DOI: 10.21062/mft.2025.008 http://www.journalmt.com

Assessment of the Possibility of Using the Continuous Wavelet Transform and Fourier Transform to Analyse Geometric Structures Obtained on the Surface of Turned High-Molecular Polymers

Paweł Karolczak (0000-0002-0595-1580), Maciej Kowalski (0000-0003-3413-8334)
Wrocław University of Science and Technology, Faculty of Mechanical Engineering, wyb. Wyspiańskiego 27, 50-370 Wroclaw, Poland, E-mail: pawel.karolczak@pwr.edu.pl

The article presents the possibilities of using wavelet transform and fast Fourier analysis (FFT) to evaluate the signal collected during roughness measurement. During the tests, high-density polyethylene was turned using variable cutting parameters. During cutting, the tool feed was changed to obtain roughness structures of different types and with varying degrees of anisotropy. The measured roughness profiles were filtered with Daubechies 6 (db6), Morlet and "Mexican Hat" wavelets and examined using Fourier analysis. The research carried out shows how the machining conditions affect the surface features and the stability of the cutting process under variable machining parameters for high molecular weight polymers. The effectiveness of the continuous wavelet transform (CWT) in detecting the nature of disturbances in the generated roughness signal is also presented. In addition, the operation of the wavelet transform was supplemented with data obtained from Fourier analysis, in order to identify the locations of these disturbances.

Keywords: Wavelet analysis, Fourier analysis, Roughness, Polymers, Turning

1 Introduction

Today, machining remains a fundamental manufacturing technology in the industry. The possibilities of machining, its versatility and its accessibility make it the first among other manufacturing technologies. The rapid development of the automation of machining processes that is currently being observed will ensure that these processes will continue to be a leading manufacturing technique in the near and perhaps even further future. Current industrial trends requiring maximum production flexibility from manufacturers, the development of Industry 4.0 and many other factors mean that machining is and will continue to be the main choice among manufacturing techniques [1,2].

The implementation of each technological process forces technologists to control its effects. In the case of machining processes, one of the most frequently measured and evaluated characteristics of the surface of machined parts, along with waviness, is its roughness. Measurement of the geometric structures of the surface allows to assess the quality of the obtained surface, as well as to classify it for further machining or consider it as a finished product.

Although modern measurement systems provide the user with great opportunities to analyse the obtained results, these results are usually affected by errors caused by the measurement method itself or the measurement conditions. Filtering tools are used for surface analysis to remove anomalies generated during measurement or to separate the measured signal into its components. The most commonly used in surface layer condition measurements is the Gaussian filter. The Gaussian filter is relatively easy to use, described in detail and standardised, and likely to be available in all devices for analysing surface geometric structures. It is calculated on the basis of the Fourier transform, which is a basic tool for signal analysis and processing. Both of these tools work well for filtering stationary signals or general filtration. However, in the case of non-stationary signals or when we want to filter out specific components or analyse the results in terms of specific properties, they lose their importance. In such cases, the possibility of using the wavelet transform should be considered - a tool that allows an infinite number of wavelets to be applied to the signal analysis, giving an infinite number of possibilities for analysing the measured signals.

2 Polymers and their machining conditions

Polymers have many advantages. The most important are: low density, good specific strength, resistance to active environments and unfavourable atmospheric factors, temperature stability, thermal and electrical properties, ease of shaping finished products on a very large scale, in relatively simple technological processes. However, the main disadvantages of polymer materials include low creep resistance, a small operating temperature range, and the problematic process of recovery and reprocessing polymer materials.

Plastics are being developed intensively. New additives are being introduced, manufacturing processes are being modified and processing and final product technologies are being improved. This is one of the reasons why these materials are profitable to use in large-scale and mass production [3].

