisely the motivation for the research presented in this publication. The presented research used optical measurement methods most commonly used in scientific and industrial applications. The study shows differences in the number of non-measured points depending on the optical measurement method used on curvilinear surfaces, as well as the effect on spatial parameters. This has not yet been sufficiently described in the current literature. These results can serve as a guideline for the selection of a measurement method for models manufactured in MEX from flexible materials, which would be difficult to measure with contact methods due to the possibility of damage to the device during measurement.

2. Material and Methods

The tests were carried out on six specimens with varying shapes - concave and convex - and different radii. These components were fabricated using MEX technology. Investigations of the surface topography were carried out using three optical methods: - interferometric, - confocal and focus variation. Figure 1 below shows a flowchart illustrating the research methodologies.

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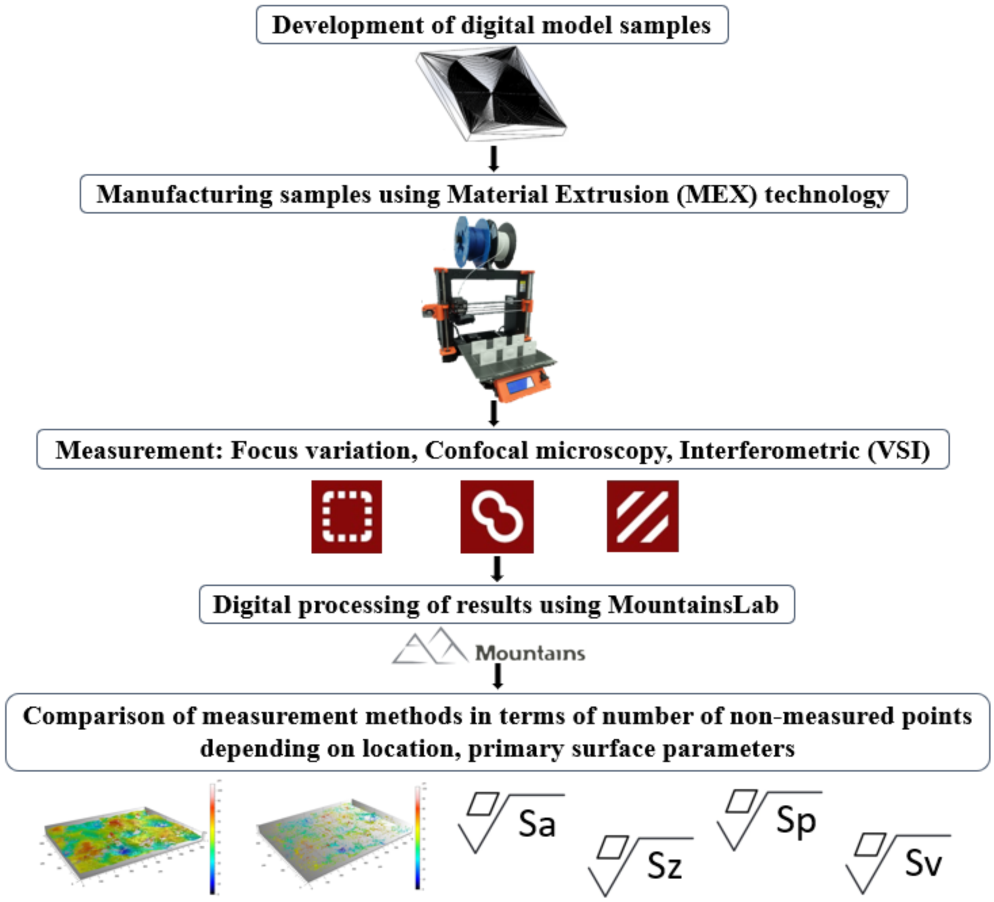

Figure 1. Flowchart showing the research procedure.

2.1. Design

The test specimens were designed using SolidWorks software (2024, Dassault Systèmes, Vélizy-Villacoublay, France). The designed specimens were characterised by concave and convex shapes, with radii of R100, R125 and R150, as shown in Fig.2 and Tab. 1. The aim of such designed samples models characterised by curvilinear surfaces (concave and convex) was to reflect the shape of components that are used in industry, e.g. seals, bearing races and other free-form components, which can be problematic. At the same time, this shape was deliberately chosen to enable measurement, as optical systems are characterised by geometry adapted to measuring flat surfaces, and too large curvatures prevent measurement.

