COMPARATIVE ANALYSIS OF THE SURFACE TOPOGRAPHY OF MODELS MANUFACTURED USING SLS TECHNOLOGY

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The measurement of the geometric structure of a surface is a key issue in determining the useful characteristics of the component under study. The main objective of the presented research was to compare methods of assessing the geometric structure of the surface of models made using additive technology of Selective Laser Sintering (SLS). In the research carried out, optical measuring instruments using the following methods were used: focal differential, confocal, interferometric and contact profilometer as a reference method. Tests for the optical methods were carried out using a LEICA DCM8 multisensor instrument with a x50 magnification lens and for the contact method using a Form Talysurf PGI 1230 profilometer. The samples were made from PA 2200 polyamide powder. The test results showed differences in the number of non-measured points and the measurement time. The lowest number of non-measured points and the shortest measurement time were the results obtained using the focal variation method. The results from the contact method showed lower values for all evaluated roughness parameters than the optical methods.

KEYWORDS

Surface texture, 3D printing, selective laser sintering, PA 2200, 3D printing.

1 INTRODUCTION

The development of additive technologies and the ever-expanding range of available materials determines the necessary selection of appropriate methods for measuring surface texture (SGP). There are many classifications of additive methods, but the most popular division is the one presented in ISO/ASTM 52900:2021 [ISO/ASTM 52900:2021], which divides additive technologies into seven groups: binder jetting (BJT), directed energy deposition (DED), material extrusion (MEX), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL), vat photopolymerization (VPP). 3D printing technology has a lot of advantage but the key problem is anisotropy of e.g. mechanical properties and other quality factor [Bochnia 2016]. The surface of 3D printing varies depending on the technology and process parameters used, however, the application of coatings and the creation of composites has become very popular in recent years, which has a positive effect on the quality of the surface texture [Kozior 2022], [Sakakibara 2020]. When it comes to evaluating the parametric surface texture of models manufactured with additive technologies, there are no guidelines for selecting an appropriate surface measurement method. There are many methods of surface texture evaluation which are classified in ISO 25178-6 [ISO 25178-6]. However, the various methods have their limitations Among the most significant is the so-called number of non-measured points (NMP).

The issue of the surface texture produced mainly by additive technologies is a very important aspect, so it is undertaken by many research centres from around the world e.g. [Maculotti 2023], [Newton 2019], [Li 2022], [Newton 2023]. Work related to the measurement of surface texture of models manufactured using 3D printing has been undertaken by employees of the Kielce University of Technology. The authors in [Zmarzły 2023] presented the results of samples produced by four methods: PolyJet Matrix (from the MJT group) from FullCure 720 material, Fused Deposition Modeling (from the MEX group) from ABS P430 material, Selective Laser Sintering (from the PBF group) from PA 2200 material, and Selective Laser Melting (from the PBF group) from 316 L steel-based material. The paper presents the results of surface topography measurements using two methods: optical (interferometric) and contact. As presented in the results, the highest number of non-measured points was registered for models made using SLS technology, which was in the range of 98.8 ÷ 99.6%. Such a large number of non-measured measurement points was reflected in the incomplete approximation of the surface by the mathematical software, which translated into discrepancies in the obtained results for the contact and optical methods.

Parametric evaluation of surface texture is also the subject of many research projects such as POLSKA METROLOGIA (Ministry of Education and Science of the Republic of Poland within the “Polish Metrology” program. Project number PM/SP/0077/2021/1, Metrology of surface irregularities in additive techniques) [Turek 2023], where the authors performed contact and optical (focus variation) measurements of the surfaces of MJM-produced models for three materials Digital ABS-Plus (AR1), VeroClear (AR2) and RGD720 (AR3). During the study, spatial parameters of surface roughness such as Sa, Spk, Sk, and Svk were analysed. Similarity was shown in the results obtained for AR1 and AR2 resins regardless of the measurement method. For the AR3 material, significantly higher values of the analysed parameters were observed, as well as an apparent effect of the measurement method on the average values of the parameters, higher values were obtained with optical measurements, where for the parameter Sa from optical measurement the value was almost twice as high as that from contact measurements, for the parameter Spk and Sk the results of optical measurements were about 1.5 times higher than those obtained from contact measurements, for the parameter Svk of optical measurements was almost four times higher than that from contact measurements.

Roughness parameters are extensively described in publication [Grzesik 2015], where their influence on functional characteristics such as tightness, friction, wear, adhesion and fatigue are discussed. Wit Grzesik analysed the influence of the parameters Ra, Rz, Rq, Rpk, Rmr, and correlated them with functional areas of functional characteristics, and determined whether the influence was significant, noticeable, insignificant and marginal. Based on this information, a number of 2D and 3D parameters were selected in this publication, which carry a lot of information about the performance characteristics of SLS-produced models.

In the paper [Bazan 2023] the authors conducted a study where they compared the results of measuring the topography of models produced by two additive technologies: Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF) of PA12 material, the surfaces were post-processed. The surface texture was measured using focus variation microscopy. The samples manufactured by the SLS method before processing showed higher values for Sa, Sz, Sdq, Sds, Str, Sdr parameters than the samples manufactured by the MJM method.

