Surface roughness of photoacrylic resin shapes obtained using PolyJet additive technology*)

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Streszczenie: The article presents the results of analyzing the surface roughness of samples manufactured using the PolyJet additive technology. Three types of photopolyacrylic resins were used in the production process of the test samples. The samples were measured using stylus and optical measurement methods. The presented research extends information on the surface roughness of resins used in the PolyJet 3D printing process. It is a starting point for further improvement of measurement procedures for polymer materials.

Keywords: additive techniques, polymer materials, surface roughness, stylus measurements, optical measurements.

Chropowatość powierzchni próbek wykonanych z żywicy fotoakrylowej otrzymanych przy użyciu technologii przyrostowej PolyJet

Streszczenie: Zbadano chropowatość powierzchni kształtek wykonanych z trzech rodzajów żywic foto poliakrylowych metodą przyrostową PolyJet. Stosowano stykową i optyczną metodę pomiarową. Przedstawione badania poszerzają wiedzę w zakresie chropowatości powierzchni żywic stosowanych w procesie druku metodą PolyJet oraz stanowią punkt wyjścia do dalszych badań dotyczących usprawniania procedur pomiarowych w odniesieniu do próbek wykonanych z materiałów polimerowych.

Słowa kluczowe: techniki przyrostowe, materiały polimerowe, chropowatość powierzchni, pomiary stykowe, pomiary optyczne.

Additive manufacturing (AM) techniques are the fastest-growing technologies to produce even the most geometrically complex models [1]. The digital model is divided into layers in additive methods before manufacturing the object. The thickness of a single layer largely depends on the additive manufacturing method used. The model manufacturing process involves applying material in layers until a complete model is obtained [2]. There are many ways to manufacture models additively. Considering the ISO/ASTM 52900 [3] and ISO/ASTM 52910 [4] standards, seven additive processes have been defined. Differences in their functioning occur mainly in hardening subsequent layers and the type of material used. Models manufactured using additive techniques are used in the aviation [5, 6], automotive [7], medical [8, 9], and dental [10, 11] industries.

Because functional models are more often produced using additive technologies, quality requirements are imposed on them, including assessing geometric accuracy [12, 13] and surface roughness [14–16]. Obtaining appropriate surface roughness parameters affects the technical properties of the object. The created surface affects the wear of cooperating parts and thermal processes during operation. Assessing surface roughness is also a key factor for objects manufactured using the PolyJet method from photocurable resins [17–19]. This AM method is used to

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create injection molds [20, 21], casting molds [22] and surgical templates [10, 23] for further usage. The most significant factors on the surface roughness in the PolyJet method are the layer thickness [24], orientation of the model in the printer space [25–28], speed [29] and 3D printing mode used [30]. The ISO 21920 [31] and ISO 25178-2 [32] standards are currently mainly used to describe the designed object concerning surface roughness parameters correctly. However, there is still no standard development relating directly to additive methods. Because the PolyJet method can be used in 3D printing a wide range of materials with different properties, it is necessary to research classification for method in terms of the obtained surface roughness parameters. So far, only tests on samples made of FullCure 720 [18], RGD 836 [19] or VeroBlue 840 [28] have been described in the literature. Expanding research in the context of newly developed resins used in the PolyJet 3D printing process is necessary.

It is crucial to guarantee the accurate determination of the surface roughness parameters. This involves the development of specific guidelines related to the selection of the system, measurement parameters and procedures for numerical data processing [33–35]. The profile method is the most regulated procedure in measuring the surface texture to assess surface roughness parameters, which are included in the ISO 21920-2 [31] and ISO 3274 [36] standards. Nowadays, optical methods are increasingly used in the process of assessing surface roughness [37–39]. Although the measurement using these methods is much shorter than the stylus method, additional problems arise with this method [40, 41]. They most often concern the selection of measurement parameters, which determine, among others, the measurement area's size and thus apply appropriate filtration parameters [42, 43]. Additionally, the measurement introduces many errors related to, among others, noise on the measured surface, signal loss and the material's susceptibility to reflectivity [44–48]. Therefore, the measurement methodology must be adapted to the specific geometry and material measured each time.