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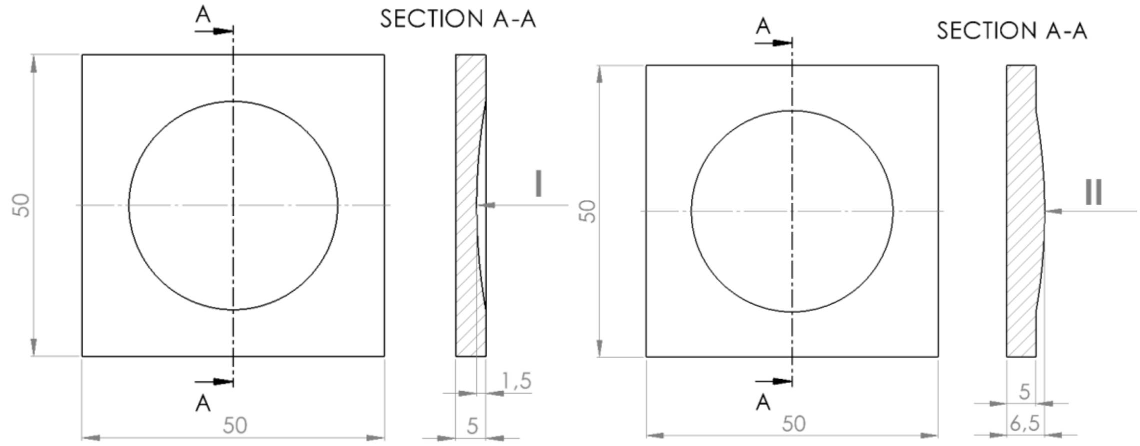

(a) **(b)**

Figure 2. Shape of specimens with dimensions: **(a)** concave 1-3**; (b)** convex 4-6.

Table 1. Radius values for all specimens.

Specimen number	Dimension	Radius value, mm
1	I	100
2	I	125
3	I	150
4	II	100
5	II	125
6	II	150

The designed specimens were saved in STL format, which creates a model solid from triangles. For both concave (1-3) and convex (4-6) samples, the deviation tolerance parameter of the save was 0.0035 mm, while the angular parameter was 0.5 degrees. An example of the recording result is shown in Fig.3. The number of triangles from which the solids of samples 1-6 were formed is shown in Tab.2.

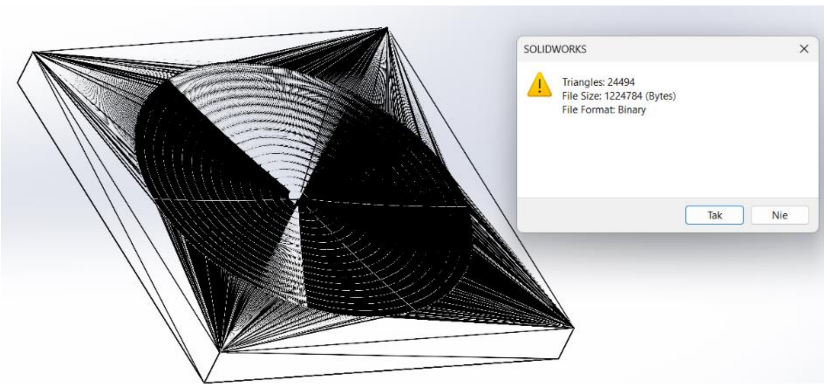

Figure 3. Save specimen 3 in STL format.

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Table 2. Number of triangles for specimens 1-6.

Specimen number	Number of triangles
1	28814
2	25934
3	24494
4	28814
5	25934
6	24494

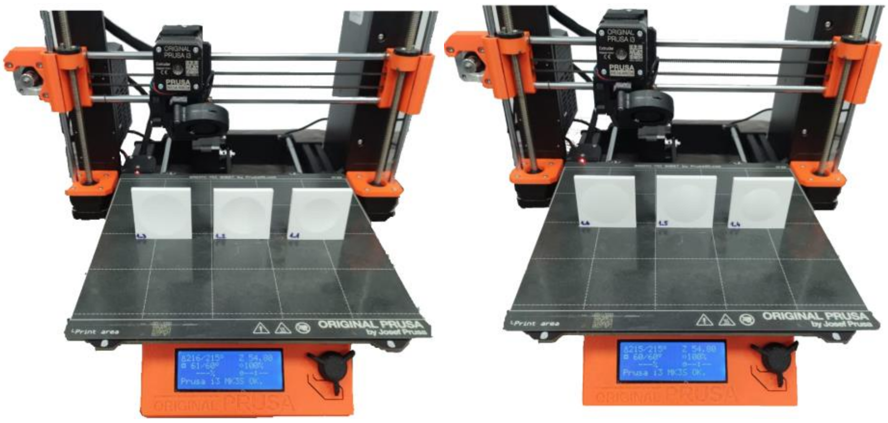
2.2.Manufacturing

The specimens were produced using the Fused Filament Fabrication (FFF) technology belonging to the MEX group. The equipment used for fabrication was the MK3S+ printer from Prusa (Prusa Research a.s., Prague, Czech Republic). The material used to manufacture the samples was FILAFLEX 60A WHITE (Recreus Industries S.L, Elda, Spain), which is one of the softest MEX printing materials available on the market. The print parameters for all samples are presented in Tab.3.

Table 3. Printing Parameters for specimens.

