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Analysis of roundness profile of powder bed fusion additively manufactured samples using hybrid wavelet-Fourier method

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ABSTRACT

The aim of the research was to show the feasibility of using a modern, hybrid method of analysis, filtering to detect defects created on samples with a cylindrical shape manufactured by the selected additive technology. The studies focus on diagnostics, assessments of roundness profiles with the modern filtering technique, which employs both wavelet and Fourier transformations. The hybrid combination of two algorithms potentially allows for enhanced, in-depth diagnostics and the identification of the key morphological characteristics that could potentially influence the functional properties of the completed product. An evaluation covered the variability of the irregularities in roundness profiles, taking into account not only the height at which the profile was measured but also the 3D printing angle (orientation). The study showed the importance of verifying the distribution of irregularities across the entire surface of the components, given the substantial disparity in the data in each signal, whereas the employed algorithm further facilitated the accentuation of distinct characteristics of the roundness profiles. The conducted analysis permits carrying out a thorough diagnosis and assessment of the profiles, highlighting the disparity in the character of the roundness profiles as a function of the powder bed fusion (PBF) technology parameters (printing direction) and measurement (location of the profile across the height), which allowed finding functional relationships. The advantage of using the hybrid method in comparison with the classical evaluation method using only Fourier transforms was demonstrated. Therefore, the results presented in the article have the potential for practical use in both the research area and industrial applications and can be supplementary to ASTM/ISO 52901 and ASTM/ISO 52902.

Keywords: wavelet transformation, Fourier analysis, surface texture, additive technology, roundness, surface quality.

INTRODUCTION

3D printing technologies have been known since the 1980s of the 20th Century due to the advancement in 3D printing technologies, it is now not only possible to create not only prototypes, but also fully functional models with a number of practical uses. The medical and automotive industries are particularly noteworthy in this context. In the case of the medical industry, metal 3D printing primarily include technologies from two groups presented in the ISO/ASTM 52900 standard (1): Powder Bed Fusion and Directed Energy Deposition. In both cases, we have at our disposal materials based on titanium powder, such as Ti6Al4V, which has proven effective in the creation of fully operational implants for patients. The findings of the depicted studies may be applicable in the engineering field, given that the majority of implants do not necessitate finishing treatments, in order to maintain a desired level of porosity. In these technological applications, the crucial element involves choosing an appropriate printing strategy including numerous technological parameters such as the printing direction (2, 3), laser power and speed (4), diameter of the beam, layer thickness (5), and the protective atmosphere. Hence, in the presented publication, an examination is conducted on one of the fundamental technological parameters that could potentially affect form error, namely, the roundness deviation.

In the article (6), an instance of use 3D printing technology for the creation of bone implants in patients afflicted with primary bone tumors is illustrated. An analysis was conducted on fourteen patients who had received personalised implants, printed using 3D printing technology. The analysis of research outcomes and complications from the period of 2015 to 2019 mandated the extraction of the implant in a solitary instance.

In a following study (7), a model of samples also manufactured from titanium-based Ti6Al4V powder was analysed, with an evaluation on the influence of surface porosity on the adhesive proliferation of living tissues of the 3T3 Swiss albino mouse. Simultaneously, in certain instances, the process of 3D printing was enhanced by the supplementary application of electrospinning technology, consequently manufacturing a composite material. Titanium-based samples with increased porosity demonstrated significant cellular adhesion and proliferation. Concurrently, it has been demonstrated that specific interventions, like the supplementary incorporation of nano-matt, can enhance the formation of intricate geometric attributes, which pose challenges in design, digital manipulation in 3D printing, production, and measurement due to the exceptionally delicate character of the disparities stretching to several tens of micrometres. When it comes to fabricating medical implants through the use of 3D printing technology, the evaluation of their precision via the measurement of geometric discrepancies warrants distinct consideration.

The performance of the final mechanism is significantly influenced by the appropriate surface geometry of components, particularly those fabricated using 3D printing technology (8). A considerable number of studies connected to 3D printing focus on assessing the impact of 3D printing's technological parameters solely on the dimensional accuracy of the manufactured parts, while overlooking the practicality of the resultant models (9). In numerous instances, this method proves insufficient, given that sole reliance on dimensional evaluation does not yield information about the form error of the component being examined. This is especially relevant for cylindrical shaped elements which execute rotary or sliding movements, or that constitute parts of flexible connections (10) as well as pipe joints (11). Subsequently, the examination of roundness deviation is required, which, as defined by ISO 12181-1:2011, is the minimum distance from a point on a roundness profile to the reference circle, and the measurement process can be carried out on various types of instruments even with an incomplete round profile (12).