Plastic material machining is significantly different from metal machining. Polymers are characterised by low temperature resistance, low thermal conductivity, low elasticity modulus and low density and hardness compared to metal alloys. However, this does not constitute an obstacle to the effective machining of these materials. However, these are not common processes because plastics are easily shaped using other technologies intended for polymer materials, such as injection or extrusion. In any case, the problems that arise during their production using plastic processing methods lead scientists to address the question of the profitability of using these methods. A comprehensive analysis of the costs of producing complex-shaped plastic elements for various variants of the manufacturing process is shown in [4]. It can be concluded that machining of plastics seems justified, for example, in the case of unit and small-batch production, if high dimensional and shape accuracy are required from the products. The selection of processing conditions for plastics is also ambigous. Therefore, work [5] presents the optimisation of laser cutting parameters for pure and modified polypropylene. Articles [6,7] propose the use of the Taguchi method to optimise polyethylene turning conditions, and the work [8] shows the impact of the machining conditions on the condition of the surface layer of high modulus polyethylene (HMPE).

Due to the differences mentioned above between polymers and metals, the machining of these materials can also be carried out even on machines with low power and low spindle torque. High-speed steel and sintered carbide will work well as tool materials. When polymeric materials are turned, positive geometry inserts will be more suitable, as they generate less cutting resistance and separate the workpiece material more easily. Despite the existence of general recommendations for machining plastics, the problems that arise when selecting optimal conditions for machining plastics are still very widely described. In the work [9,10,11], the possibility of selecting the best cutting conditions for plastics was presented with a particular emphasis on plastics from the polymer group.

The popularity of plastics machining is related not only to the issue of selecting cutting parameters but also to the influence of temperature on the process and the quality of the obtained surfaces. The work [12] describes the processing of polyethylene pipes and the influence of the conditions under which it is processed on the temperature in the cutting zone and the surface quality obtained. The article [13] shows the possibilities of optimising the drilling temperature when drilling holes in high-density polymers - ordinary and with a reinforcement phase. However, in [14], the influence of ionising beta radiation on the general thermal properties of thermoplastic materials (flammability index and ignition temperature) was discussed.

An important issue that should be considered when machining construction materials is the impact of forces on the quality of the machined surface. Work [15] deals with the influence of these factors on the surface conditions of steel and brass alloys and elements made of plastics, work [16] - aluminium alloys, and work [17] - martensitic steels used for the production of injection moulds for plastics. Also in the field of plastics processing, we can also find works in which the authors deal with the influence of forces on the condition of the resulting surface layer. Therefore, in [18] the use of computational techniques of FEM was proposed to estimate the forces and mechanisms of chip formation during polymer machining, and in the works [19, 20] the forces and surface roughness measured during the machining of polymer composites were presented.

3 The use of wavelets in various fields of technology

In the literature, there are proposals to use different wavelets for the analysis of both stationary and non-stationary signals. The oldest of them, but also the simplest, is the Haar wavelet. It is discontinuous, which means that it cannot approximate continuous smoothed functions. Furthermore, the possibility of frequency localisation is low. This wavelet is still found in signal descriptions due to its simplicity. Thus, in the works [21] and [22] it was proposed to use this wavelet to analyse the condition of the cutting tool and its failure during finishing milling operations, as well as to analyse the condition and optimise the operation of drive systems. However, it is best known as a tool for image modification, such as decomposition or compression. These are the two most important applications of discrete wavelets [23].

The extension of the Haar wavelet is the Daubechies wavelet family. It is characterised by compactness of the carrier, a relatively simple form and an accurate approximation of the functions. The Db1 wavelet, i.e. first order Daubechies, corresponds to the first known wavelet presented, i.e. the Haar wavelet. As the order of the wavelet increases, the number of coefficients describing it increases and it becomes smoother, which makes it a tool often used for signal analysis. In [24], it was used to assess the chip formed during the turning of S45C carbon steel, while in [25] it was used to assess the vibrations generated during the turning.

Another wavelet that appears in signal analysis research is the Morlet wavelet. This wavelet is continuous and is characterized by a good frequency resolution. Another feature of this method, namely the lack of a scaling function, means that it is not used for multi-resolution analysis. However, it is an explicit wavelet and can be presented with mathematical relationships in the time domain. The possibilities for using this wavelet were shown in [26] - as a tool to describe the state of surfaces with various structures. In [27], it was used to assess the condition of the surface at the junction of the reinforced material and the concrete, and in [28], it was used to assess the phenomena that occur in the structure of motor vehicles during a collision. In applications related to the condition of the surface after abrasive machining, the Morlet wavelet was shown to assess the condition of the honed surface in [29].

