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MULTISCALE ASSESSMENT OF ADDITIVELY MANUFACTURED FREE-FORM SURFACES

Damian Gogolewski

Kielce University of Technology, Department of Mechanical Engineering and Metrology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland (✉ *dgogolewski@tu.kielce.pl*, +48 413 424 453).

Abstract

The article reviews the results of experimental tests assessing the impact of process parameters of additive manufacturing technologies on the geometric structure of free-form surfaces. The tests covered surfaces manufactured with the Selective Laser Melting additive technology, using titanium-powder-based material (Ti6Al4V) and Selective Laser Sintering from polyamide PA2200. The evaluation of the resulting surfaces was conducted employing modern multiscale analysis, i.e., wavelet transformation. Comparative studies using selected forms of the mother wavelet enabled determining the character of irregularities, size of morphological features and the indications of manufacturing process errors. The tests provide guidelines and allow to better understand the potential in manufacturing elements with complex, irregular shapes.

Keywords: free-form, wavelet transform, multiscale analysis, surface texture, additive manufacturing.

1. Introduction

Surface plays a vital role in terms of perception of individual machinery elements. Adequate surface shaping significantly changes the capabilities and functions of an object. Surfaces are responsible for a number of properties and actively participate in certain processes such as heat transfer [1], friction, wear [2, 3], wetting and mass-transfer [4–7], lubrication, adhesion, sealing [8] or affect the ability of different materials to bond, for example, tissues and implants [9]. Modelling an appropriate geometric surface structure and creating its morphological features improves individual surface capabilities, reducing its wear [10] or increasing safety [11].

One of the types of surfaces currently widely employed in various aspects are free-form surfaces. Such surfaces are not defined by equations or mathematical functions, and the distribution of irregularities significantly impact the product's properties and its actual application. Surface shape has no continuous translational or rotational symmetry relative to the axes [12]. Nowadays, free-form surfaces are used owing to both their properties and for aesthetic purposes. The applications include the automotive (car bodies, panel displays), aerospace (turbine blades), medicine (implants) or household appliance industries.

The development of industry provided possibilities for increasingly more precise production of surfaces with undefined geometry. CNC (*Computerized Numerical Control*) machine tools are used for this purpose [13, 14]. But unconventional manufacturing technologies that enable producing elements of any shape are also being employed in more and more cases. The development of additive technologies and construction materials utilized allowed these technologies to be adopted to manufacture fully functional machine parts of complex and irregular shapes [15, 16]. However, the possibility to precisely produce a model designed in CAD software, with its subsequent analysis, remains the key issue. The nominal, real, and

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measured surfaces or shape are not identical. There is a number of factors that affect theoretical differences and the assessed model [17, 18]. When analysing the current state of the art, one can note that there are currently ongoing works assessing the quality of created free-form surfaces [19, 20]. The authors of [21] evaluated the accuracy of reconstructing free-form surfaces in CMM/CAD/CAM/CNC systems. On the other hand, [22] shows a sampling method studied in order to accurately reproduce free-form surfaces. A number of modifications to the manufacturing process and additional treatments aimed at improving the quality of surface geometrical structure have also been developed [23–25].

The advancement of modern manufacturing technologies entailed the improvement of alternative surface measurement and assessment methods. It was concluded that the application of the classic approach based on Gaussian filtration and the ISO 25178 standard to assess free-form surfaces was insufficient. Therefore, researchers worked on multiscale methods that enable assessing surfaces using various scales [26, 27]. In addition, alternative parameters that are a modification of ISO parameters and which can be employed for a qualitative and quantitative assessment of free-form surface have also been developed [28, 29]. Wavelet transform is one of the methods that allows to evaluate a surface in many scales. The wide spectrum of the mother wavelet form with characteristic properties [30–33] determines its potential for diagnosing both surfaces [34–36] and, indirectly, the manufacturing process [37–39]. Currently, there is a lack of research focusing on the texture of free-form surfaces with the use of modern analytical methods. Based on the current state of the art, it can be concluded that wavelet analysis provides potentially vast opportunities in terms of diagnosing surfaces containing non-periodic irregularities. Verifying the quality of additively manufactured surfaces, especially the ones of important applications, or free-form surfaces still poses a research gap and requires further investigation. Classic methods previously applied to the evaluation of free-form surfaces based on measurements using CMMs (*Coordinate Measuring Machines*) should be supplemented with surface texture assessment. This will highlight the important features created as a result of the manufacturing process. The main goal of the research was to evaluate the possibility of additive manufacturing of free-form surfaces, taking into account the influence of the building angle and the type of technology. The analysis of the geometric structure of the surface was carried out using a modern multiscale method - wavelet transformation. Studies fill the research gap and increase the applicability of modern multiscale methods, which are part of the Fourth Industrial Revolution, Metrology 4.0.