The article compares the stylus and optical methods for assessing the surface roughness of details made of three photopolyacrylic resins. The aim of the research was to develop recommendations for roughness measurements using optical methods and to expand knowledge about the quality of surface production using the PolyJet additive method.

EXPERIMENTAL PART

Materials

Digital ABS-Plus (AR1), VeroClear (AR2), and RGD720 (AR3) photocurable resins were provided by Stratasys (Rehovot, Israel) and used when printing the model. Printing was repeated three times to check the repeatability of the 3D printer. The physical and mechanical properties of the materials selected in the research process are presented in Table 1.

The research model was designed in Geomagic X-Design (Senningerberg, Luxembourg) software. The binary format was used to write data to the STL (Stereolithography) file. When exporting data to the STL format, the chord deviation was set to 0.005 mm, and the angular deviation was set to 1°. Thus, the established parameters allow you to generate an STL file more accurately than the 3D printer used in the research process. Therefore, errors in saving the model to the STL format will not affect the state of the surface texture of the printed research model. The entire model production process using MJT technology was conducted in a closed space on the Object 350 Connex3 printer from Stratasys (Rehovot, Israel).

T a b l e 1. Resins characterization

Resin	Tensile strength MPa	Flexural strength MPa	Notched Izod impact strength J/m
AR1	65–75	65–75	90–115
AR2	50–65	75–110	20–30
AR3	50–65	20–30	20–30

Methods

3D printing

In the 3D printing process, at the beginning, the material in the form of liquid resin was heated to a temperature of approximately 50°C, which allowed it to achieve