Parameters of the printing	Result and unit
Infill – fill density	20%
Infill – fill pattern	Gyroid
Layer height	0.2 mm
Speed for print moves	20 mm/s
Temperature - nozzle	225°C
Temperature - bed	30°C

The samples were produced in two print cycles of three each due to the risk of the so-called “stringing” phenomenon occurring [18]. The positioning of the samples on the working platform of the 3D printer is shown in Fig.4.



(a) **(b)**

Figure 4. Arrangement of specimens on the working platform of the PRUS MK3S+: **(a)** concave specimens 1-3**; (b)** convex specimens 4-6.

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2.3.Measuring

The surface topography was investigated using a Leica DCM8 optical microscope (Leica, Wetzlar, Germany). The microscope uses measurement methods:

- focus variation – is a method in which the sharpness of the image of a surface in an optical microscope is used to determine the height of the surface at each point of it [7,19].

- confocal - is based on illumination of the tested surface through a pinhole and transmission of the obtained image through a second pinhole in the detector's aperture. [7,19].

- Interferometric (Phase shift interferometry - PSI, Extended phase shift interferometry - ePSI, White-light vertical scanning interferometry – VSI) - is based on the use of an optical microscope with illumination of a known wavelength, which is integrated with an interferometer to produce a set of consecutive optical images with interference striations, which are processed into surface topography [7,19].

Lenses were used to carry out the research:

- for the interferometric method - VSI - Microscope Objective HC PL FLUOTAR 10x/0.30 MIRAU [20,21], magnification 10x, numerical aperture 0.3, resolution 1.3 µm/pixel – 1360 x 1024 pixels, measurement area 1.75 mm (X) x 1.32 mm (Y).

- for focus variation and confocal methods - Microscope Objective HC PL FLUOTAR 20x/0,50 [21,22], magnification 20x, numerical aperture 0.5, resolution 0.64 µm/pixel – 1360 x 1024 pixels, measurement area 0.87 mm (X) x 0.66 mm (Y).

The choice of the measurement area was determined by the field of view of the optical objects used, as in the presented studies the author wanted to avoid sticking together measurement areas, which affects the surface topography.

The centre point of the measuring location was the same for all methods, as the position of the sample on the measuring table of the Leica DCM8 microscope was not changed, but the objective in the turret holder of the instrument was changed, and the measuring table was moved in relation to the coordinate system of the microscope, allowing controlled movement of the sample.

Figure 5 shows a measurement of the surface topography using a Leica DCM8 optical microscope.

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Figure 5. Measurement of the specimen with a Leica DCM8 microscope in the central area.

Each of the six specimens was measured at five locations on the curvilinear surface. For each specimen, a central measurement location was established and four locations located in different quadrants of the XY coordinate system as shown in Figure 6.

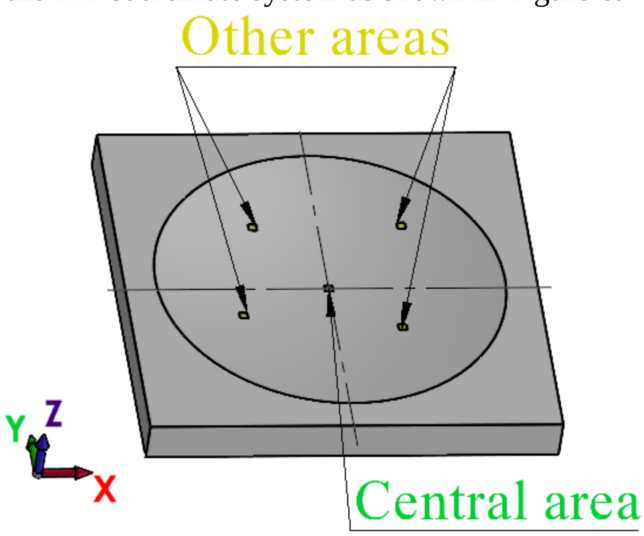

Figure 6. Location of measurement areas.

The analysis of the results of the surface topography was carried out using MountainsLab software (Premium 10, Digital Surf, Besançon, France). The software used the options: level, remove form, fill in non-measured points. For level, the remove surface with the *least squares plane* (LSPL) option was used, for remove form the *total least squares sphere* (TLSSP) option was used, the filling of non-measured points was carried out using *a smooth shape calculated from the neighbours*. The spatial parameters that were analysed were the primary surface parameters and S - Filter λs and C - Filter λc were not used. No filtering was chosen for roughness and waviness due to the fact that this study is intended to compare measurement errors/problems such as non-measured measurement points, ghost points in three optical methods.

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3. Results and Discussion

The results obtained were analysed in terms of the spatial height parameters of the primary surface before and after filling with non-measured points, as well as the number of non-measured points and the location of their occurrence. The results of the research were presented in the form of average values and the basic statistical parameter of standard deviation. The angle between the tangent at the specimen's rounded region and the vertical measurement axis is 90° at the centre of the specimen, whereas at other locations it averages 86°.