In the study (13) the roundness tolerance of cylindrical components, fabricated through FDM (also known as FFF and MEX) printing technology with the use of PLA (polylactic acid) material, was assessed. In their studies, the scholars have demonstrated that the first layer of printing process is crucial when assessing the manufacturing tolerance of cylindrical components. It is important to note that in the production of components using FDM (fused deposition modeling) technology, the start and end of the layer coincide when the printer nozzle completes a full rotation, causing a material accumulation and the creation of a phenomenon known as a 'seam'. This substantially influences the augmentation of the roundness deviation value. Research has demonstrated that altering the temperature of printing or the printing speed the initial layers could potentially aid in the reduction of these types of shape deviations. The article presents intriguing studies on the topic of progressive hydrogel production (14). The evidence suggests that the formation of channel networks with high roundness is a consequence of the high roundness values in the fibres of the PVA filament. This is a disadvantageous occurrence as improperly configured channel networks limit the delivery of oxygen and nutrients to cells, thereby inhibiting their growth. The article discusses the research on dimensional accuracy and form errors of FFF (fused filament fabrication) printed spur gears using PLA and Nylon (15). Research has demonstrated that the roundness deviation in spur gears fabricated from nylon is significantly less than that of identical gears made from PLA. In the study (16), it is demonstrated that the predominant influence on the value and character of roundness and waviness deviation in cylindrical specimens within PJM (PolyJet Matrix) technology is the direction of printing. The vertical orientation of the samples ($Pd = 90°$) (printing direction) yielded the minimum values for deviations in both roundness and waviness. In the study (17) the sphericity of each grain of Ti6Al4V metal powders applied in SLM (selective laser melting) technology was examined. The topic of the article (18) pertains to the examination of the impact of technological parameters of SLM technology on the precision of holes. It has been demonstrated, among other findings, that the deviation in roundness escalates along with the augmentation of laser power. The article (19) provides a comprehensive comparative analysis of two the most common additive technologies, namely FDM and PJM. An assessment was carried out on the dimensional accuracy, form error, surface texture, and tolerance grades of the specimens fabricated using the specified 3D printing technologies. It has been demonstrated that PJM technology enables the production of samples exhibiting deviations in forms (roundness, cylindricity). This article presents (20) a thorough review of the techniques for evaluating the surface quality of components fabricated using additive technologies.

The rapidly expanding sectors employing additive technologies, the unique manufacturing characteristics associated with 3D printing, the technical constraints of such technologies, and several factors directly influencing the quality of manufactured components, and thereby their surfaces, could potentially lead to the development of extra morphological features or other anomalies, defects. These could impact the properties of the components, both positively, as in the situation of implant production where appropriate porosity is crucial, and negatively, where additional post-processing steps might be necessary for certain surfaces. The complexity of surfaces has necessitated that traditional analyses based in roughness or waviness frequently require to develop the novel algorithms to capture surface complexity (21, 22). Now widely used in roundness evaluation is Fourier transform (23, 24) however the developed multiscale approach which a comprehensive evaluation of irregularities are more and more often use in filtration process. An example of a multiscale method which permits such an evaluation is the wavelet transformation. The method developed over the last forty years allows for the assessment of irregularities in relation to scale and the multiplicity of mother wavelets with characteristic properties enables the detection of other key aspects in the signal (25), and influences the results of the analysis (26). Increasingly more often applied in various fields of science and technology (27–29) as well as in surface metrology (30–32) wavelet transformation allows for the detection of profile differences that often cannot be recorded by conducting analysis with other methods. Consequently, the wavelet transformation can be effectively employed as an supplement to other methods (33, 34). Undertaking the analysis through a discrete methodology results in the removal of high-frequency elements (detail signal) and low-frequency elements (approximated signal) at respective levels of decomposition. This permits the assessment of disparity distributions within distinct frequency bands, at a particular scale. The authors' research, both simulated and conducted on actual objects (35) has verified the effectiveness of the proposed approach that combines both the wavelet and Fourier transformations. Hence, it was deemed that the assessment of the roundness profiles of parts produced by contemporary non-traditional additive technologies might be vital for evaluating the quality of the produced parts. An analysis of the current literature indicates that akin studies have not been conducted and the presented research bridges a void regarding the thorough evaluation of surface topography of elements manufactured through 3D printing. In addition, the presented research results can provide guidelines for further standardization of 3D printing. Currently, the ASTM/ISO 52901 standard establishes the necessity of specifying the method of irregularities measuring between the purchaser and the 3D model manufacturer, which, in the case of roundness profiles, should also be taken into account with special emphasis on specifying the measurement method and analysing the test results. Therefore, the results presented in the article have the potential for practical use in both the research area and industrial applications.

METHODS AND MATERIALS

Manufacturing of specimens

The experimental specimens were fabricated using powder bed fusion (PBF) additive manufacturing technique. The specimens were fabricated from a titanium powder material, Ti6Al4V, (provided by EOS GmbH, Krailling, Germany), using the 3D printer model EOS M290. The specimens were fabricated applying the following technological parameters: Inskin laser's power – 340 W, a laser spot size – 100 µm, a laser speed – 1250 mm/s, a hatch distance – 0.12 mm, and a layer thickness – 60 µm. The temperature of the operational platform was maintained at 35 °C. Additionally, the 3D printing process took place in an atmosphere of inert gas – argon, and post-production, the samples underwent thermal treatment (for the purpose of internal stress reduction) at a temperature of 800 °C. The positioning of the samples on the platform is depicted in Figure 1 (overview view without rotor blade positioning).