The last wavelet that appears most often in works on signal analysis, „e.g." to assess the condition surface after turning of C45 steel with a hardness of 55HRC [30], or to assess damage to bearings operating in an electric motor [31] - is the Mexican Hat wavelet. This wavelet does not have a scaling function. Its advantage is a good frequency resolution. It comes from the family of Gaussian wavelets; it is proportional to the function that is the second derivative of the Gaussian probability density.

In practice, several different wavelets can be used simultaneously to describe the phenomena that occur during machining processes. Thanks to this, it is possible to obtain comprehensive information about the course of the examined process and the phenomena that occur during it. Such an approach to the subject of wavelet analysis in the case of high-pressure water jet processing was shown in [32]. Most of the works in which wavelets were used to assess machinability and the course of the cutting process concern the assessment of forces and their impact on the machining process, which was shown for turning - in [33, 34, 35] and milling in [36].

4 Testing conditions and selection of wavelets

Samples made of low-density polyethylene LDPE were tested. The face surfaces were machined (transverse, external turning) using an ISO13 thread cutter NNGd-s. The use of such a tool, due to the small contact surface and the sharp cutting edge, allows point turning, which produces less heat in the cutting zone. The turning of polyethylene samples was performed on a TUR 560MN CNC universal lathe.

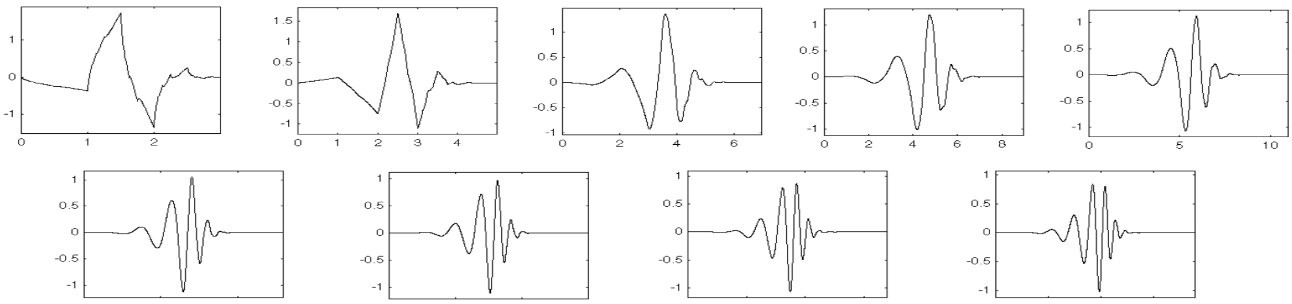

Fig. 1 *Changes in the shape of Daubechies wavelets with their increasing order*

Turning tests on low-density polyethylene samples were performed for various feeds f = 0.04; 0.095; 0.105; 0.135; 0.17; 0.195; 0.235; 0.375 mm.rev^{-1}. The depth of the cutting layer for each sample was a_p = 3 mm. After turning, the samples were measured withe the contact method using a Taylor Hobson Form Talysurf 120L profilographometer. TalyMap Gold software was used to process the data. The diamond measuring needle had the shape of a cone with an opening angle of 60° and ended with a round with a radius of 2 μm. 2D roughness profiles were extracted for each sample. These profiles are the basis for conducting research using wavelet analysis. Wavelet analysis was done in MATLAB and the Wavelet Toolbox. It has a graphical interface that allows you to analyse the results obtained after performing wavelet analysis.

The choice of the base wavelet should be strictly dependent on the nature of the signal components being sought. In the case of surface analysis, as previously shown, the most common used wavelets are Morlet, Daubechies and Mexican Hat. These types of mother wavelets allow for achieving high time accuracy. This means that they will be useful in the analysis of impulse signals. With respect to surface roughness measurement, it is recommended that the shape of the mother wavelet be similar to the signal recorded by the profilometer. Attention should be paid to the sharpness and smoothing of the signal peaks and the base wavelet [37]. For the tested material, the roughness profiles most similar to those obtained using a normalised Gaussian filter were obtained for the 6th order Daubechies wavelet and the previously mentioned Mexican Hat and Morlet wavelets. Fig. 1 shows the Daubechies wavelets arranged in ascending order and, for comparison, the Morlet wavelet (Fig. 2) and the Mexican Hat (Fig. 3).