3.1.Primary surface – parameters

Height parameters analysed were: Sp - maximum peak height, Sv - maximum pit depth, Sz - maximum height, Sa - arithmetic mean height[19]. The following is a comparative analysis of these primary surface parameters for the mean values of the five analysed areas before and after filling, which were calculated according to ISO 25178-2 [19]. The filling operation was performed using the option to "use a smooth shape calculated from the neighbours".

Table 4. Primary surface parameters before and after filling

Specimen number	Parameter, μm	Confocal		Focus variation		Interferometric	
		Result before filling	Result after filling	Result before filling	Result after filling	Result before filling	Result after filling
1	Sp	35.01	36.04	319.05	328.00	31.55	42.94
	Sv	55.98	54.96	433.31	424.36	71.87	60.48
	Sz	91.00	91.00	752.36	752.36	103.43	103.43
	Sa	16.91	17.11	18.18	22.28	15.27	18.18
2	Sp	30.12	31.07	295.86	304.20	23.09	35.92
	Sv	52.25	51.30	420.29	411.94	55.94	43.12
	Sz	82.37	82.37	716.15	716.15	79.04	79.04
	Sa	16.49	16.63	19.26	21.97	15.22	18.29
3	Sp	27.92	28.80	313.37	322.77	18.77	29.75
	Sv	53.07	52.19	429.32	419.91	51.23	40.26
	Sz	80.99	80.99	742.68	742.68	70.00	70.00
	Sa	16.63	16.71	18.49	21.84	14.18	18.84
4	Sp	28.77	29.72	342.44	350.24	21.76	33.36
	Sv	49.71	48.77	412.11	404.32	53.14	41.54
	Sz	78.49	78.49	754.55	754.55	74.90	74.90
	Sa	16.71	16.80	18.60	20.17	12.83	17.99
5	Sp	34.07	34.78	344.99	352.93	19.79	30.83
	Sv	47.39	46.69	422.32	414.38	50.92	39.88
	Sz	81.47	81.47	767.31	767.31	70.71	70.71
	Sa	16.70	16.63	22.01	22.82	13.66	18.56
6	Sp	31.75	32.58	323.19	330.94	18.71	28.25
	Sv	48.20	47.37	435.23	427.48	50.78	41.25
	Sz	79.95	79.95	758.42	758.42	69.50	69.50
	Sa	16.98	17.00	22.10	22.48	11.78	16.79

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Analysing the Sp parameter before and after filling, it can be observed that it increases after filling for all samples and methods. For the results obtained with the confocal and focus variation methods, it increases on average by less than 3% after filling, while for the interferometric method it increases on average by less than 52%. In all samples analysed, this parameter before filling has the lowest value in the interferometric method and the highest value in the focus variation method and is on average more than fourteen times higher.

The parameter Sv decreases after filling in for all samples and methods analysed. It assumes the highest values for the focus variation method. In the results obtained with the confocal method and the focus variation method, the value of this parameter decreases by less than 2% on average, while for the interferometric method it decreases by more than 20%. The results before and after filling obtained with the focus variation method are higher than those obtained with the confocal method before and after filling of non-measured points by more than 8 times, while for the interferometric method before filling they are more than seven times and after filling by more than nine times.

The parameter Sz, like the previous parameters analysed, takes on the highest values for the results obtained using the focus variation method. When comparing the values before and after filling in all specimens, it remains at the same level. The results obtained using the focus variation method are more than nine times higher both before and after filling than those obtained using the confocal and interferometric methods.

When considering the parameter Sa, it takes on the highest values for the results where the focus variation method was used. When considering the change in value before and after filling, it can be observed that it increases in all cases except for sample 5 for the results from the confocal method, where the value decreases by approximately 0.4%. The highest change after filling can be seen in the results obtained with the interferometric method, as it increases on average by 30% with a standard deviation of 10 μm, while for the confocal method it increases by almost 0.5% with a standard deviation of 0.57 μm, for the focus variation method it increases by 11.4% with a standard deviation of 8.23 μm. Comparing the average results of the Sa parameter obtained with the focus variation method, it is higher by more than 18% before filling and more than 30% after filling than for the confocal method, and higher than the results obtained for the interferometric method before filling by 43% and 21% after filling.

3.2.Numbers of non-measured points

Figure 7 shows a graph with the calculated mean value of the non-measured points from the five areas on the curvilinear surface for all 6 specimens, together with the standard deviation shown.