Fig. 1. Research model: a) AR1, b) AR2, c) AR3

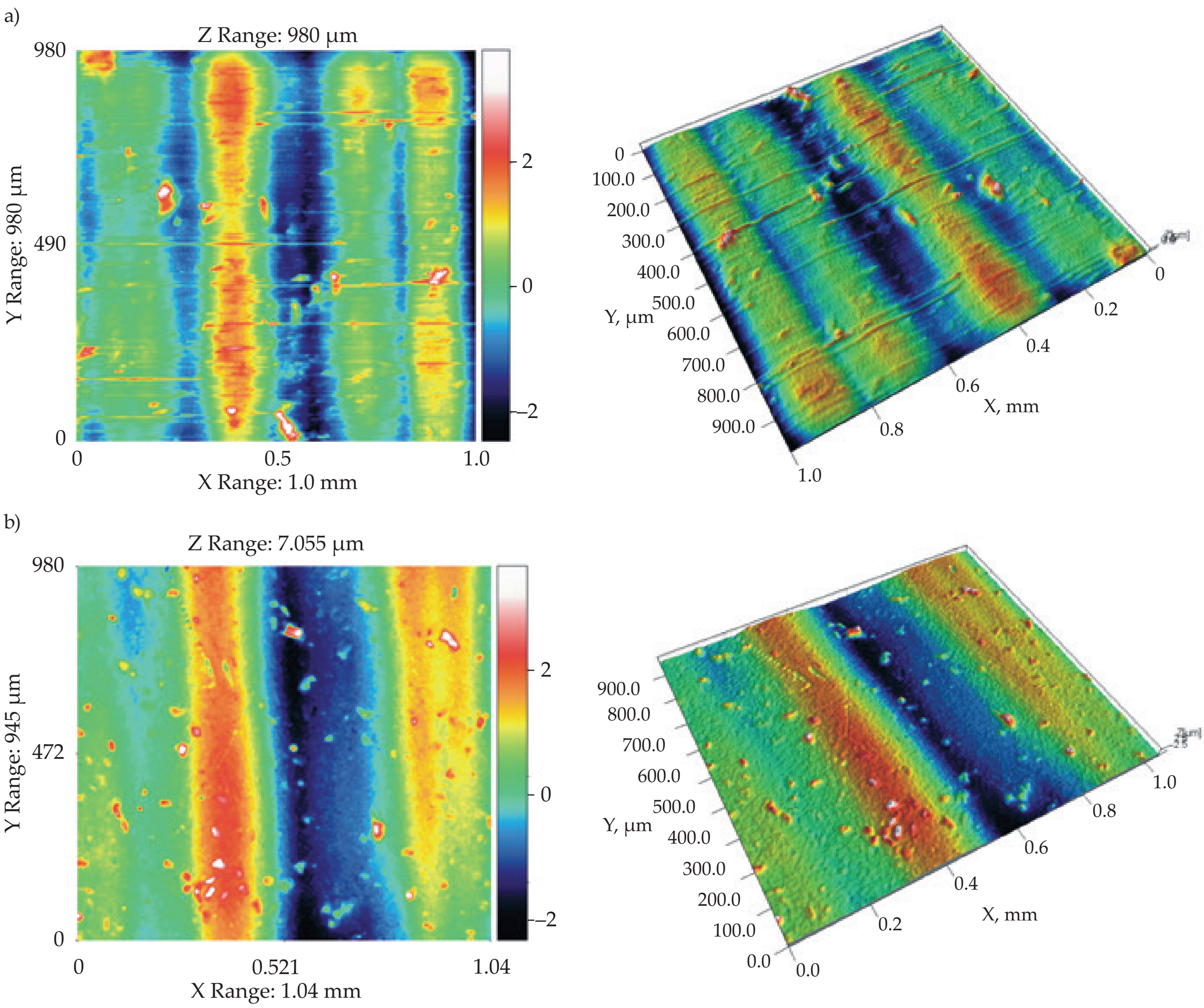

Fig. 2. Visualization of 2D and 3D surface roughness maps for AR1: a) obtained with the stylus method, b) obtained with the focal change method (FV)

its optimal viscosity. The high-quality mode was selected to balance the printing speed and the precision of the model. This mode made it possible to print research samples with a layer thickness of 0.016 mm. Additionally, the Matte mode was selected to increase the print quality of the model surface. During the printing process, thin layers of acrylic resin were applied and hardened immediately after application by exposure to ultraviolet lamp. This procedure eliminated the need for additional model exposure, which other technologies require. Materials in the form of liquids were dispensed from print heads that moved toward the x and y axes. Half of them distributed the model material, while the rest – the support material. The model material reproduced the cross-section of the model, and the remaining space was filled with supporting material. After completing one layer, the platform was lowered by the set layer thickness along the z-axis. Then, another portion of the material was applied. While the layer was hardening with UV radiation, it was simultaneously connected to the previous one, thus creating the entire model. After printing, the support material was removed mechanically using a pressure washer to obtain the final geometry of the model (Fig. 1).

Surface measurements

3D measurements of the surface texture were carried out using the stylus method using the TalyScan 150 profilometer (Taylor Hobson, Leicester, England) and the optical focus variation method using the InfninteFocus G4 microscope (Alicona, Graz, Austria). The area obtained along the print layers was measured. This surface is characterized by periodicity due to building the model layer by layer. Due to the optical properties of the samples, optical measurements were performed using replica technology. RepliSet-F5 silicone rubber from Struers (Copenhagen, Denmark) was used for the replicas. The measurement parameters are presented in Table 2.

Five measurements were made on each test sample in different places within the selected surface. A single