2. Materials and Methods

The surfaces to be tested were designed using the NX software (Siemens, Plano, Texas, USA). They were formed based on an irregular extraction of several random points. Test samples with a modelled surface were manufactured using SLM (*Selective Laser Melting*) and SLS (*Selective Laser Sintering*) additive technologies, as a function of the building angle relative to the platform. Both technologies are based on the layer-by-layer building of the model. Individual layers of powder are sintering/melting in the shape of individual model cross sections. The limitations of each technology affect the quality of the manufactured parts, with one of the crucial parameters being the model-building angle. It plays an important role due to the layered nature of both technologies, the staircase effect, and the spilling material between layers which directly affect the ability to produce characteristic morphological features or irregularity distributions on the surface. Three samples with various angles were prepared for each technology (20°, 45°, 70°), resulting in six test samples. The samples were saved as .stl files using the Magics software (Leuven, Belgium), with a linear and angular accuracy of +/-0.01 mm.

The first group of samples (No. 1-3) was manufactured using the SLM technology with titanium-powder-based material (Ti6Al4V), manufactured by EOS (EOS GmbH, Krailling, Germany). A 3D printer – an EOS M290 machine – was used to build the sample models. The samples were made with the following technological parameters: Inskin laser power - 340 W, laser speed - 1250 mm/s, hatch distance - 0.12 mm, laser spot size - 100 μm, layer thickness - 60 μm. The platform temperature was set at 35 °C, argon was used as the shielding gas, power fulfilled ASTM F1472 and ASTM F2924 standards, and samples were heat treated at 800 °C for 2 h in argon inert atmosphere as instructed by EOS. A view of surface of sample No. 1 is shown in Fig. 1a.

The second group of samples (No. 4-6) was manufactured using the SLS technology with PA2200 (PA12-based polyamide), manufactured by EOS. A Formiga P100 3D printer was used to build sample models. The samples were made with the following technological parameters: Inskin laser power - 21 W, laser speed - 2500 mm/s, hatch distance - 0.25 mm, laser spot size – 0.4 mm, layer thickness – 0.1 mm, energy density 0.056 J/mm2, temperature 150 °C, inert gas atmosphere – nitrogen. A view of surface of sample No. 4 is shown in Fig. 1b.

a) b)

Fig. 1. View of sample surface a) No. 1, b) No. 4.