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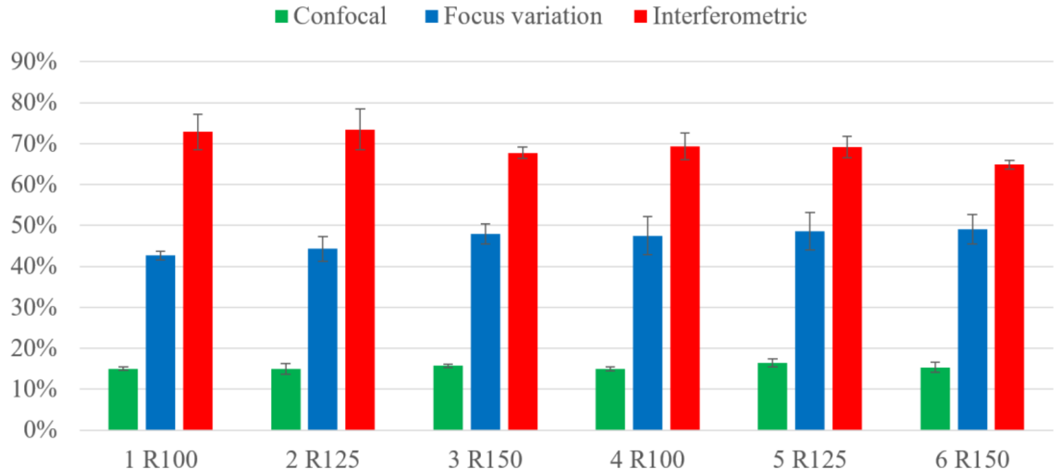

Figure 7. Value of non-measured points for all specimens.

Analysing figure 7, it can be observed that in all cases analysed, the value of non-measured points is lowest for the values obtained using the confocal method, with an average of about 15%, for the focus variation method the average is about 47%, while for the interferometric method it is highest at about 70%. The value of non-measured points with the interferometric method is about four and a half times higher than with the confocal method and one and a half times higher than with the focus variation method.

Figure 8 shows a comparative analysis between the measurement areas. The central area is compared along with the mean value and standard deviation from the other four areas.

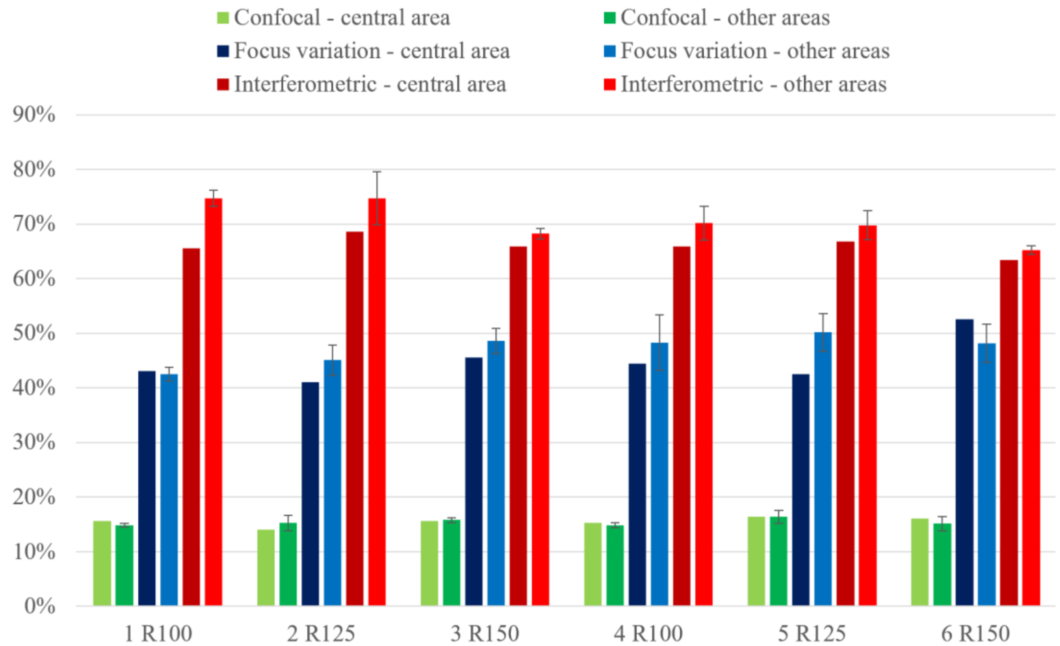

Figure 8. Comparative analysis between the central measurement area and the others.

Comparing the results shown in Figure 8, it can be observed that for the values obtained with the confocal and focus variation methods, the area in which the measurement was carried out has no influence on the parameter of non-measured points. For the values obtained with the

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interferometric method, it can be observed that the measurement location has an influence on the value of the non-measured points, as the results from the central location are lower for each sample (taking into account the standard deviation value) than the results from the other measurement locations, and on average they are lower by approximately 6%.

The analysis of the number of non-measured points presented in figures 7 and 8 is important because too many non-measured points affect the overall reliability of the research, as shown by a review of the literature. The location of the measurement points affects the value of the surface topography parameters, and the surface approximation method (surface approximation) method is appropriate in the location of non-measured points, and therefore one should aim to select a measurement method that is characterised by the smallest number of non-measured points, which in the case of the presented research allows for the recommendation of the confocal method with the smallest number of non-measured points.

3.3.Location of non-measured points

Figure 9 shows an image of the surface topography of specimen 6 from the central location measured using the confocal method.