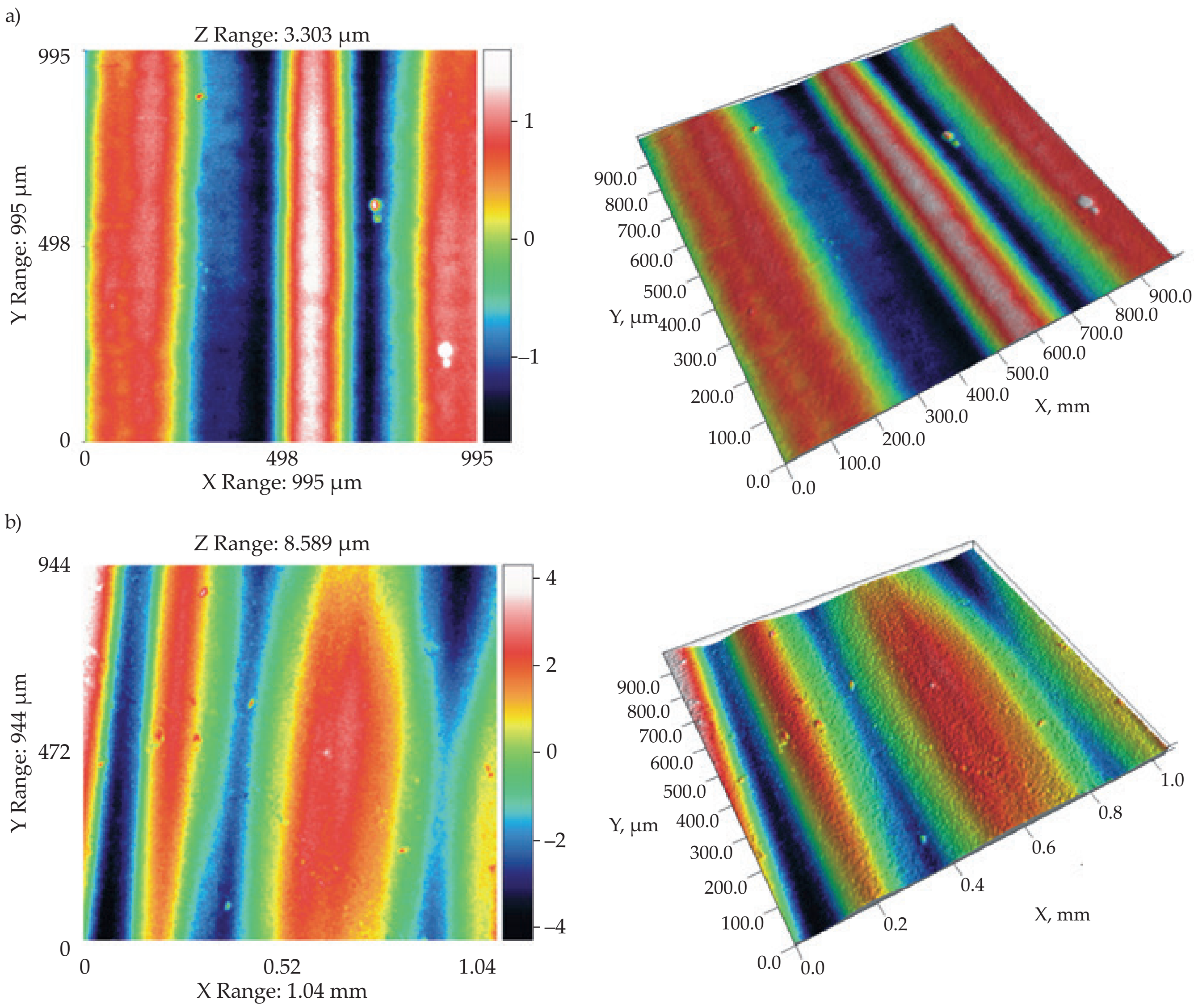

Fig. 3. Visualization of 2D and 3D surface roughness maps for AR2: a) obtained with the stylus method, b) obtained with the focus variation (FV) method

T a b l e 2. Measurements parameters

Parameter	Stylus method TalyScan 150	Focus variation InfninteFocus G4	
Material	AR1, AR2, AR3	AR1, AR2	AR3
Replica/ No replica	Without replica	With replica	With replica
Probe/ Objective	Stylus radius 2 µm	Objective ×50	Objective ×20
Vertical resolution	60 nm	50 nm	200 nm
Horizontal resolution / pixel size	1 × 5 µm	0.35 × 0.35 µm	0.44 × 0.44 µm

measured area had dimensions of 1×1 mm. This area was adjusted for measurement using the optical focus variation method based on the publication [43]. As a result of measurements using the TalyScan 150 profilometer and the Alicona Infinity Focus microscope, data representing the measured point cloud were obtained. Processing and analysis of measurement data were performed in the SPIP 6.4.2 program. Data processing included removing the geometry profile with a first-degree polynomial.