Measurement of the roundness profile

In order to carry out a hybrid evaluation of the roundness profile of elements fabricated via PBF additive technology, a significant quantity of measurement data is required, thus the specialised Talyrond 365 measurement system from Taylor Hobson was employed. This is a high-precision measuring device, particularly used for executing precise measurements in the bearing industry (36). It employs the principle of radial change method with rotary table, which enables the evaluation of elements not exceeding a weight of 50 kg. The highest allowable error for both radial and axial spindle is set at +/-(0.02 µm + 0.0003 µm/mm). The measurements of roundness profile were carried out using a contact induction probe with a 2.2 mm measurement range. Conversely, the radial accuracy stands at < 0.02 µm, applicable for a measurement range of 0.08 mm. The devise facilitates automatic alignment and calibration of the component under measurement.

To minimalize the influence of human error, automatic roundness profile measurements were executed on five sections of each specimen produced through PBF technology. The separation between individual sections was 5 mm. The interval for the sampling procedure was set at 0.1°. In each profile, a total of 3,600 data points were collected. The roundness profiles of test specimens are exemplified by the measurements shown in Figure 2.

RESULTS

The research aimed to assess the roundness profiles of components produced additively, based on the build angle and the height at which the profile was measured. The executed harmonic analysis revealed that the spectrum, formulated for each individual roundness profile of the measured samples, enables the identification of differences amongst them. The data on the predominant harmonics for each profile, which varied by angle, can be recorded as depicted in Figure 3. Owing to the printing direction, dominance was observed in ovality, triangularity, or quadrangularity. The occurrence of this phenomenon can be explicitly associated with the impact of the printing direction, support material parameters, and primarily, the method of support removal. It is worth mentioning that insufficient flatness of the base surface during the measurement can lead to excessive ovality.

Nonetheless, substantial amplitude values were not registered for the higher-order harmonics tasked with the high-frequency data. Therefore, it is crucial to rigorously evaluate such irregularities, as they potentially have an impact on the endurance or dependability of the component/device. In this regard, a fundamental element of thorough evaluation and diagnosis is the examination of surface irregularities distribution with respect to scale. Prior research has indicated that the exclusive application of the Fourier transform fails to identify significant components (35), and distinct profile characteristics may merely distort the spectrum (23). Thus, it was deemed suitable to