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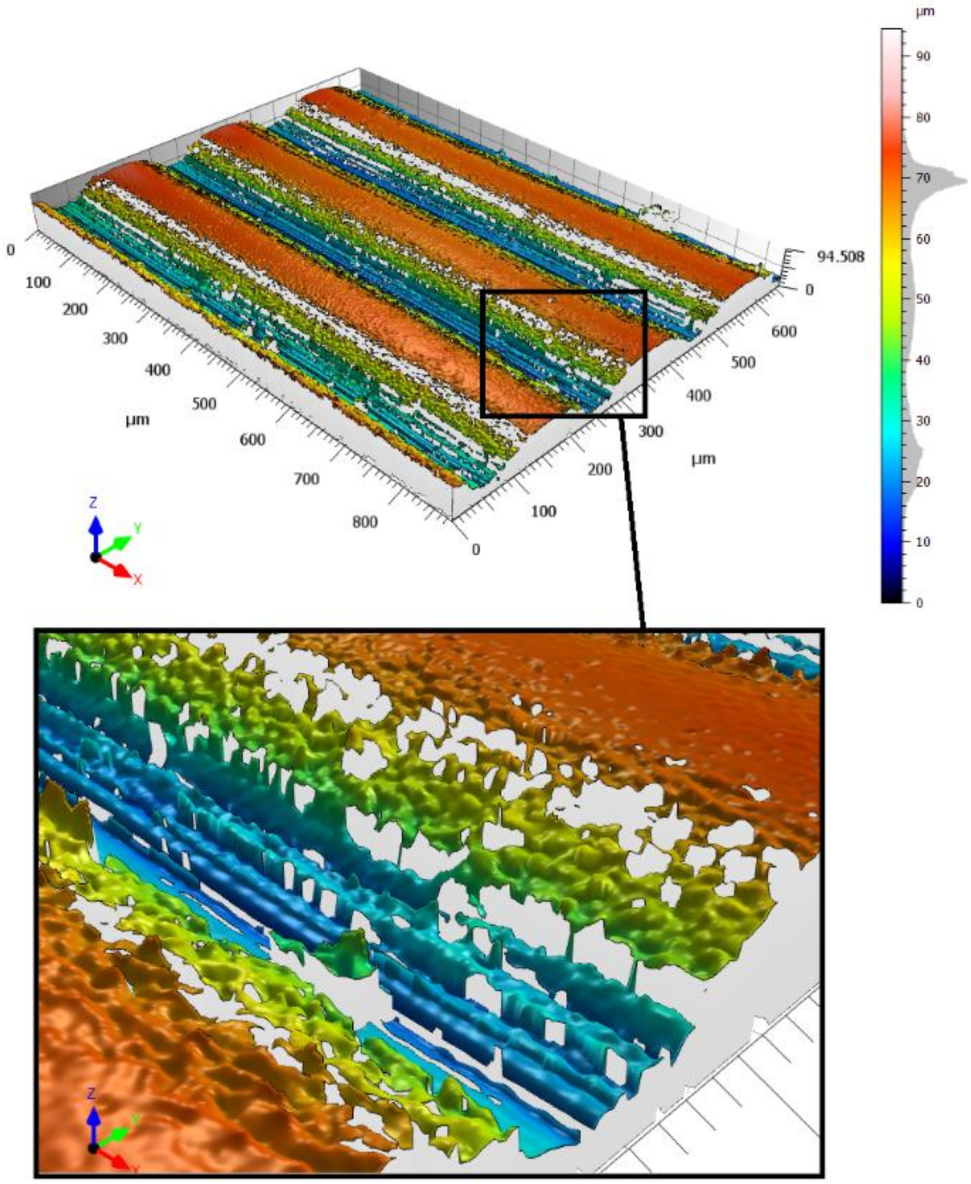

Figure 9. Surface topography of specimen 6 in the central area obtained using the confocal method.

As can be observed in figure 9, the phenomenon of non-measured points occurs to a large extent on slopes, and to a small extent on peaks and valleys. The surface is characterised by an anisotropic structure, which is related to the technology from which the samples were made.

Figure 10 shows an image of the surface topography of specimen 6 from the central location measured using the focus variation method