The authors of the paper [Pawlus 2018] compared the results of surface texture measurements obtained with a contact device, a white light interferometer and a confocal profilometer. The components tested were made of steel, grey iron and bronze. The results showed that there are differences between contact and optical methods and that they depend on the type and nature of the surface, and that among the optical methods used in the study, white light interferometry performed better.

Research on the problem of non-measured points, i.e. the subject matter that is analysed in this publication, has been described extensively in the paper [Pawlus 2017]. The authors of the publication extensively described the problems of optical microscopy in the context of surface measurement with a simulated variable number of non-measured points. Using surface approximation for a variable number of NMPs, roughness parameters were determined. The results showed that the introduction of a slight modification of the surface texture model by introducing 1-2% NMP has a significant effect on the value of roughness parameters, and in selected cases the change in parameter values exceeds even 25% (Sda, Sha, Sdv, Shv).

The problem of selecting an appropriate method for the evaluation of the geometric structure of the surface is extremely important, e.g.: due to the measurement time, the number of non-measured points (for optical methods) and the possibility of damaging the measured surface due to the properties of the material from which the sample is made (for the contact method). This happens very often in the case of measuring so-called soft materials, which are increasingly used in the 3D printing process.

The paper [Softić 2021] also deals with the subject of non-measured points, however, for the 3D scanning method, where the number of measurement points depends on the light falling on the object under investigation during the measurement. Due to the geometry of the model, some of the light does not cover the surveyed surface which significantly reduces the accuracy of the measurements increasing the number of non-measured points.

Due to the fact that a large part of the research presented in this literature description and in other scientific publications is related to the evaluation of surfaces produced by conventional methods, the results presented in this article on 3D printing and SLS technology, due to the condition of the surface (lack of orientation) and the properties of polyamide, make it difficult to measure with selected optical methods (numerous non-measured points occurring) and seem to have great utilitarian application.

The study conducted by the authors of this publication shows significant differences in measurement time, number of non-measured points, depending on the measurement method used, and can be used as a guideline for choosing a method of measuring the geometric structure of the surface for models produced by SLS.

2 MATERIAL AND METHODS

The research presented here consisted of evaluating the surface texture of models manufactured using 3D printing technology - SLS and PA 2200 polyamide powder, based on PA12 polyamide. Surface texture measurements were made using a contact and optical measurement system. Using the LEICA DCM8 optical system, measurements were made using three different methods:

- Interferometric;
- Confocal;
- Focus variation;

2.1 Samples manufacturing

A model of the samples in the shape of a cuboid with dimensions of 60 mm x 60 mm x 5 mm was designed using SolidWorks software (2022, Dassault Systèmes, Vélizy-Villacoublay, France) and saved in STL format (approximation using a triangle mesh). The STL model was characterized by a structure composed of 12 triangles. The samples were fabricated using Selective Laser Sintering technology, using a Formiga P100 machine (EOS, Krailling, Germany). The aim of the study was to compare measurement methods, so the influence of technological printing parameters and the condition of the powder was not analysed. The material used was a powder that had been refreshed according to the manufacturer's recommendations. A total of 5 specimens were made, which were situated on a virtual build platform in such a way that a 60 mm x 60 mm surface was parallel to the 3D printer platform, as shown in Fig. 1.

Selective laser sintering consists in the layering of powdered material on the working platform of the device using a scraper, which is then sintered by the laser in places corresponding to the currently constructed cross-section of the model. The working platform is then lowered by a given layer thickness (0.1-0.2 mm) and the cycle is repeated until the model is completely manufactured [Rokicki 2016].

The 3D printing process of the sample was carried out using the following technological parameters:
- layer height - 0.1 mm;
- P - laser power – 21 W;
- v - laser scanning speed - 2500 mm/s;
- h - hatch distance – 0.25 mm;
- X - beam overlay ratio – 1.68;
- building chamber temperature - 150°C;

$$E_d = \frac{P}{vh}x \tag{1}$$

During the manufacturing process, the working chamber of the 3D printer was filled with an inert gas, nitrogen. Using equation (1), the energy density delivered to the sintered polyamide layer was calculated, which in the case of the present samples was 0.056 J/mm^2.

2.2 Samples measurement

The samples were measured using a Form Talysurf PGI 1230 contact profilometer (Taylor Hobson, Leicester, England) and a Leica DCM8 optical microscope (Leica, Wetzlar, Germany) - Fig. 3. The measurement of the contact method was carried out to compare several optical methods with it and was taken as the reference measurement. Before the measurement started, several initial measurements were taken at different sample locations and no significant differences between the measurements were noticed.

The measurement was taken at the centre of the sample, as shown in Fig. 1. The measurement area for each method was the same at 2.4 mm x 2.4 mm. Such a measurement area required a filter of λc = 0.8 mm and was used for contact and optical measurements to compare the research results. To obtain the same measurement area for each method, a ‘stitching’ procedure was used for the optical methods.

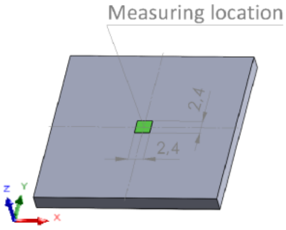


Figure 1. Sample measurement location.

2.2.1 Contact measurement

Contact profilometry is a method of measuring surface topography in which the movement of a stylus in direct contact with the surface being measured is converted into a signal that is a function of position [Pawlus 2014]. Consequently, this method does not suffer from the problem of non-measured measurement points and can therefore be considered as a reference.