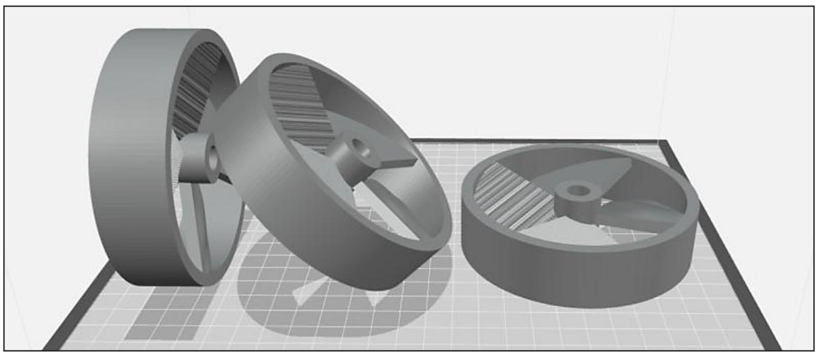


Figure 1. Isometric view of tested samples on the virtual 3D printer platform

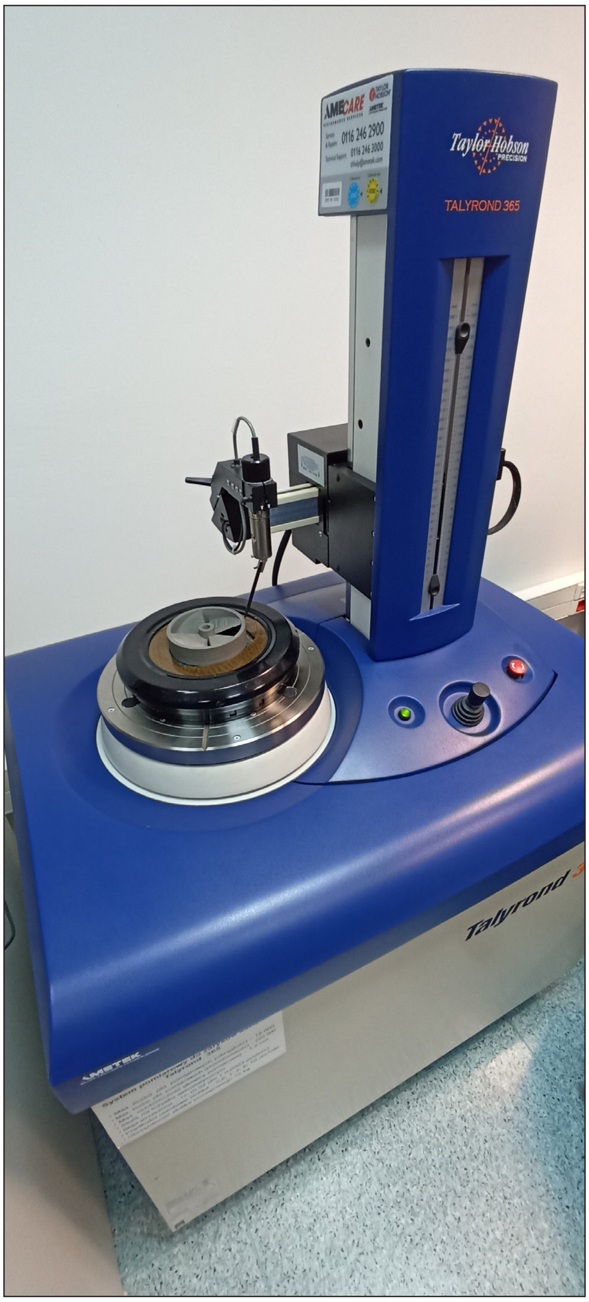
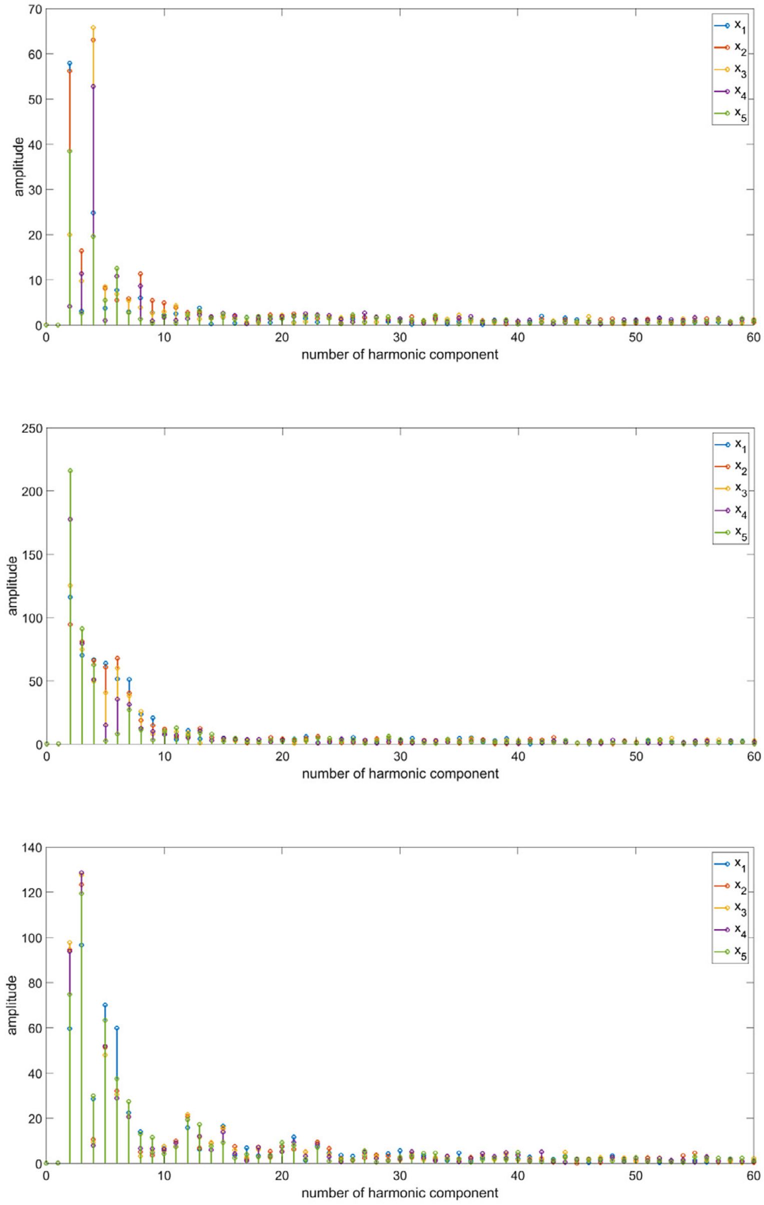


Figure 2. Assessment of roundness profile

conduct the analysis employing a hybrid method that merges wavelet and Fourier transformations. With the objective in mind, various waveforms were selected, each possessing characteristic properties, especially considering the support width, a critical parameter of the mother wavelets.