RESULTS

2D and 3D surface topography map

Surface topography maps of samples from AR1 and AR2 (Figs. 2 and 3) are similar. Several directed, gentle hills and dale are visible, perpendicular to the direction of building the model. The individual layers of bonded material cannot be recognized. There are also numerous hills with a relatively small area. More of these small peaks are reproduced in optical measurement, probably due to the higher resolution of this measurement. In the case of stylus measurement, the AR1 sample also shows bands representing imperfections related to the passage of the measuring tip. When the measuring tip encounters

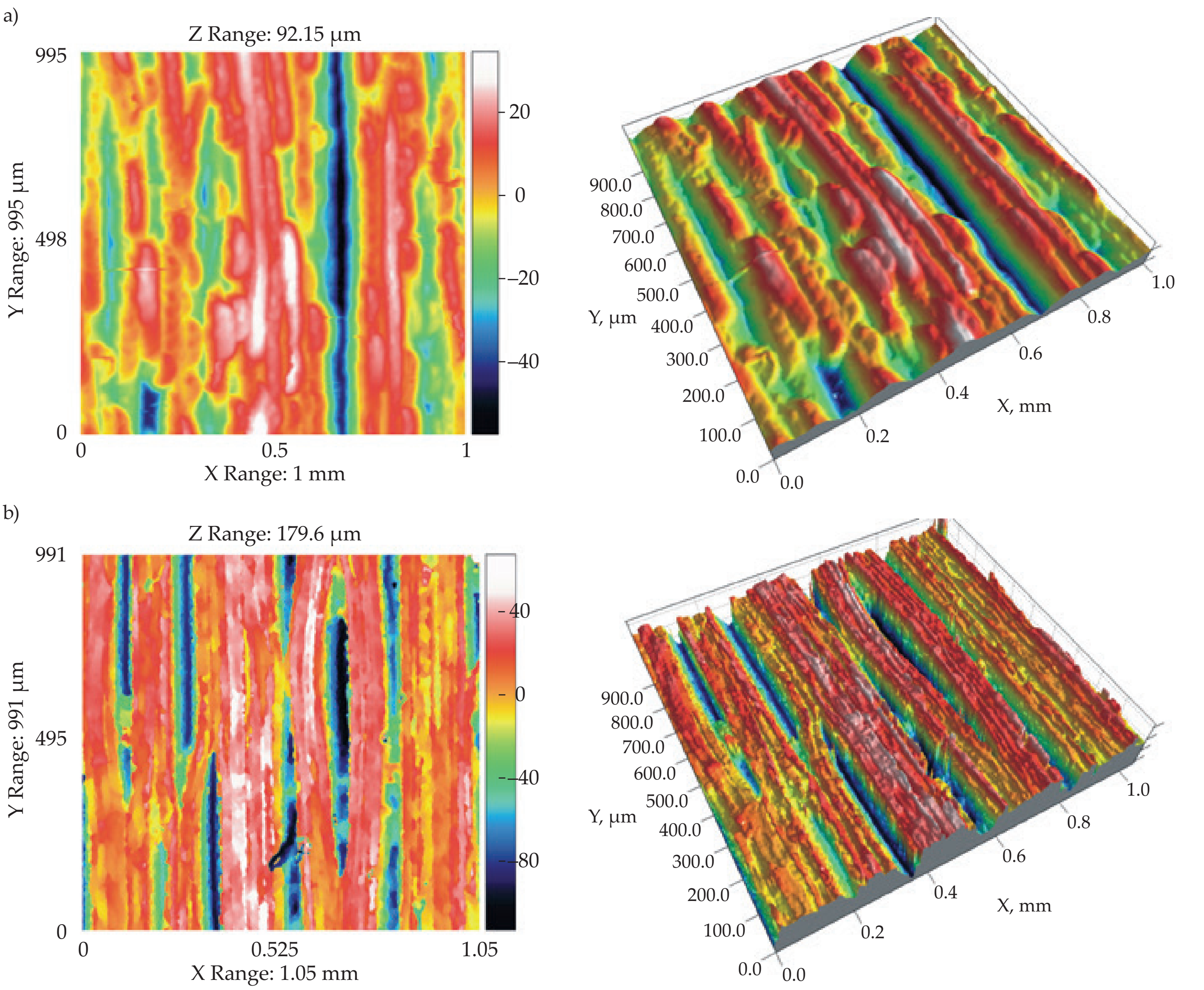

Fig. 4. Visualization of 2D and 3D surface roughness maps for AR3: a) obtained with the stylus method, b) obtained with the focus variation (FV) method