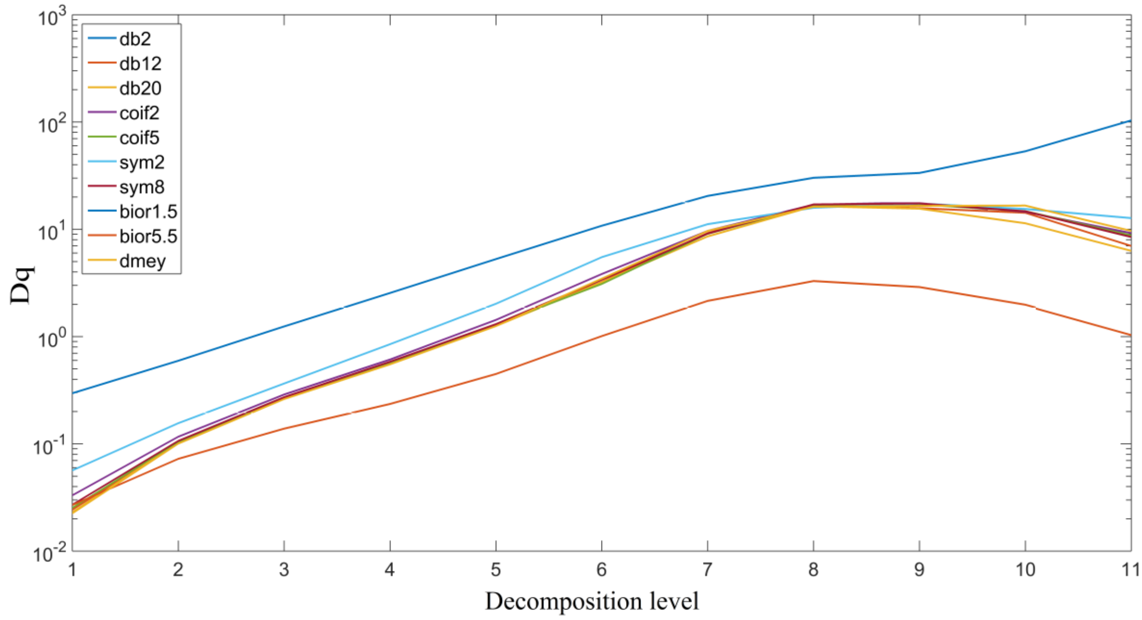
The modelled surface irregularity distributions were measured using a Form Talysurf PGI1200 stylus profilometer over an evaluation length of 30 mm and a sampling density of $\Delta x = 1$ μm. Several representative profiles were selected for each sample. TalyMap Platinum 6 (Digital Surf, Besançon, France) and Matlab software (The MathWorks, Natick, Massachusetts, USA) were used in the study. Surface texture was analysed using the selected multiscale method, *i.e.*, the one-dimensional discrete wavelet transform. To this end, a number of mother wavelet forms with different characteristics and properties were selected for the analysis. The following wavelets were used: db2, db12, db20, coif2, coif5, sym2, sym8, bior1.5, bior5.5 and dmey. Furthermore, the ANOVA analysis with a post-hoc Tukey's test was employed for the statistical analysis of surfaces at individual decomposition levels, obtained through the application of mother wavelets. Shapiro-Wilk tests were used to test for normal distributions of residuals. A surface discrimination ability with a probability of at least 95% (p-value lower than 0.05) was deemed sufficient.

3. Results

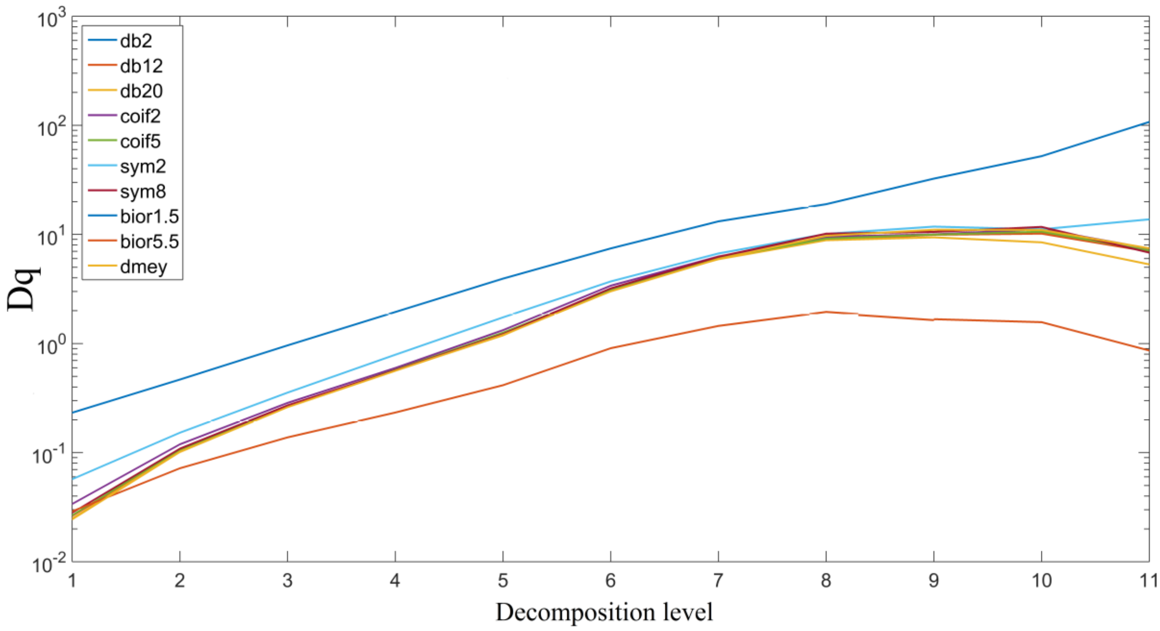
The research was conducted in two ways. The first aspect assessed was the multiscale evaluation of free-form surfaces manufactured additively as a model-building angle increment function. Irregular, non-periodic morphological features which lead to a difference between the nominal and actual models are formed on model surfaces during the manufacturing process. They impact the perception of such a surface and its subsequent application. Multiscale surface analysis based on wavelet transform enables assessing the formed irregularities, taking into account the size of individual features, and the assessment of its porosities, resulting differences or manufacturing process errors.