In examining the spectra established at various decomposition levels, corresponding to high-frequency changes in surface irregularities (Figure 4, commencing from the left from the initial level of decomposition), it can be discern modifications in both the measurement height of the profile and the perspective of the 3D printing angle. Nevertheless, the intensity of these changes varies, contingent upon the evaluated scale and the decomposition level. The obtained data of the spectrum infers that there is a reduction in amplitude values at different decomposition levels as the printing angle increase (Figure 4). The specific coefficients are ascertained by the wavelet coefficients that are generated during the examination, responsible for the high-frequency information. It can be stated that with the angle increases, the irregularities in the roundness profile proportionately smaller and are dispersed in an arbitrary, non-stationary way. In this context, it is noteworthy that for the profiles that yielded lower amplitude values at various levels depending on the printing angle, the dominant harmonic values derived from conducting Fourier analysis on the measured roundness profile (Figure 3) were comparatively larger relative to the 0° printing angle at which the wavelet coefficients for high-frequency data assumed greater values. Moreover, a heightened spectrum value differentiation was observed for this angle (0°), relative to the altitude at which the profile's measurement was conducted. The research indicated that the profiles measured at the foundation exhibited higher amplitude values at the preliminary levels of examination. However, these amplitude values became more akin as the decomposition process progress. This may be due to an error resulting from the specifics of the technological process where deformation may occur due to melting of the material, from the interaction of more layers on the lower sections of the sample and further finishing processes. Analogous findings can be drawn for the 45° printing direction. The trend of wavelet coefficient distributions at individual levels of analysis for this angle is similar to that of a sample built at 0°. Analysis of the values of the coefficients showed a strong correlation at the various levels of decomposition, nevertheless, a significant influence can be noted, on the values of the coefficients, of the technological limitations of the manufacturing process, including the influence of the layered nature of the model, as observed in the results of the analysis. The circumstances contrast for samples created 90° angles, where the influence of the altitude at which the profile was measured was non-existent, where all the profiles were aligned perpendicular to the building platform. Studies have indicated that for such profiles, the coefficients undergo random alterations that preclude the identification



a) b) c)

Figure 3. Spectral density of amplitude: a) 0°, b) 45°, c) 90°

of functional correlations, in terms of diagnostics of the manufacturing process. In this case, an important role play post processing which for additively manufactured parts in this technology is an necessary operation to perform. Removal of support material can interfere with the quality of the surface texture, as shown in Figure 4c. Evaluation of the irregularity distributions as a function of the height of the sample showed random variation in values, which may indicate that this is indeed problematic and affects the quality of the manufactured parts. Additionally, the potential randomness of irregularities changes primarily only occurs up to the fourth level of decomposition. This level ascertains data concerning relatively minor modifications, for later phases the amplitude values progressively increase.

Upon further analysis of the mother wavelet form's impact (Figure 4a, Figure 5), it is observable that nearly similar components of roundness profiles were systematically filtered as the decomposition process progress. Discrepancies in the spectra exist at various analysis levels, yet the essence of the spectrum remains similar. The sole distinctive level of analysis where noteworthy disparities in the mother wavelet function are observed refer to the fourth level. Subject to the shape of the wavelet, substantial elimination of high-frequency components may be observed at this levels, whereby for wavelets with a shorter