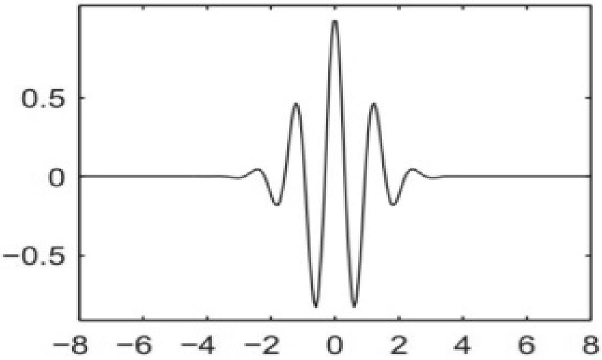

Fig. 2 *Morlet wavelet*

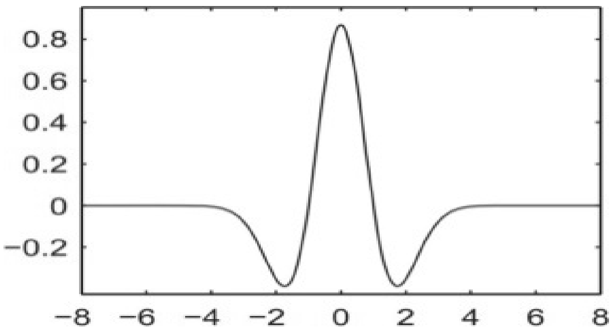

Fig. 3 *Mexican Hat wavelet*

5 Results and Discussion

5.1 Continuous wavelet analysis

Continuous wavelet analysis was performed for all selected wavelet types and seven feeds were selected to turn the sample. The characteristics of polyethylene and its behaviour when cutting with variable machining parameters (especially with feeds selected in a wide range) allowed the surface to be obtained with various structural features. This made it possible to check how selected types of wavelets respond to the variable nature of the geometric features of the roughness. Due to the large number of results, the paper presents the possibilities of using selected wavelets for feeds f = 0.04; 0.095; 0.17; 0.375 mm.rev^{-1}.

The roughness profile obtained by turning with a feed of 0.04 mm.rev^{-1} is characterised by high irregularity, the directionality (characteristic of turning) is unnoticeable, and there are no visible blade marks. Fig. 4 shows the result of wavelet analysis using the "Mexican Hat" wavelet. The color scale reflects the fit of the wavelet to the profile. The zones marked in red are the places where the wavelet and profile correlation are the highest. They represent the local extremes of the signal, where the larger the scale parameter (vertical axis), the greater the decrease or increase in the profile, and thus the more visible, i.e. global, for the entire signal. It can be seen that the highest correlation occurs at the place of the greatest break in the roughness profile at the 360th point of the profile.

The spectrum obtained in the analysis using the Morlet wavelet has visible horizontal bands, which means that the signal correlates with a wavelet of a specific length and we can determine the frequency components in the signal. The Morlet wavelet has the highest correlation in places wth the largest local amplitudes. In Fig. 5, two bands are visible for the scale parameters 25 and 50.