The conducted quantitative and qualitative tests indicated that there were dependencies between the quality of a manufactured free-form surface and the model-machine platform location angle. The presence of morphological features of various sizes was recorded depending on the angle value. These dependencies were noted at individual analysis stages. Parameters commonly used in surface texture assessment [34, 40], marked as Dq (Root Mean Square), Da (Arithmetical mean height), Dsk (Skewness) and Dku (Kurtosis) were selected for the quantitative assessment. They were determined for the signals of details formed at successive decomposition levels. The results are mean values of the obtained coefficients determined for the measured profiles of individual free-form surfaces. It should be stressed that statistical assessment demonstrated that the difference in values within individual surfaces was relatively minor. The results of root mean square calculated for the location of the surface as a function of angle increment relative to the building platform for the SLM technology are shown in Fig. 2.

a)



b)



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c)

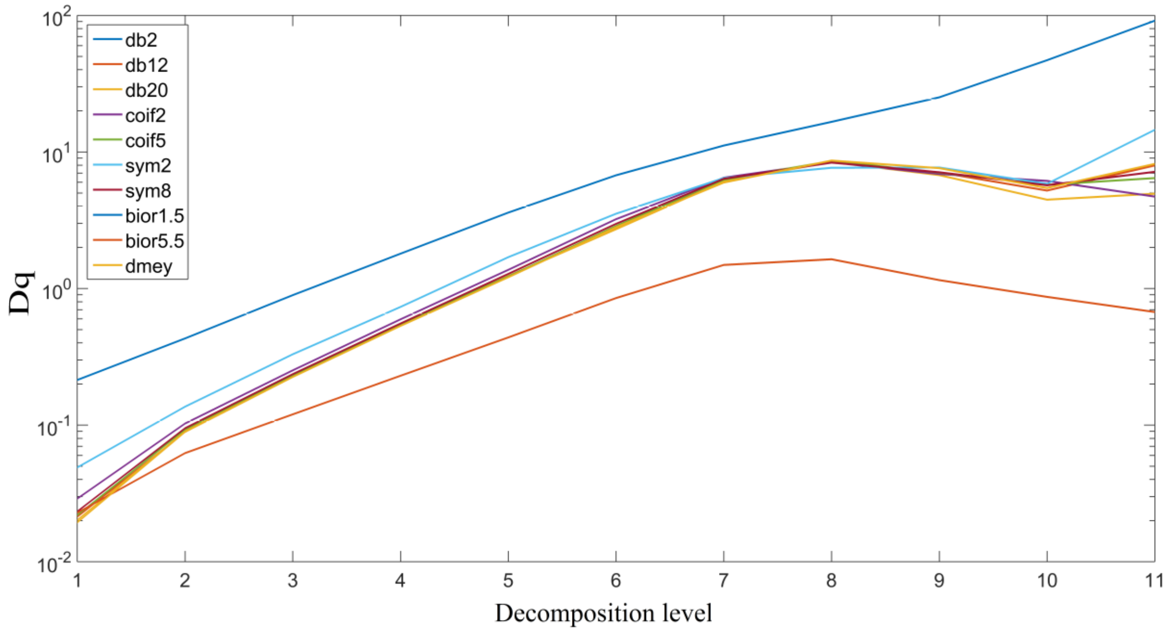

Fig. 2. Values of the Dq parameter as a function of angle increment relative to the building platform – SLM technology a) 20°, b) 45°, c) 70°.

When analysing the obtained data, it should be concluded that analogous value changes together with decomposition progress were obtained for both manufacturing technologies. The root mean square parameter values increased as decomposition progressed, albeit with different intensity, depending on the building angle. It can be noted that lower values of the parameters determined for information responsible for high-frequency irregularity changes were obtained for the evaluated free-form surface profiles together with the growth of the building angle. However, this characteristic changes for details formed at subsequent analysis levels. A reversal in this trend was recorded depending on the employed wavelet at the seventh or eighth stage. Parameter values decrease, which may prove the filtering out of irregularities formed due to manufacturing process errors at earlier stages, thus obtaining low-frequency components. Similar changes in the values were recorded for the SLS technology, however, the fluctuation in individual values is more dynamic. This may prove a greater smoothing of surfaces made from polyamide and a smaller amount of local surface defects.