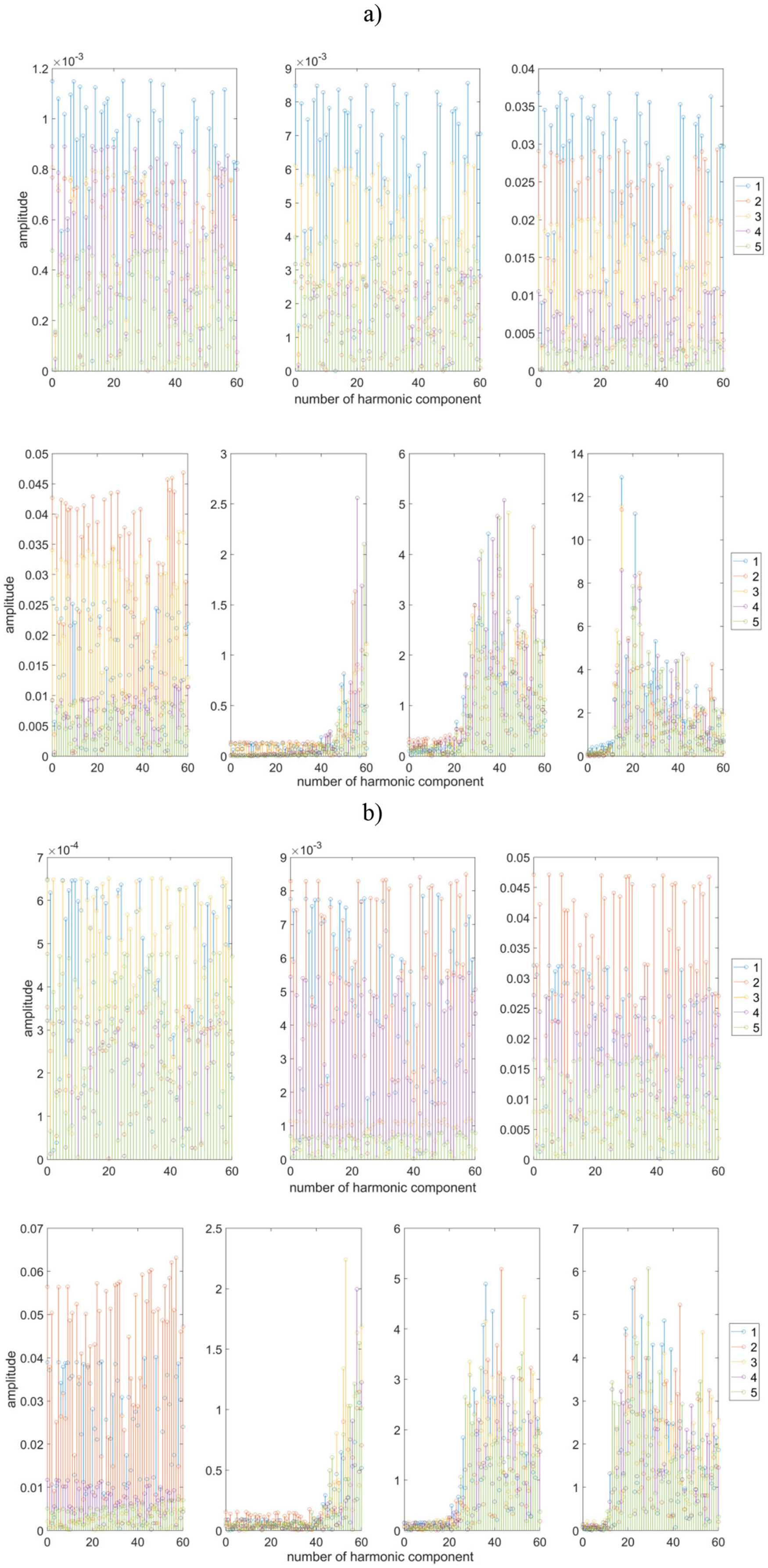


Figure 4. Signal spectrum for seven levels of analysis, mother wavelet *db20* (Daubechies mother wavelet; the number of vanishing moments equal to 20) *db20*: a) 0°, b) 45°, c) 90°

c)

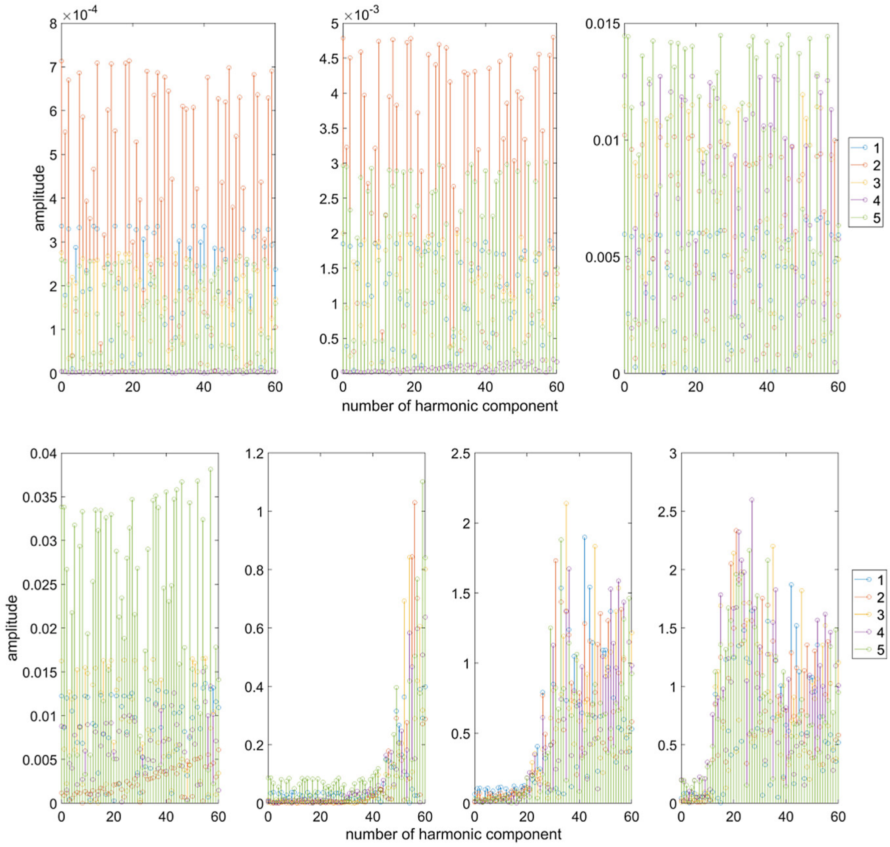


Figure 4 cont. Signal spectrum for seven levels of analysis, mother wavelet *db20* (Daubechies mother wavelet); the number of vanishing moments equal to 20) *db20*: a) 0°, b) 45°, c) 90°

support, the high-frequency components are emphasis for individual harmonics at an different levels. The values of the obtained coefficients also appear to be characteristic, due to the properties of the filters. For wavelets of higher orders, harmonic values reach lower values at particular levels of analysis. It can be concluded that this is due to the characteristics of the mother wavelets, which directly affects the results, nevertheless, statistical analysis of the obtained values, for the evaluating wavelets, showed no influence of the type of wavelet. The analysis carried out showed the validity of the hybrid approach and its effectiveness in the aspect of surface diagnostics, but the influence of the form of the wavelet made it possible to highlight significant differences in the spectra with respect to their character.