In the study presented here, surface texture contact topography measurements were taken using a Form Talysurf PGI 1230 contact profilometer - shown in Fig. 2. A measuring tip with a rounded radius of 2 µm was used for the measurement.

Figure 2. Measurement of the test sample using Form Talysurf PGI 1230

The key measurement parameters are as follows:
- Measured area: 2.4 mm x 2.4 mm;
- Number of profiles: 900;
- Speed of movement of the stylus: 0,25 mm/s;
- Sampling step in axis ΔX = 1 µm;
- Sampling step in axis ΔY = 2.7 µm;
- Resolution in axis Z = 0.8 nm;
- Stylus tip rounding radius: 2 µm;
- Angle of the stylus tip: 60°;

2.2.1 Optical measurement

Three differing techniques were selected to measure samples using optical methods, as explained below.

The interferometric method [ISO 25178-6], [Newton 2023], [Wieczorowski 2013] is based on the use of an optical microscope with illumination of a known actual wavelength, which is integrated into an interferometric cap and produces a set of consecutive optical images with interference striations, which are the basis for the evaluation of surface topography. The interferometric method has the highest vertical resolution of all optical methods. There are many variations of the interferometric method such as: Phase Shifting Interferometric microscopy (PSI), White-light Vertical Scanning Interferometry (VSI). White-light vertical scanning interferometry (VSI) is used where Phase Shifting Interferometry (PSI) fails, i.e. where the surface under measurement is characterised by steep slopes and irregularities. The PSI method is used to measure smooth surfaces with discontinuities of up to 150 nm [ISO 25178-6], [Wieczorowski 2013], [Leica Microsystems CMS GmbH 2014]. The VSI interferometric method was used in the surface studies carried out.

The confocal method as described [Wieczorowski 2013] ‘involves illuminating the surface to be examined through a hole in the aperture and transmitting the resulting image through a second hole in the aperture to a detector’. Confocal profiling provides the highest lateral resolution that can be achieved with an optical profilometer. In this way, spatial sampling can be reduced to 0.10 µm, which works well for surface slope measurements [ISO 25178-6], [Leica Microsystems CMS GmbH 2014]. Focus variation [ISO 25178-6], [Wieczorowski 2013] is a method of using the focus (or other property of light that is reflected at the point of focus) of an image to estimate the height of a surface at any point. This technique can measure on steep sides and very rough surfaces, but cannot measure very smooth surface roughness [ISO 25178-6], [Leica Microsystems CMS GmbH 2014], [Zheng 2020].

Figure 3. Sample measurement using a LEICA DCM8 microscope.

The surface measurement was carried out at the same location on the test specimen. Two lenses placed in the turret mount of the Leica DCM8 were used: the Mirau SR 50X for the interferometric technique and the EPI 50X for the confocal technique, and focus variation.

Optical measurements were taken of an area of 2.4 mm x 2.4 mm, which was created by combining 88 parts (11 rows, 8 columns), as shown in Fig. 4. In addition, a ‘stitching’ procedure with an overlapping value of 15% was used to combine the analysed areas (green area in Fig. 4). A single part had a dimension of 350 µm x 264 µm (green area - Fig. 4).

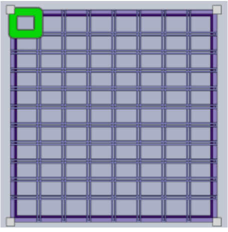


Figure 4. Partition of the measurement area in LEICA SCAN 6.5.6.

3 RESULTS

In the research, 2D (for the profile) and 3D (for the surface) roughness parameters were analysed to compare the methods. In addition, the number of non-measured NMP points for the optical methods was also analysed, as well as the measurement time for all measurement methods used.

The software used to analyse the results obtained during measurement with the Leica DCM8 microscope was LEICA SCAN 6.5.6. The maximum measurement range in the Z-axis for the Leica EPI 50X objective is 141 µm, and therefore the same Z-axis range was determined for the Leica Mirau SR 50X objective. The setting of the origin of the Z-axis coordinate system and the ‘LIGHT’ parameter were selected individually for the method and for the sample. For all methods used, the highest possible resolution was set. The ‘Speed factor’ parameter was set by software to the lowest possible value, for each method, meaning that the software defined the measurement using the optimum step between planes [Leica Microsystems CMS GmbH 2014]. For the interferometric and confocal methods, the measurement parameter ‘THRESHOLD’, which, according to the instrument manufacturer [Leica Microsystems CMS GmbH 2014] ‘The Threshold setting decreases or increases system sensitivity to the optical signal by setting a lower level of measurement reliability - below this level, data points are ignored’ was set at - 5%, while for the focus variation method it was set at - 1%. This change was motivated by an earlier study [Malara 2024], in which, for focus variation measurements of SLS- manufactured specimens for a PA 2200 material, the measured point results were 21% when the THRESHOLD parameter was set to a value of 5%. A broader analysis of this problem concluded that changing the value of the THRERSHOLD parameter significantly reduced the NMP number. Tab. 1 below shows the average sample measurement time for each of the methods used, while Tab. 2 shows the number of non-measured points.