The analysis of other parameters showed that the arithmetic mean height changes almost in the same way as the parameter determining the root mean square, yet with lower values. Different results were obtained for the skewness and kurtosis parameters. It should be noted that the skewness obtained for individual surfaces and wavelets reached values close to 0, while their trend was negative as decomposition progressed. In the case of evaluated profiles, the kurtosis parameter values reached values higher than 3, while these values were much higher at the initial and final decomposition levels of the conducted studies.

The application of a wide mother wavelet form spectrum enabled inference concerning the impact of the wavelet on signal analyses obtained at successive levels, but also determining guidelines regarding the selection of an appropriate type or family. Statistical studies comparing the outlines obtained within individual scales showed that there was a difference in individual profile irregularity values as a function of the mother wavelet. Nevertheless, the ANOVA analysis with a post-hoc Tukey's test showed that only the bior1.5 wavelet was statistically different in most cases. This may be caused by the fact that it was the only wavelet form which used different support width for decomposition and lossless reconstruction (Fig. 3). It should be inferred that individual wavelet transform impact the results obtained within individual bands. However, these changes are minor and are concentrated at individual stages of analysis.

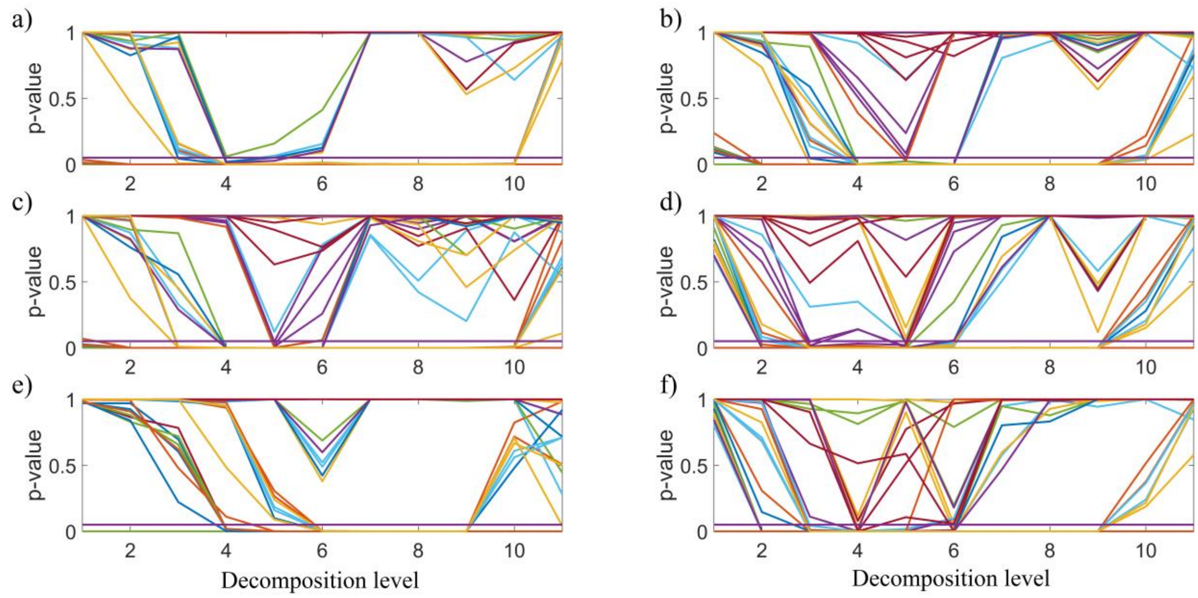

Fig. 3 p-value as a function of angle increment relative to the building platform, parameter Dq a) 20°, c) 45°, e) 70° – SLM, b) 20°, d) 45°, f) 70° – SLS; the purple horizontal line indicates the critical value.

The second aspect was a comparative analysis of both manufacturing technologies in terms of formed surface irregularities. The comparative studies of obtained parameter values for individual location angles enable differentiating both technologies with respect to the quality of the surface texture and the multitude and magnitude of individual morphological features. The similarity of individual surface was statistically evaluated using the ANOVA analysis. The p-value parameter value for individual scales and decomposition levels was calculated (Fig. 4). A surface discrimination ability with a confidence of 95% or more ($p < 0.05$) was deemed sufficient.