the mentioned small hills, it may detach from the surface. It may also deform the measured surface. Topography maps of the AR3 sample (Fig. 4) reveal that the nature of its surface is different than that of samples from other materials. The structure is still directional. The bands of hills and dale are also perpendicular to the direction of building the model, but there are many more of them, and the slopes of the irregularities are much steeper. In the images obtained from optical measurements, single layers of material can be distinguished. These layers are grouped into several or a dozen or so layers. After stylus measurement, the image of the structure is softer, smoother and contains fewer details. The effect of the stylus tip acting as a geometric filter is visible.

Figures 5-9 show the surface topography parameters (S_a, S_{pk}, S_k, and S_{vk}) obtained based on stylus and optical (non-contact) measurements using the focus variation method. There is a noticeable similarity in the results obtained for AR1 and AR2 resins, regardless of the measurement method (Tab. 3). For these two materials, the statistical significance of differences in the mean values of the tested parameters was examined using a two-way analysis of variance. The analysis of variance showed, assuming the significance level $\alpha = 0.05$, that neither the type of material, the measurement method, nor their interaction had a statistically significant effect on the parameters S_a, S_{pk}, S_k and S_{vk} (Tab. 4). This means that statistically the average values of the tested parameters of AR1 and AR2 materials, measured by contact and optical methods, are equal. The average value of S_a parameter of AR1 and AR2 materials from all measurements was 1.45 µm, and S_{pk}, S_k and S_{vk} parameters were 1.5 µm, 3.94 µm and 1.61 µm, respectively. In the case of AR3 material, much higher values of the analyzed parameters were observed compared to the other two materials. The influence of the measurement method on these parameters is also evident. Higher values were obtained with optical measurement. The average value of S_a parameter of samples measured optically was almost twice as high as in the case of stylus measurements. S_{pk} and S_k values

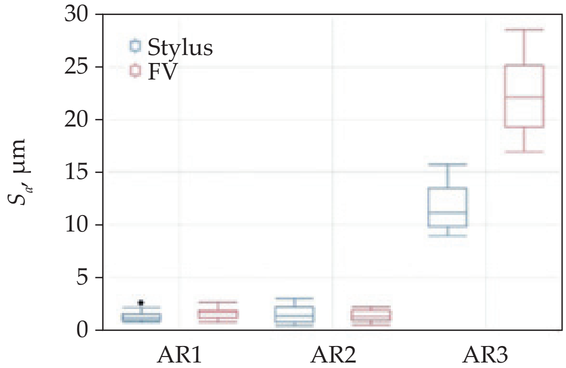

Fig. 5. S_a **parameter determined from stylus measurements and the focus variation (FV) method of samples printed from various materials**

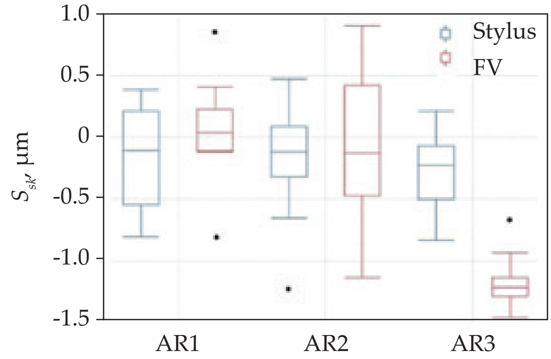

Fig. 6. S_{sk} **parameter determined from stylus measurements and the focus variation (FV) method of samples printed from various materials**