DISCUSSION

There is no universally applicable approach to catch the complexity of surface topography irregularities and identify any defects in the production process. Thus, the emphasis of this research was on discovering alternative methods that could enhance the analysis of measurement data, specifically in relation to the diagnostic assessment of the manufacturing process. An assessment of roundness profile using both the traditional Fourier transform and the increasingly prevalent multiscale approach can enhance our comprehension of the processes involved in the production of finalised models, especially regarding the rapidly advancing field of additive technologies. Understanding how and to what extent the production process and individual technological parameters affect the material and the final model necessitates the search for comprehensive solutions, new algorithms for diagnostic evaluation (34, 35), even though classic algorithms are still widely used (37, 38) and surface description measures (39, 40). Additively produced components, especially those derived from the melting of metal powders, exhibit additional morphological characteristics attributable a)

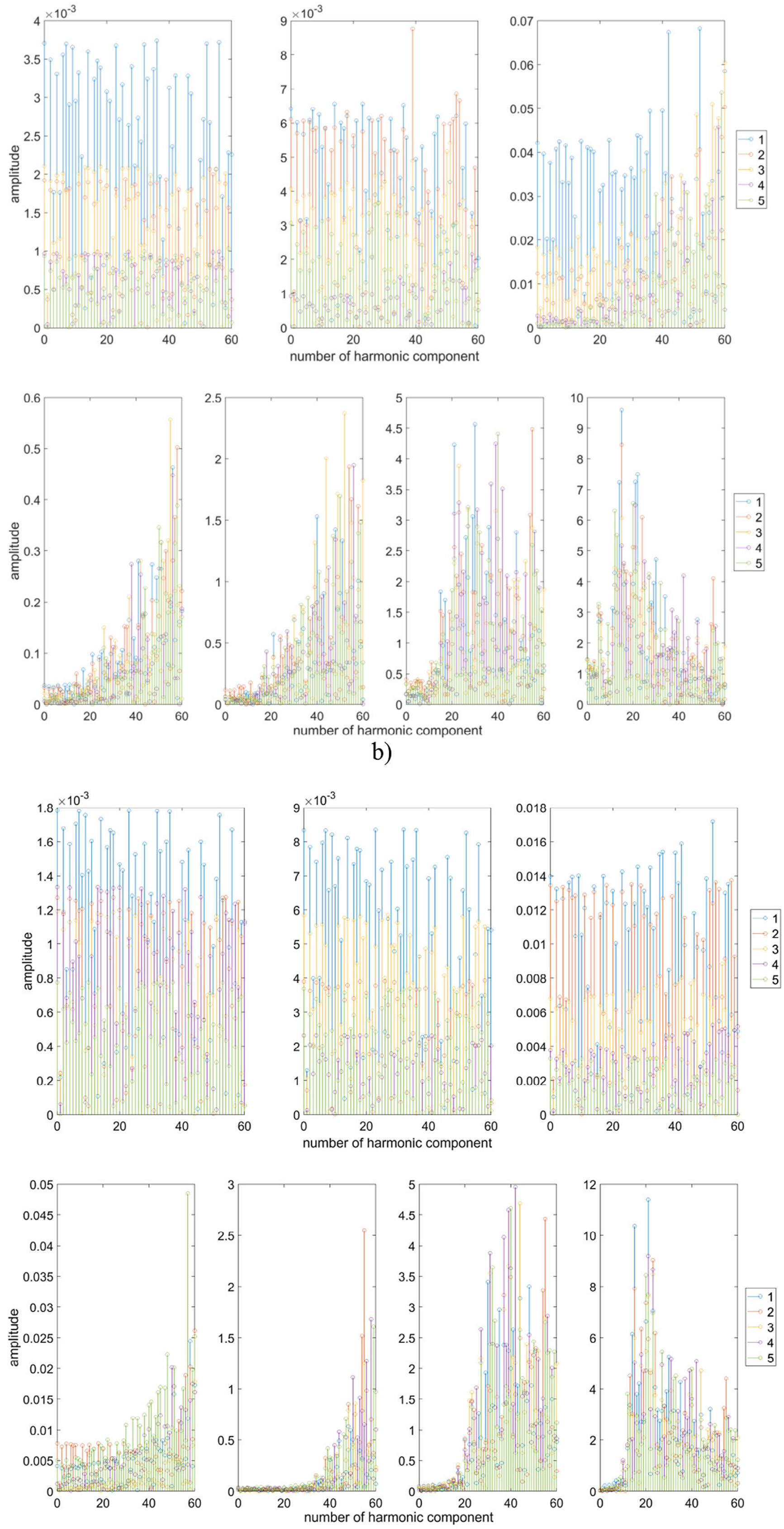


Figure 5. Signal spectrum for seven levels of analysis, printing direction 0°: a) *db2* (Daubechies mother wavelet; the number of vanishing moments equal to 2), b) *db10* (Daubechies mother wavelet; the number of vanishing moments equal to 10)

to the technological process parameters and may require additional finishing operations. It is essential to accurately capture, diagnose, and evaluate these characteristics in relation to the defined quality standards (30, 41). The study thus endeavours to appraise distinct roundness profile in relation to both the printing direction and the altitude at which it was measured, with the aim of investigate potential errors in the manufacturing process.