The conducted studies showed a dependence between process parameters, sample material and the quality of the free-form surface layer. However, the size of individual irregularities formed on the surface is the key issue. Similar high-frequency information associated with noise or small morphological surface features were filtered out at the first two levels of analysis in both technologies. The differences between individual surfaces were recorded up to Level 3. The presence of additional morphological features on surface manufactured with the SLM technology, not found within similar areas of surfaces manufactured with the SLS technology were recorded for this range of the scale. The application of the SLM technology resulted in the creation of more non-periodic, random surface irregularities and defects. Higher values of selected surface geometric structure parameters, relative to the second analysed manufacturing technology were recorded in the case of surfaces manufactured through melting metal powders.

Figure 4 shows the p-value parameter values for the first four levels of analysis, however, the values obtained for successive levels are higher than the assumed confidence range ($p < 0.05$). Statistical values were determined similarly for other assessed parameters, *i.e.*, arithmetical mean height, skewness and kurtosis. The obtained results confirm the considerations based on the example of the root mean square parameter. Only the signals obtained at the first stages of analysis and for selected wavelets fail to show a statistical difference between the surfaces. The values obtained may indicate an accurate reproduction of low-frequency surface features, however there is a need to pay special attention to small, local surface defects in the form of cracks, cavities and material particles created by the manufacturing process.

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a)
b)

Fig. 4. p-value for the lowest increment angle with respect to the building platform, a) Dq parameter b) Da parameter. Grey horizontal line indicates the critical value.

In addition, the research enables evaluating the application of the mother wavelet for surface discrimination. It can be noted that the statistics decrease along with an increase in support width. It can also be stated that the width of individual key morphological features was appropriately larger than the support width for wavelets of a lower order and vanishing moment number. The bior1.5 mother wavelet was a particular case, where similar statistics values for individual assessed parameters were recorded at individual stages of analysis.

The study fills a research gap regarding the possibility of using additive technologies to build free-form surfaces. Multiscale evaluation of surface topography is crucial in terms of surface perception and diagnostics. Understanding how, how many and what size features are created on a surface requires the use of modern algorithms to identify important aspects of surface irregularities created by the manufacturing process used [41, 42]. The classical ISO approach or its modifications [28, 29] for a curved surface needs to be supplemented in particular when they are manufactured using additive methods. For these technologies, the advantages of using multiscale methods have been demonstrated for flat surfaces [27, 43], which is undoubtedly a supplement to what is used in industry or science [44, 45]. This confirms the validity of using individual multiscale forms, with various characteristic properties, for surfaces with free-form geometries, especially those manufactured additively.

4. Conclusions

The article assesses the possible application of additive technologies to forming surfaces of complex, irregular shapes. The research conducted with the use of free-form surfaces enabled determining the quantity and size of morphological features created on the surface as well as individual manufacturing process errors. The study involved using a novel approach based on wavelet transformation. It enables identifying and evaluating individual irregularities relative to the scale size. The study showed that, relative to the surfaces manufactured with the SLS technology, the surfaces manufactured using the SLM technology were characterized by the occurrence of additional morphological features formed on the surface. However, their number and size reduced with an increasing building angle. The differences in surface texture quality are particularly clear starting at Level 3 of the analysis. No significant differences between the surfaces manufactured with the same building angles were recorded for the first and second stages, responsible for high-frequency changes and morphological features of relatively low sizes.

Statistical analysis conducted for selected mother wavelets demonstrated that no significant differences between the signals formed at subsequent analysis stages were found for most cases. Different features were obtained only for the bior1.5 wavelet. This may be caused by the employing various support width for decomposition and reconstruction. In addition, the research enabled evaluating the application of individual mother wavelets for surface discrimination. The impact of the wavelet form on the ability to discriminate between surfaces and detect key morphological features was assessed, taking into account its properties.

The research paper presents quantitative and qualitative tests of surfaces manufactured through additive technologies, which can be employed to better understand the nature of the phenomena occurring in the course of element shaping in terms of their impact on the resulting texture. The approach based on a comprehensive multiscale surface topography assessment can provide new perspectives for looking at surface irregularities and defects.

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Damian Gogolewski received the Ph.D. degree in 2018. He is currently Assistant Professor at the Kielce University of Technology, Poland. His research activities focus on surface metrology, multiscale analysis and characterization, wavelet transformation and measurements of geometrical quantity.