Method	**Average sample measurement time**
Contact	10 h, 00 min
Interferometric	02 h, 17 min
Confocal	04 h, 30 min
Focus variation	00 h, 53 min

Table 1. **Average sample measurement time for all methods**

Method	**Average value of NMP, %**
Contact	-
Interferometric	5.00
Confocal	7.14
Focus variation	2.98

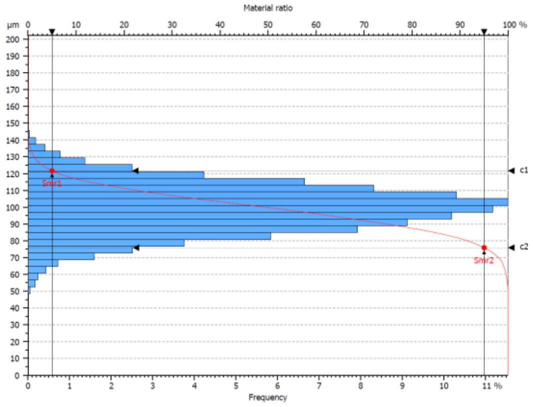
Table 2. **Average value of the number of non-measured points – NMP.**

Tab. 3 presents the results of the spatial parameters -S, and profile parameters - R for the mean values of the five samples tested. In the case of the Interferometric and focus variation methods, the analysis of the results was only performed for four samples, due to an insufficient measurement range in the Z-axis, which resulted in an incorrect ‘cut-off’ of the surface for sample number 2 (Fig. 10). The parameters presented were calculated according to the standard for spatial parameters - ISO 25178-2 [ISO 25178-2], and for parameters in profile - ISO 21920-2- ISO 21920-2 [ISO 21920-2]. A Gaussian filter of λs = 2.5 µm and λc = 0.8 mm. was used, allowing division into three section lengths. Fig. 5 shows an example of Abbott-Fireston material ratio curves and the cumulative function of the depth distribution.

Parameter \ **Method**	**Contact**	**Interferometric**	**Confocal**	**Focus variation**
Sa, µm	9.35	9.62	9.96	10.08
Sp, µm	47.47	73.21	69.98	74.11
Sv, µm	50.45	62.76	58.43	80.34
Sz, µm	97.92	135.97	128.41	154.44
Ssk	-0.09	0.07	0.05	0.04
Sku	3.16	3.60	3.60	3.84
Ra, µm	7.53	7.70	8.02	8.12
Rt, µm	44.89	59.20	57.92	69.57
Rp, µm	17,68	24,31	23,89	21,98
Rv, µm	18,96	23,00	21,79	22,50
Rz, µm	36,64	47,31	45,68	44,48
Rk, µm	18.79	21.63	21.94	22.40
Rvk, µm	12.82	14.16	14.92	15.55
Rpk, µm	11.34	14.79	14.92	15.39
Rsk	-0.10	0.06	0.08	-0.01

Table 3. **Average values for areal and profile parameters.**

a)



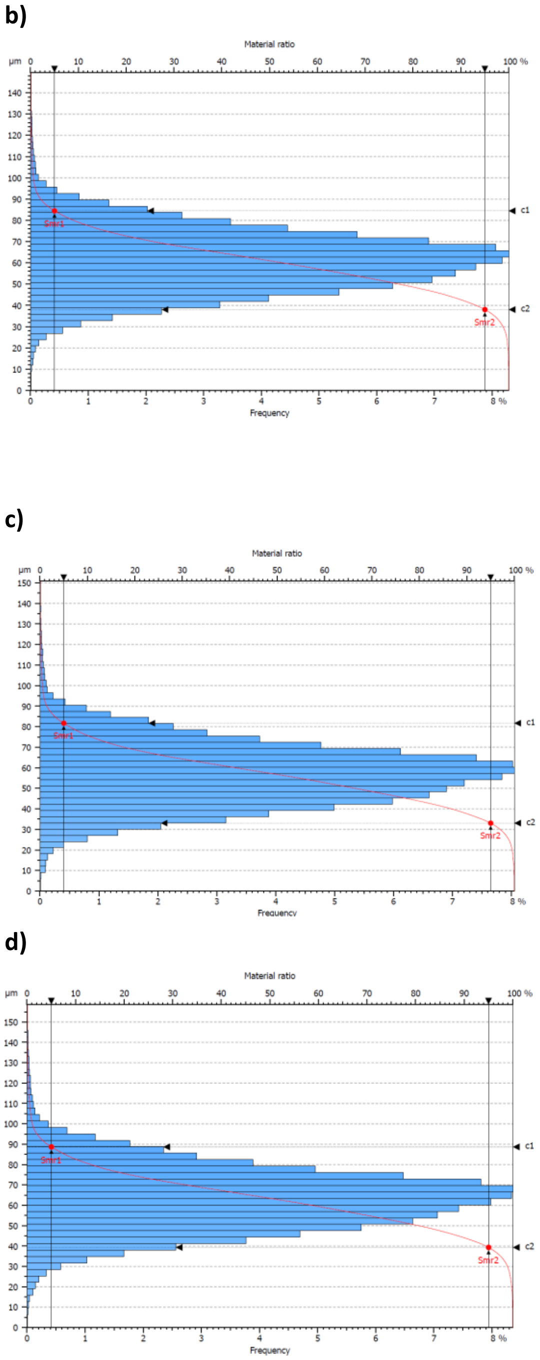


Figure 5. Histogram of material contribution curves - Abbott-Fireston curve: a) contact measurement, b) interferometric method, c) confocal method, d) focus variation method.