The presence of discrepancies in a specific angle value potentially facilitates the detection of manufacturing process errors, notably in components that are comparatively height or thin-walled and positioned perpendicular to the building platform. This can potentially lead to the establishment of guidelines instrumental in ensuring product quality. The hybrid approach emphasises the disparities in the spectra at different levels for the evaluated profiles, allows to find functional relations with respect to process parameters. Applying solely Fourier analysis reveals the differences, however, it does not allow a complex evaluation, pointing out specific features that are frequently inproperly filtered, leading to a distorted spectrum. Especially in regard to the evaluation of high-frequency data, a process which, during the analysis of actual, non-stationary signals, becomes challenging due to the inability of visual spectrum assessment to detect variances. Thus, it is important to implement new methods that allow in-depth evaluation of irregularities. And as a consequence, it will contribute to the development of guidelines that can be supplementary to ASTM/ISO 52901. Therefore, it can be stated that the results presented in the article have the potential for practical use in both the research area and industrial applications.

The investigation also possesses certain limitations which are anticipated to be expanded upon in the future, particularly considering the potential to manufacture thin-walled elements and the evaluation of possible distortions or process errors that impact the final product. Moreover, evaluation the profiles immediately at the base and atop the component, that is, the region of the initial and final layers during manufacturing, will enable an assessment of the potential existence of errors, leakages, material flow, and other flaws in the production process. It is imperative to continue investigations in this particular field.

CONCLUSIONS

This study assesses the potential application of an advanced hybrid algorithm for the assessment of roundness profiles of components produced additively. The approach to implementing the algorithm was based on executing Fourier analysis on the detail signals derived from the wavelet decomposition. The examination of the aforementioned results has culminated in the ensuing conclusions:

1. The roundness profile in components manufactured using the additive PBF technology, derived from titanium powder-based powder - Ti6Al4V, demonstrates a significant degree of variability. Upon performing, the Fourier analysis reveals dominant harmonics, their variations subject to the printing direction; however, harmonics of higher orders have not shown significant amplitude values.
2. The study, applying the wavelet transformation algorithm, revealed that with the increasing of the printing direction, there is a recording of smaller amplitude values at each level of decomposition, the irregularities in the roundness profile are equivalently reduced and dispersed in a stochastic, non-stationary way.
3. At the 0° printing direction, the lowest amplitude values were observed for the predominant harmonics, but at specific decomposition levels for this positioning, a significant amount of high-frequency data was filtered out, with the amplitude values increasing for chosen mother wavelets.
4. At a 0° printing direction, there was a noticeable increase in the diversification of spectral values, as a function on the height at which the profile was measured. The research indicated that the profiles assessed at the foundation exhibited heightened amplitude values at the preliminary levels of examination, with this data being filtered as the decomposition advanced. This may be due to an error resulting from the specifics of the technological 3D printing powder bed fusion process where deformation may occur due to melting of the material and it defects (powder coagulation, cavities) from the interaction of more layers on the lower sections of the sample and further finishing processes. Similar observations can be made for the 45° printing direction. The trend of wavelet coefficient distributions at individual levels of analysis for this angle is similar to that of printing direction 0°. The analysis of the values of

the coefficients showed a correlation at the different levels of decomposition, nevertheless, a significant influence, on the values of the coefficients, of the technological limitations of the 3D additive manufacturing process, including the influence of the layered structure of the model, can be observed, as noted in the results of the analysis.
5. The investigations on samples prepared at 90° angle revealed a stochastic alteration in the coefficients, precluding the identification of any functional correlations. Additionally, the potential randomness of irregularities changes primarily only occurs up to the fourth level of decomposition. In this case, an important role is played by post-processing which, for additively manufactured parts in this technology, is an necessary operation which has to be carried out. Removal of support material can interfere with the quality of the surface topography. Evaluation of the distributions as a function of the height of the parts showed random variation in values, which may indicate that this is still troublesome and affects the quality of manufactured parts.
6. Upon further analysis of the mother wavelet form's impact, it is observable that nearly similar components of roundness profiles were systematically eliminated as the decomposition process advanced. Discrepancies in the spectra exist at various analysis levels, yet the essence of the spectrum remains unchanged.
7. Level four is the sole characteristic analysis level where substantial variations in the mother wavelet function have been observed. Subject to the shape of the wavelet, substantial elimination of high-frequency components may be observed at this levels, whereby for wavelets with a shorter support, the high-frequency components are emphasis for individual harmonics at an different levels. The values of the obtained coefficients also appear to be characteristic, due to the properties of the filters. The mother wavelet's type impacts spectral characteristics, though statistical analysis shows no direct influence of the wavelet on results. The hybrid approach proves effective for surface diagnostics, with the wavelet form highlighting critical spectral differences.
8. The development of the standardization process requires standardization of the measurement process and analysis of measurement data, which is partly realized in customer, client requirements according to standard ASTM/ISO 52901 and ASTM/ISO 52902 in the field of surface irregularities analysis and accuracy measurement. The presented research results have potential for application in supplementing the above-mentioned standard in the area of shape deviations, their measurement, data processing and analysis of results.

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