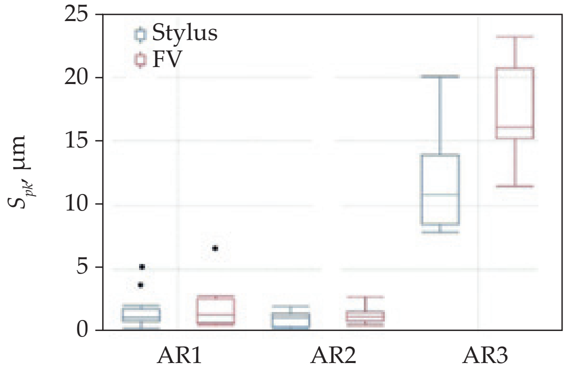

Fig. 7. S_{pk} **parameter determined from stylus measurements and the focus variation (FV) method of samples printed from various materials**

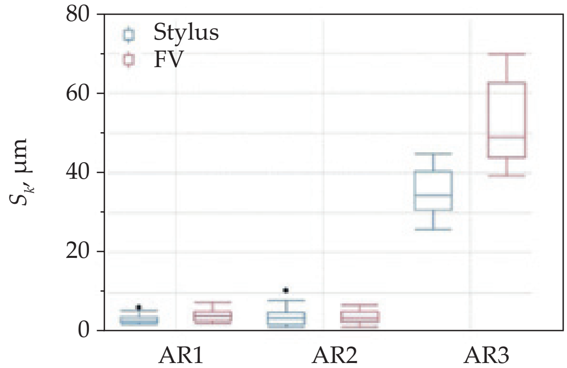

Fig. 8. S_k **parameter determined from stylus measurements and the focus variation (FV) method of samples printed from various materials**

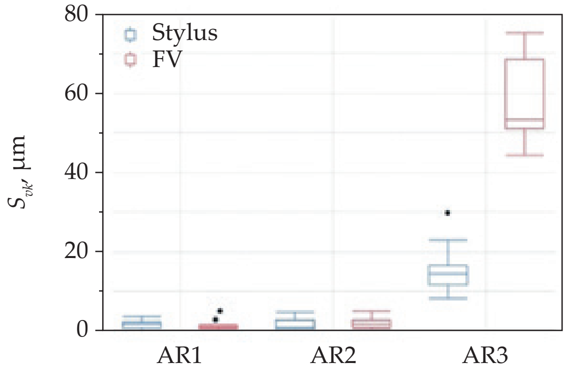

Fig. 9. S_{vk} **parameter determined from stylus measurements and the focus variation (FV) method of samples printed from various materials**

obtained from optical measurements were approximately 1.5 times higher than those from stylus measurements. The most significant differences were related to the reduced depth of the pits: the average S_{vk} value from optical measurements was almost four times higher than from stylus measurements. This suggests that the most significant differences in the representation of the measured geometry are related to the areas of the cavities. The stylus tip has difficulty penetrating deep valleys and their steep slopes. This reveals the filtering properties of the stylus as a geometric tip. The standard deviation of the topography parameters of AR3 samples was higher for optical measurements. Still, considering the average value and expressing the variability using the coefficient of variation ($CV = s/\bar{x} \cdot 100\%$), the general trend is that optical measurements are less variable.

DISCUSSION

In the case of 3D printers, each of them has specific characteristics and requirements for working conditions. This involves, among others, the printing parameters used, material and environmental conditions [1, 2]. As a result, after printing the model, differences appear between the nominal 3D-CAD model and the finished product. Currently, several studies can be observed in the literature regarding the geometry assessment [12, 13] and surface roughness [14–16] of models manufactured using additive methods. It is no different in the case of the PolyJet method [24–26]. This technology allows for producing high-quality model surfaces, making it possible to consider it in terms of, among others, producing injection molds [20, 21] or casting molds [22]. In the case of the PolyJet method, the layer thickness used, the model's orientation in the 3D printer space [25, 26] and the printing mode [30] impact the accuracy of the geometry. Considering the publication [30], manufacturing

T a b l e 3. Mean values ($\bar{x}$), standard deviation (s) and coefficient of variation (CV) of the surface topography parameters of the tested samples measured by the stylus method and focus variation