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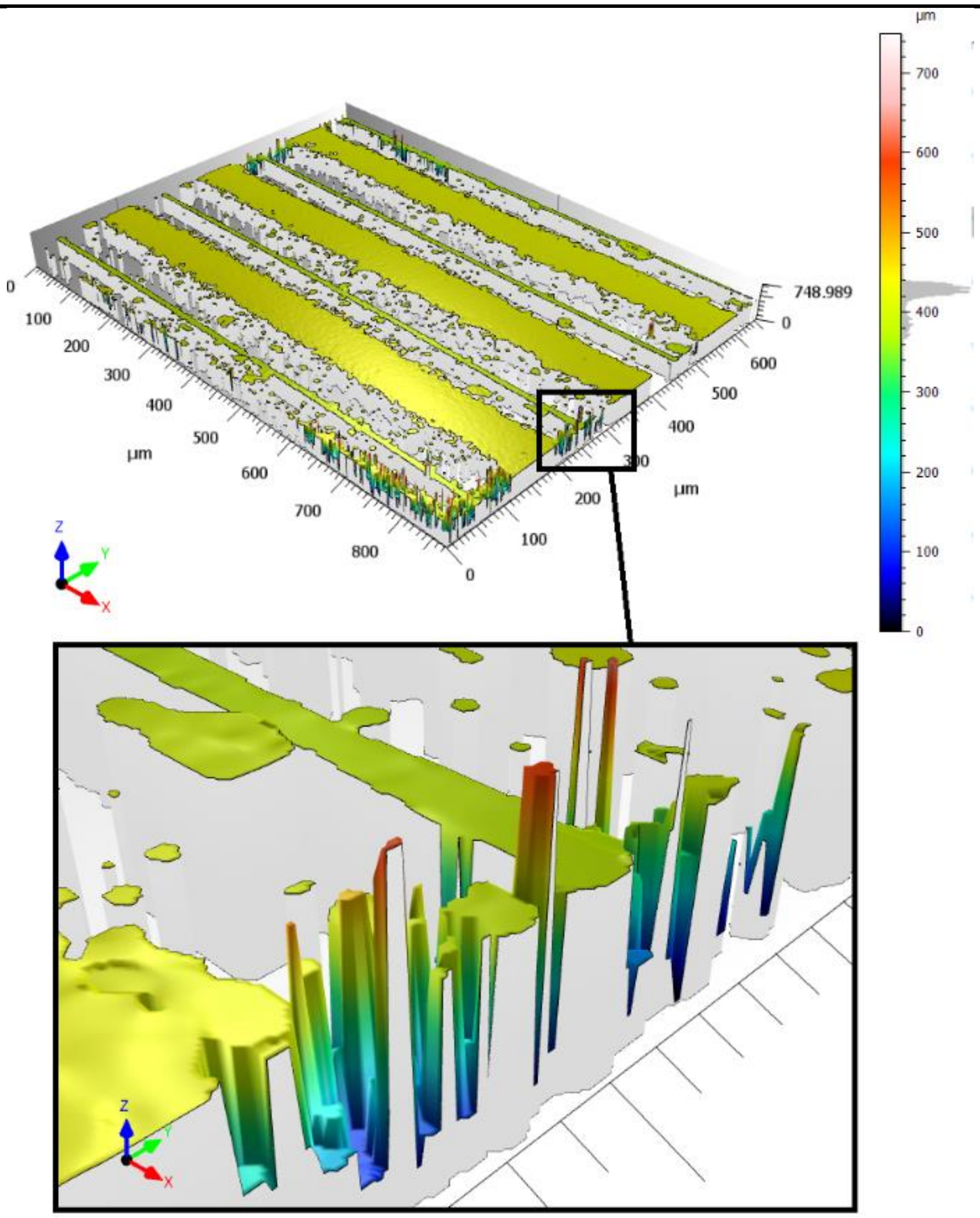

Figure 10. Surface topography of specimen 6 in the central area obtained using focus variation method (example of ghost on edge).

Analysing figure 10 above and the other surface topography images obtained using the focus variation method, it can be observed that the phenomenon of non-measured points occurs on the slopes of the surface. Peaks and valleys were measured. The measurements obtained with this method were characterised by a number of non-measured points of less than 50%, but as can be observed, ghost points appear, which are places that should be non-measured points, while the method has filled them with vertical ‘pins’, which can have a negative impact on the reliability of the survey results, in particular the height parameters.

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Figure 11 shows an image of the surface topography of sample 6 from the central location measured using the interferometric method.