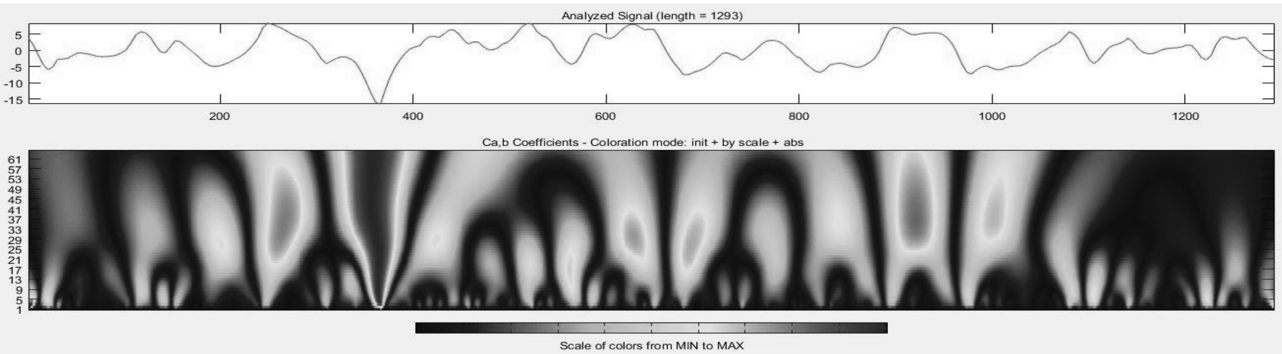

Fig. 4 *Continuous wavelet analysis using the "Mexican Hat" wavelet for a feed of f = 0.04 mm.rev^{-1}*

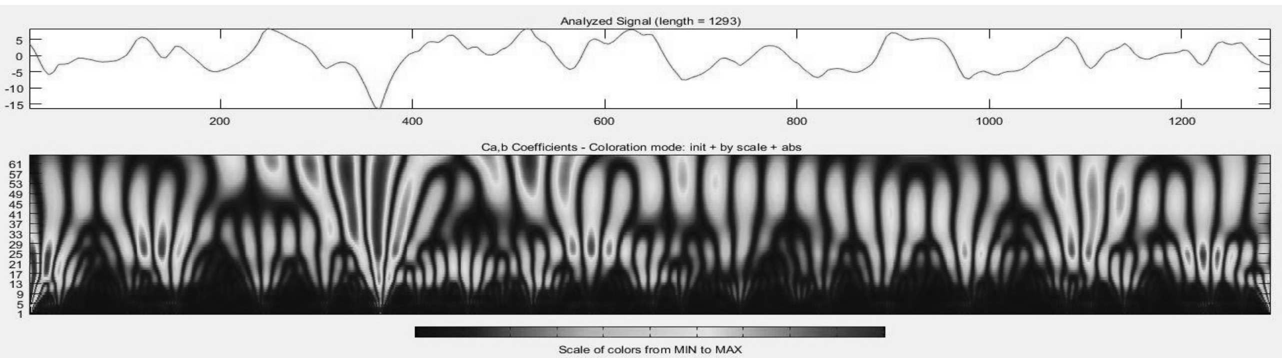

Fig. 5 *Continuous wavelet analysis using the Morlet wavelet for a feed of f = 0.04 mm.rev^{-1}*

The irregularity of the profile is shown in the analysis with the 6th order Daubechies wavelet. The sections in which the correlation is the highest coincide with the sections with the highest correlation of the Morlet wavelet. In the case of the Daubechies wavelet, correlation is shown for points with a high signal gradient. The band with the lowest scale parameter is visible (scale parameter equal to 10), for which the wavelet and the signal are correlated.

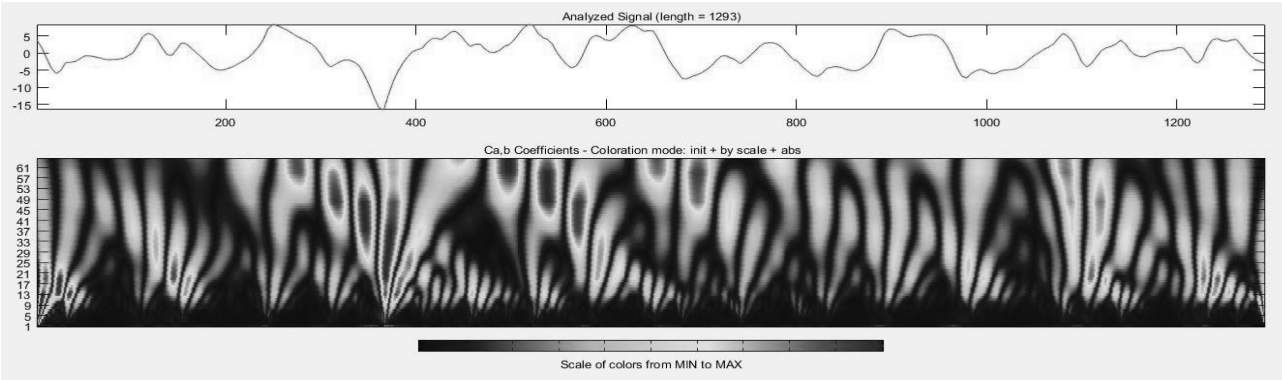

Fig. 6 *Continuous wavelet analysis using Daubechies wavelet 6 for a feed of f = 0.04 mm.rev^{-1}*