Fig. 6 shows an isometric view of the surfaces measured using all the methods analysed. In the case of SLS technology and polyamide powder, the surface is isotropic. In addition, Figs. 7-10 illustrate the measurement problems for selected optical methods.

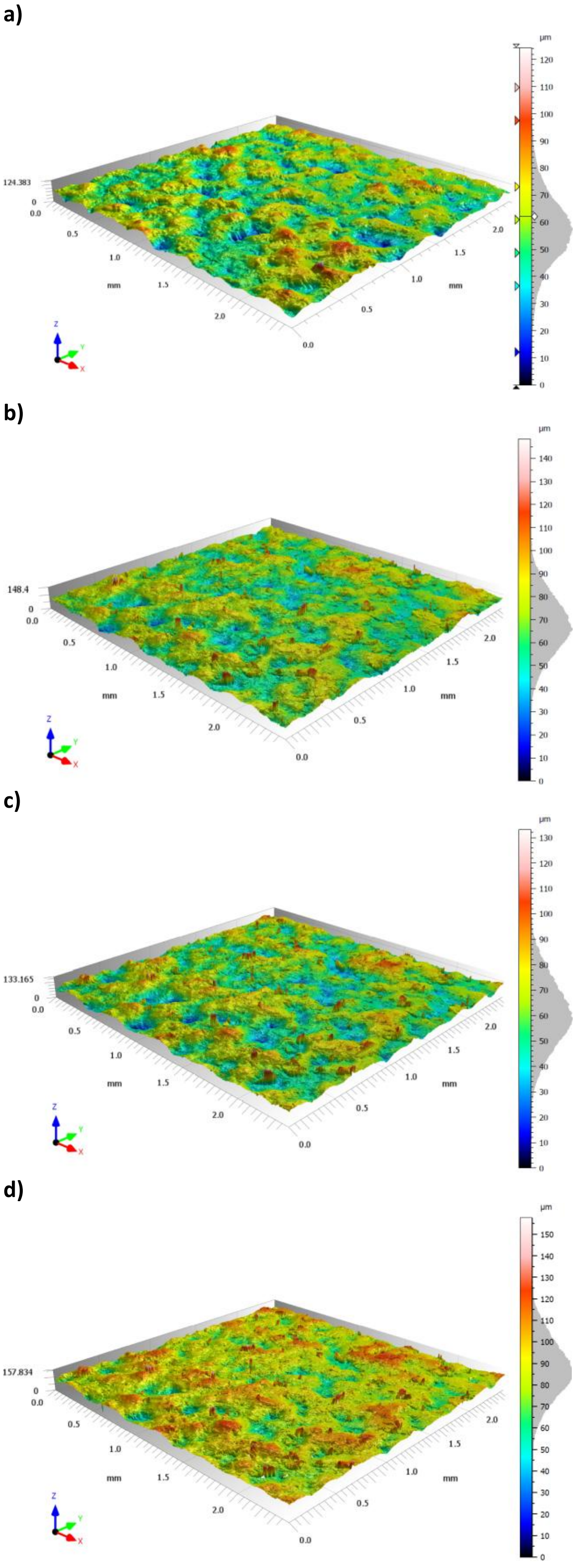


Figure 6. View of sample surface topography for all methods: a) contact method, b) interferometric method, c) confocal method, d) focus variation method.