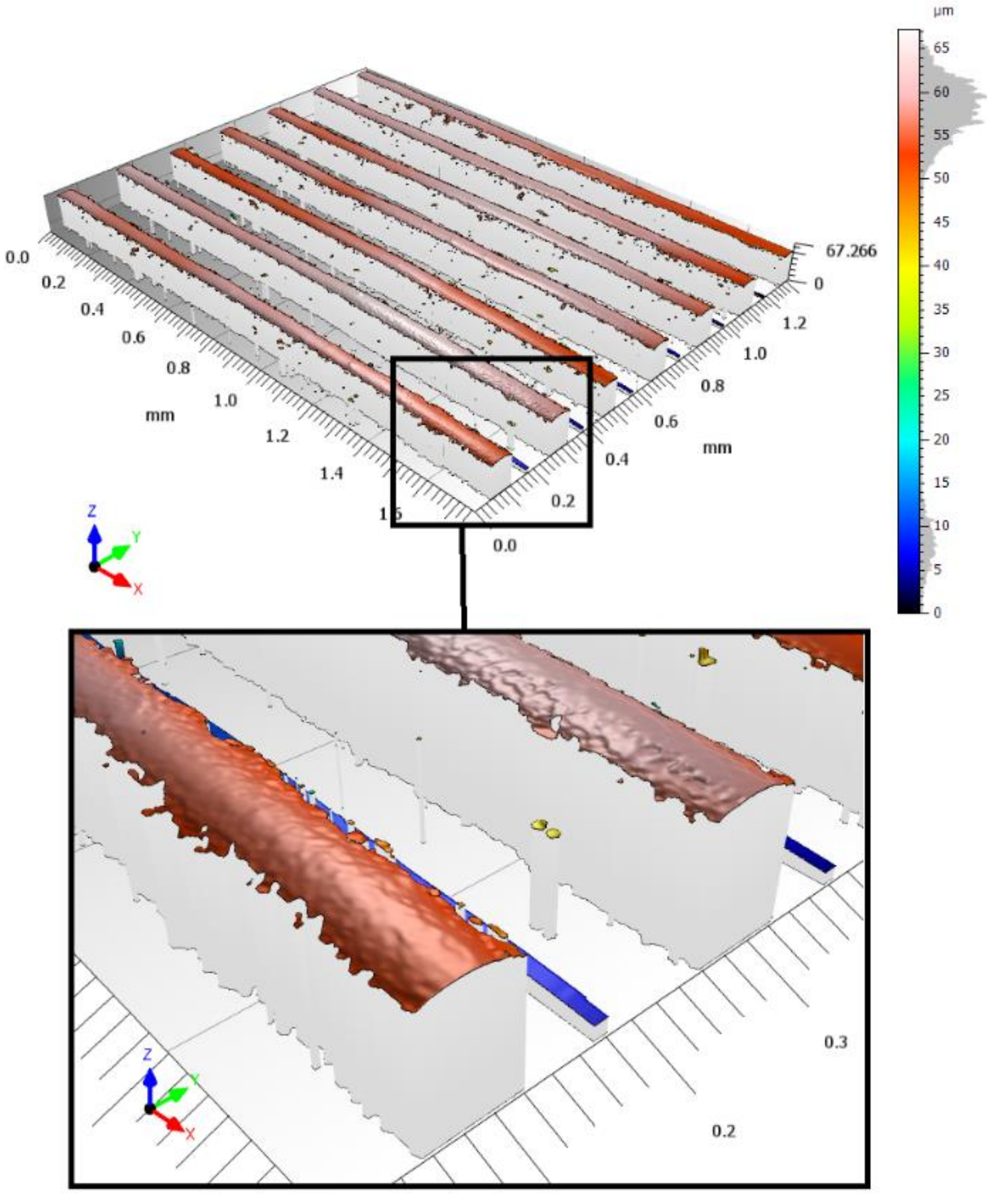

Figure 11. Surface topography of specimen 6 in the central area obtained using interferometric method.

In figure 11 it can be observed that the phenomenon of non-measured points appears on the slopes, the results obtained with this method stand out from all the methods analysed in that the measured width of the peaks and valleys in the Y axis is the highest.

When analysing the problem of measurement noise in the form of additional points that do not actually exist on the surface, a certain characteristic feature can be observed depending on the measurement method used. When analysing figure 10, which shows the measurement results for focus variation method, a large amount of noise (ghost points) is clearly visible, which is filled in by the software in an incorrect way, thus increasing the height parameters of

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the measured surface. In the case of the other two methods (interferometric, confocal), no large number of ghost points were observed, which certainly affects the reliability of the measurements. In the case of the focus variation method, these points mostly occur at the edges of the measurement area.

4. Conclusions

The author reached the following conclusions after the research:

- The development of methods for measuring the surface topography leads to the need to analyse the selection of the most optimal one, each method having its limitations. The method that gave the best results in the study was confocal, as it had the lowest number of non-measured points and no ghosts points that would affect the measurement results.
- The popularisation of the use of additive manufacturing methods require the determination of their surface topography, in ISO/ASTM 5901 [23], which deals with the requirements for purchased additively manufactured components, where one of the points concerns the determination of the surface topography and the measurement method, showing how the research carried out in this field is of great practical engineering importance. If the same measurement method is used, differences/measurements errors may arise, affecting whether the product is considered by the customer to meet quality requirements.
- The analysis of the number of non-measured points is a key issue in optical methods for measuring the surface topography, as it can influence the final result. It is not only the phenomenon of non-measured points that is crucial, but also the interpretation of the obtained results in terms of ghost points, which, as shown in the study, have a great impact on the values of the analysed parameters.
- The results indicate that, in interferometric measurements, reducing the measurement angle from 90° (at the central region) to an average of 86° (across the remaining measurement areas) adversely affects the number of measured points, thereby increasing the number of non-measured points (NMP).
- The author sees a further need for research in this area, as there is the possibility of using other lenses with a higher magnification factor that can affect the number of non-measured points, as well as analysis of other surface topography parameters.

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