The profile obtained after polyethylene turning with a feed of f = 0.095 mm.rev^{-1} is characterised by an increase in the degree of irregularity relative to the sample turned with a feed of f = 0.04 mm.rev^{-1}. When analysing the surface roughness profile, slow changes are observed from a strongly isotropic structure to anisotropicity. Since the applied feed seems to be too small to fully justify this direction of changes, it can result from increasingly intense periodic vibrations. Analysing the roughness profile using a Mexican hat wavelet reveals that this type of wavelet provides information about the extreme peaks and valleys present in the profile. The features that appear on a profile turned with a feed of f = 0.095 mm.rev^{-1}, including changes in the nature of this profile, are better reproduced with the "Mexican Hat" wavelet than those that appear for the profile shown in Fig. 4. This is particularly related to the increase in the number of sharp peaks on the measured structure. The best fit of the wavelet scale to the tested profile can be seen at level 13. Such a high value of the adjusted scale parameter may result (as mentioned earlier) from repetitive vibrations in the workpiece-tool system (Fig. 7).

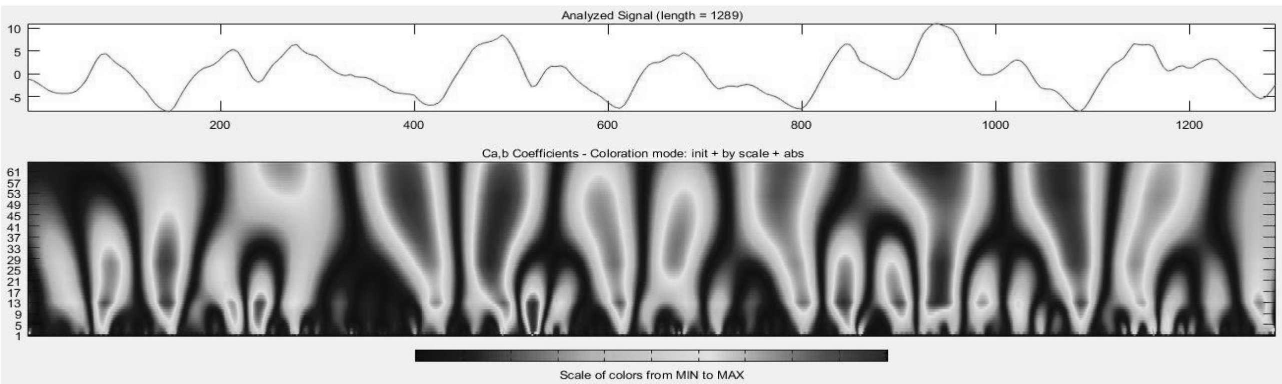

Fig. 7 *Continuous wavelet analysis using the "Mexican Hat" wavelet for a feed of f = 0.095 mm.rev^{-1}*

The use of a Morlet wavelet to describe the signal, also for the feed rate f = 0.095 mm.rev^{-1}, shows that there is a high wavelet correlation for specific values of the wavelet scale. The first such band is visible for a scale parameter of 15. Points with a high wavelet-signal correlation correspond to the extreme values on the profile preceded by hills with steep slopes. Increasing the number of such places compared to turning with a feed of f = 0.04 mm.rev^{-1} allowed better matching of the wavelet scale to the analysed signal, as shown in Fig. 8.

The result of using a 6th order Daubechies wavelet for the assessed profile shows an irregular and low correlation between the wavelet and the signal along its entire length. When analysing the profile with this wavelet, it was possible to determine the best correlations for a relatively low wavelet scale parameter of 10. This can only show narrow bands of correct correlations, which occur particularly strongly in places with the highest slope inclinations of the roughness top („e.g.“ in the zone of measurement points with range 900-1050), as shown in Fig. 9.