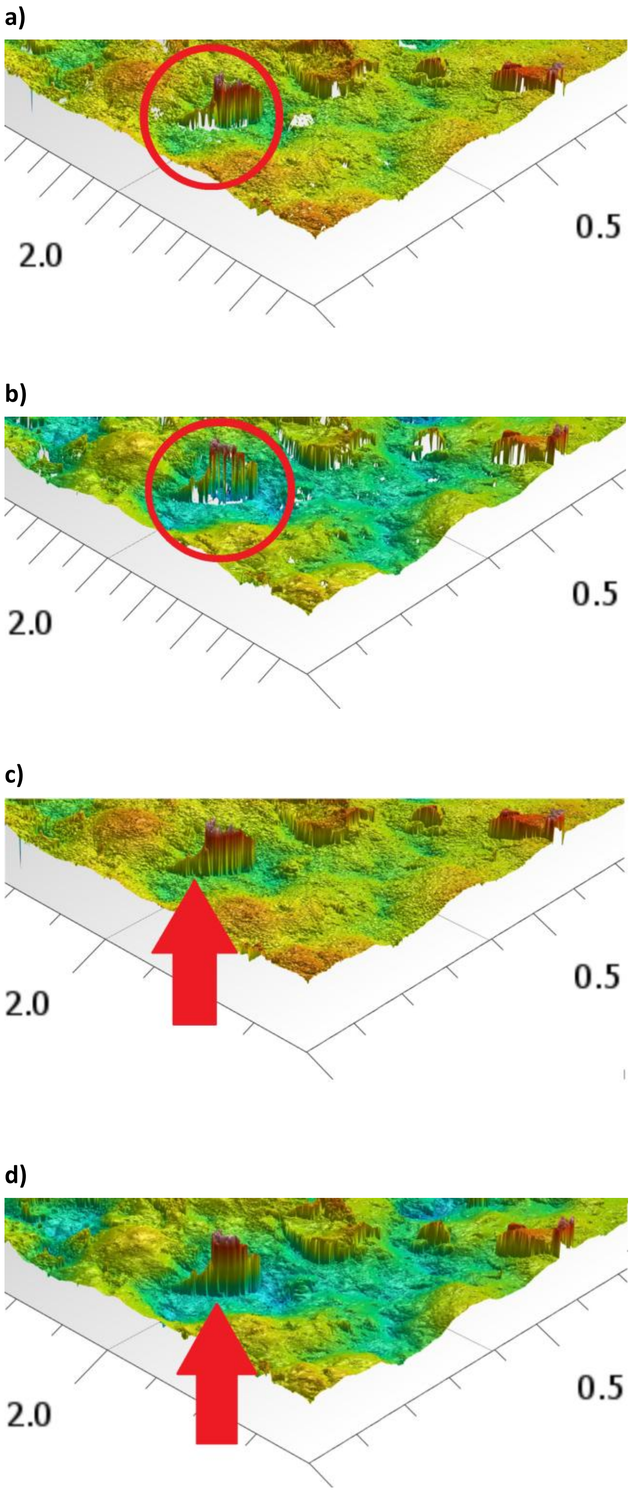


Figure 7. View of the analysed surface: a) focus variation without NMP filling, b) confocal without NMP filling, c) focus variation with NMP filling, d) confocal with NMP filling.

a)

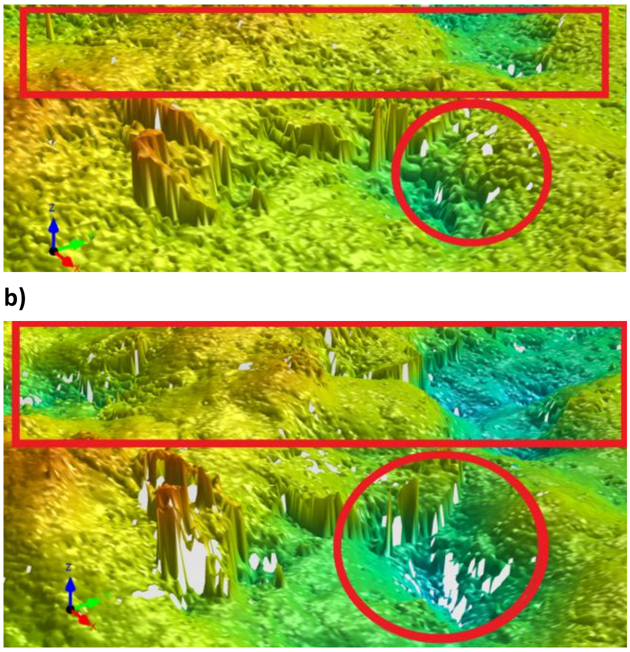
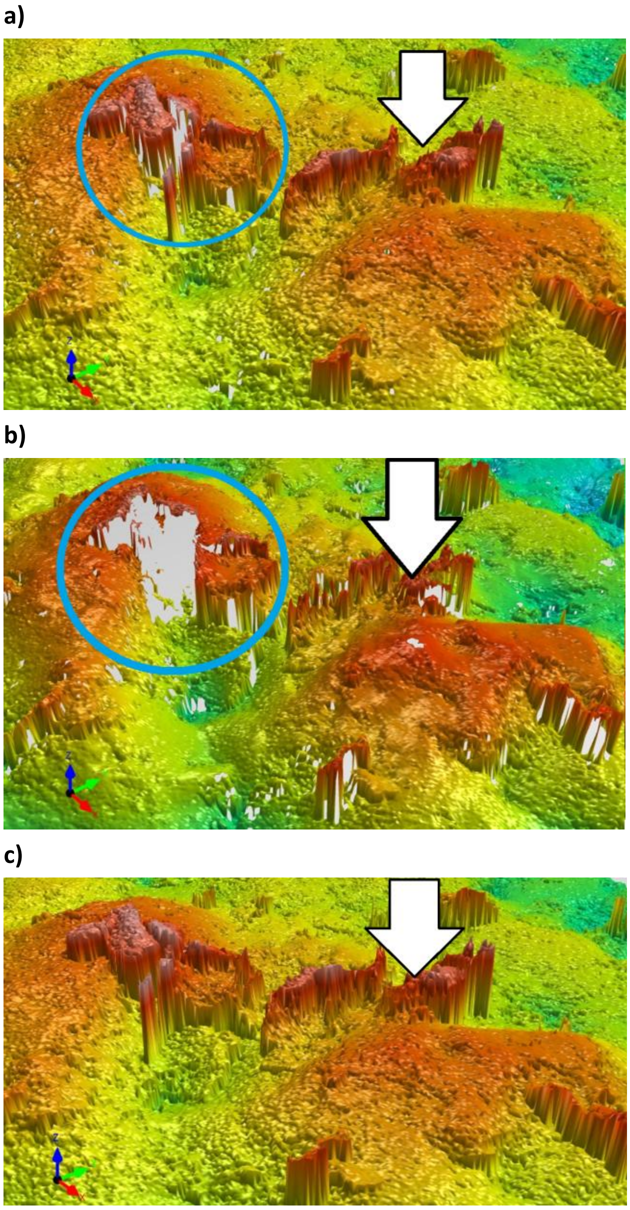