Resin	Method	S_a			S_{pk}			S_k			S_{vk}		
		$\bar{x}$ µm	s µm	CV %	$\bar{x}$ µm	s µm	CV %	$\bar{x}$ µm	s µm	CV %	$\bar{x}$ µm	s µm	CV %
AR1	Stylus	1.30	0.47	36.22	1.58	1.12	70.96	3.36	1.14	34.01	1.70	1.00	58.96
	FV	1.64	0.54	32.79	1.88	1.53	81.12	4.39	1.51	34.45	1.29	1.20	92.77
AR2	Stylus	1.47	0.73	49.96	1.10	0.62	56.78	4.02	2.32	57.72	1.56	1.38	88.30
	FV	1.39	0.56	40.25	1.42	0.53	37.59	3.98	1.66	41.81	1.91	1.21	63.11
AR3	Stylus	11.47	1.95	16.96	11.32	3.35	29.62	35.40	5.68	16.05	15.19	5.24	34.52
	FV	22.23	3.34	15.00	17.26	3.53	20.47	52.49	9.81	18.70	58.57	10.59	18.07

T a b l e 4. Effect of the material type and measurement method (stylus and focus variation) on selected parameters of surface topography

Effect	Dependent variable			
	S_a	S_{pk}	S_k	S_{vk}
Material	0.795	0.054	0.765	0.408
Method	0.359	0.207	0.235	0.933
Method and material	0.140	0.965	0.199	0.191
Model	0.393	0.151	0.355	0.536

using the PolyJet method in Glossy and Matte modes is possible. However, the Matte mode guarantees a better print in terms of surface roughness. An overall thin layer of support material is added when this mode is used. Additionally, in the Matte mode, it is possible to create models with a uniform surface and high accuracy [30]. This differs from Glossy mode, where you may notice uneven surface finish and rounding on sharp edges.

So far, attention has been paid to the materials FullCure 720 [18], RGD 836 [19] and VeroBlue 840 [28] in surface roughness tests. The measurement for these materials was carried out using the stylus method and was limited to the parameters of the measured profile. The authors of these publications obtained R_a parameter values ranging from 0.818 µm to 4.024 µm for the FullCure 720 material, from 1.381 µm to 2.606 µm for the RGD 836 material and from 0.5 µm to even 15 µm for VeroBlue. In the case of FullCure830 tests were carried out on selected areas of the surface, not single profiles [50]. Data were obtained optically using a Talysurf CCI device. Sa parameter for the FullCure830 material ranges from 0.95 µm to 2.33 µm. It is worth adding that none of the presented publications has undertaken comparative studies of stylus and optical methods to assess the surface roughness parameters of models manufactured using the PolyJet method. Drawing attention to this problem is essential because these tests may allow finding an alternative measurement method to guarantee a reliable and quick surface quality assessment. This can significantly improve the process of accepting the finished product to the market [34, 37, 42].

The selected measurement system influences the obtained values of surface roughness parameters. The stylus method is mainly used in surface roughness verification because its measurement procedures are fully described in the ISO 21920 [31] and ISO 3274 [36] standards. However, optical methods are increasingly used [40–42]. The problem, however, is that measurement procedures for this method are not fully regulated, including the selection of the optimal measurement area. Fractal analysis offers a particular solution [43, 51]. Considering the publication [51], it was decided to apply the procedures adopted to the Digital ABS-Plus (AR1), VeroClear (AR2) and RGD720 (AR3) materials. In the case of the first two, comparable measurement results were obtained using stylus and optical methods. However, in the case of the RGD720 material, significant differences were noticed in the obtained roughness. This may be due to the different material properties of AR3 compared to the first two resins. This indicates that getting comparable measurement results using stylus and optical methods is not always possible. In the case of AR3, this problem resulted from the nature of recording the unevenness of the recesses in the given measurement area.

CONCLUSIONS

Since functional models are often created using additive technologies, they are subject to quality requirements related to dimensional and geometric accuracy and surface roughness. To determine the selected values of surface parameters, it is important to ensure an accurate representation of the measured geometry, which involves the selection of an appropriate system and measurement parameters. The comparative analysis of stylus and optical methods presented in the article in the process of assessing the surface roughness parameters of models made using the PolyJet method allows us to conclude that, despite the optical properties of the samples made, the replica technology and the focus variation measurement method are an alternative to stylus methods. However, further research is necessary to improve data recording mechanisms in the assessment of surface roughness parameters.

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