Figure 8. View of the analysed surface: a) focus variation without NMP filling, b) confocal without NMP filling



d)

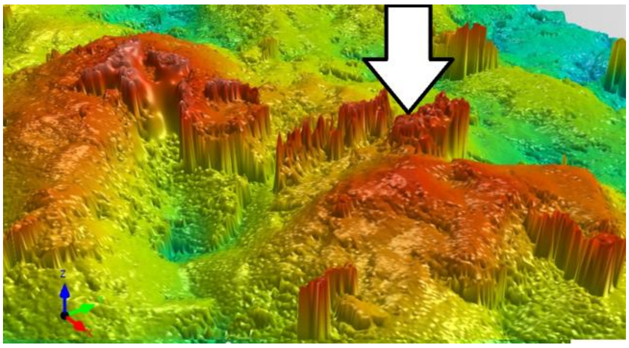
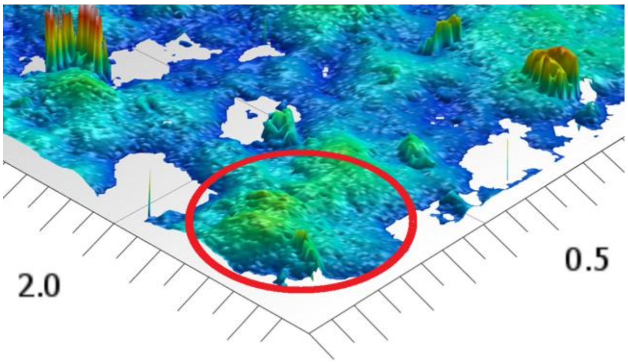
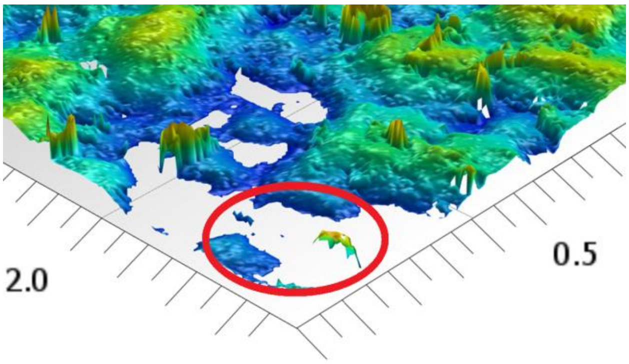


Figure 9. View of the analysed surface: a) focus variation without NMP filling, b) confocal without NMP filling, c) focus variation with NMP filling, d) confocal with NMP filling.

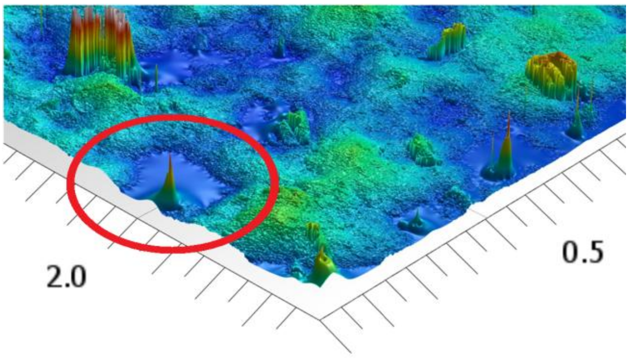
a)



b)



c)



d)

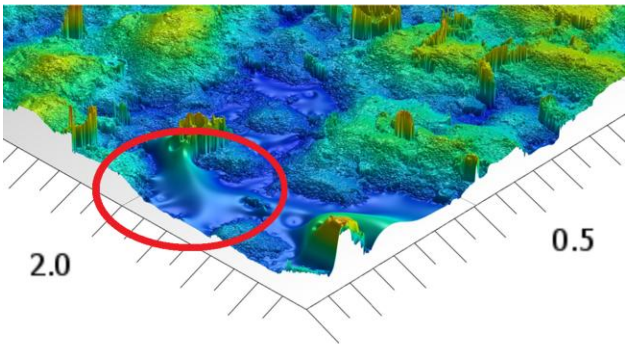


Figure 10. View of the analysed surface: a) focus variation without NMP filling, b) Interferometric without NMP filling, c) focus variation after NMP filling, b) Interferometric after NMP filling.

4 DISCUSSION

By analysing the results in Tab. 1, it can be concluded that the shortest measurement time was obtained with the focus variation method (53min) and its average measurement time was more than ten times shorter than for the contact method (10h), and five times shorter than for the confocal method (4h 30min). Furthermore, the measurement time for the focus variation method was more than two and a half times shorter than for the interferometric method (2h 17min).

Tab. 2 shows the average number of non-measured points - NMPs for all measurement methods used in this study. There are no NMPs in the contact method. Therefore, it was not further analysed in this area. The focus variation method showed the lowest NMP value with an NMP of 2.98 %. The interferometric method had a significantly higher number of NMPs (5 %), by approximately 67 % compared to the focus variation method. However, for the confocal method, the number of NMPs (7.14 %) was approximately 140 % higher compared to the focus variation method. The number of non-measured measurement points varies depending on the test material from which the test sample was made and, in the case of the polyamide analysed, the focus variation method can be considered as the recommended method for this type of measurement. The choice of the focus variation method for polyamide increases the ‘reliability’ of the measurements carried out, due to the fact that the software filling in the non-measured measurement points approximates a smaller area. Furthermore, as shown in [Pawlus 2017] a slight difference in the number of NMPs has a significant effect on the selected 3D surface parameters.

The analysis of the surface parameters from the group of 3D parameters based on the Sa parameter shows that for all the methods analysed, it takes values in the range of 9.35-10.08 µm, with a standard deviation of 0.6-0.9 µm at a similar level regardless of the technology. In the case of the assessment of the Ra parameter for the profile series, the value of the parameter for all technologies varied in the range: 7.53-8.12 with a standard deviation of: 0.49-0.88 µm. The parameters relating to the symmetry of the profile ordinate distribution for both 2D - Rsk and 3D - Ssk contact methods are characterised by minus values - slightly below zero. For almost all optical methods, the values are positive - slightly above zero. In the case of the comparison between the contact and optical methods, the parameters obtained by contact measurement, excluding the Ssk and Rsk parameters were characterised by values approximately 27 % lower than those obtained from optical measurements.

The nature of the surface ordinate distribution obtained for the optical methods is very similar, as confirmed by the similar values of the Sku and Ssk parameters. Although slightly lower values of the Sku and Ssk parameters were obtained for the contact method compared to the optical methods, this did not significantly affect the shape of the material share curve and the distribution of surface ordinates.

The higher values of amplitude parameters such as Sz for the surface or Rt for the profile obtained for optical measurements compared to contact measurements are due to the occurrence of distortions at the edges of the slopes in the form of so-called 'ghost points'.

The obtained values of the bearing curve parameters Rk - reduced core height of the roughness profile, Rpk - reduced elevation height of the roughness profile and Rvk - reduced depression depth of the roughness profile is lower in relation to the optical methods. The contribution of the Rvk parameter to the Rk parameter for all methods ranges from 66% to 69%. In the case of the contribution of the Rp parameter to the Rk parameter for the contact method, it is 60%, while for the optical methods it is 68% to 69%, which is due to the occurrence of interference at the edges of the slopes in the form of so-called 'ghost points'.

By comparing the optical methods with each other, it can be seen that in many cases the calculated roughness parameter can be incorrectly determined. As an example, Fig. 7a and 7b show the surface view obtained respectively for the focus variation and confocal methods. It can be clearly seen that, for both methods, the measurement has erroneously registered so-called 'ghost points' in addition to the non-measured measurement points marked in red. Next, in Fig. 7c and 7d, a filling process was carried out for the same surfaces, where it can be seen, that the approximation using the 'neighbouring points' method erroneously supplements the measured surface with geometrical features similar in shape to the 'ghost' points. The roughness parameters determined from the approximated surface were artificially high (for the case shown in Fig. 7). This problem occurred for all the optical methods analysed.

The surface areas were measured using the focus variation (Fig. 8a) and confocal method (Fig. 8b) and then analysed. The results measured using the focus variation method were more accurate. i.e. with significantly fewer non-measured points. This is particularly evident in the figures mentioned above comparing the rectangular red box, where for the confocal method can be seen many evenly distributed NMPs. Comparing the valley also marked with a red circle in Figs. 8a and 8b, it can be noticed that the measurement obtained with the focus variation method reflects (a smaller number of NMPs) the area in a much better way, especially on slopes, confirming the superiority of this method in optical measurements.

Comparing Fig. 9a with Fig. 9b, it can be seen that in the case of the focus variation method, there were measurement areas, which were recognised as measured by the instrument software, but were in fact filled with so-called 'ghost points', (marked in blue). Furthermore, it can be clearly seen that there are also areas where both measurement methods identified certain areas as ghost points and approximated them in a similar manner (marked with a white arrow in Fig. 9).

Fig. 10a and 10b show the surface for the focus variation and interferometric methods, which for sample number 2 were measured erroneously with the Z-axis setting too small. In addition, the red colour indicates the area where the measurement with the focus variation method expressed the surface in a much better way with its clear geometry (peaks and slopes). In Fig. 10c and 10d, the measurement area is shown in red after filling in the non-measured points with the neighbouring points algorithm. As can be seen at the intersection points (lack of range in the Z-axis) the approximation surface is smoother than measured surface, which can also disturb the further calculation of the roughness parameters.

5 CONCLUSIONS

In engineering applications, the use of optical methods allows for shorter measurement times. However, depending on the method, they have their specific advantages and disadvantages. Analysing the results obtained, it can be concluded that measurements by optical methods of models made with SLS technology of polyamide powder PA 2200 for height parameters take higher values than for the contact method which may be due to the appearance of 'ghost points'. The analysis of the surface should not only include a quantitative evaluation based on the values of the roughness or waviness parameters, but also, a qualitative one, taking into account the nature of the determined irregularities and the so-called 'ghost points.

In the case of the analysed measurements, carried out using the focus variation method, the highest number of measured points was obtained for almost all of the samples, making the number of non-measured measurement points the smallest in this case. In addition, the results of the focus variation measurement in several cases showed fewer non-measured measurement points. However, these were replaced by so-called 'ghost points'.

Reliable measurements of the geometric structure of surfaces are key elements from the perspective of manufacturing full-fledged components using additive technologies. Therefore, the authors of this paper see the need for further research in order to further standardise measurements in this area.

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