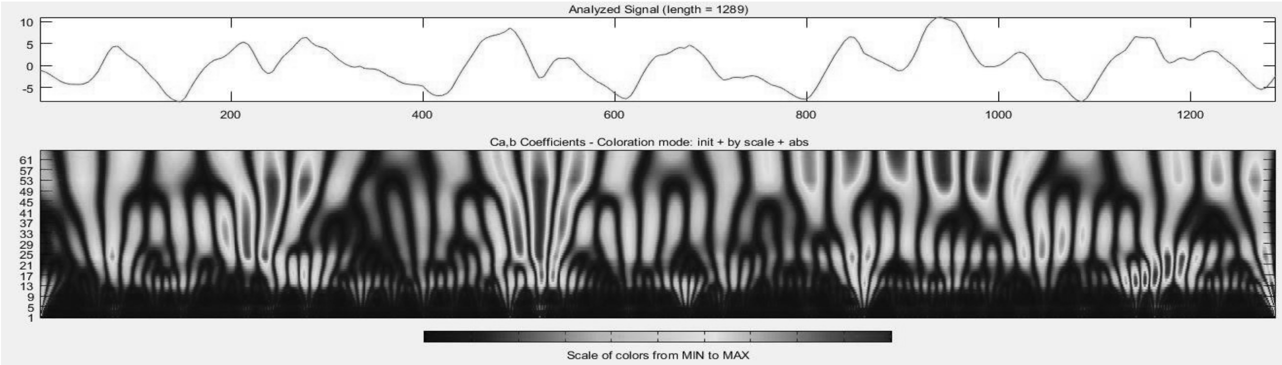

Fig. 8 *Continuous wavelet analysis using the Morlet wavelet for a feed of f = 0.095* $mm.rev^{-1}$

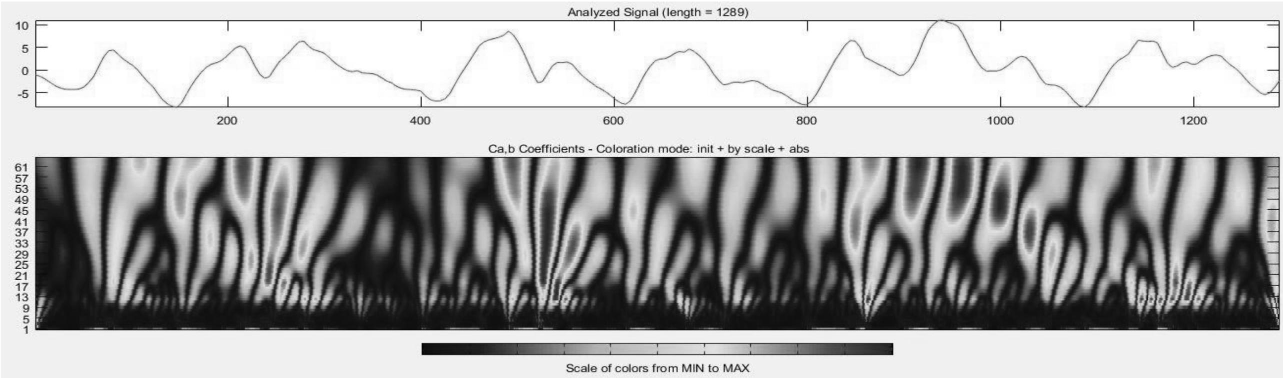

Fig. 9 *Continuous wavelet analysis using Daubechies wavelet 6 for a feed of f = 0.095* $mm.rev^{-1}$

The surface cut with a feed rate of *f* = 0.17 mm.rev-1 is characterised by an ordered and repeatable signal and a stable value of maximum roughness throughout the entire length of the tested profile. This profile is also periodic, isotropic, with visible direction of the traces after tool movement. Fig. 10 shows the analysis of the tested profile using the "Mexican Hat" wavelet. The obtained spectrum of profile distribution shows periodicity in the distribution of profile extremes. There are fewer extreme values visible in the spec-trum; they are further apart than in the case of surfaces turned with lower feeds. High correlation occurs approximately every 90 samples. The correct wavelet scale for peaks reaches a value of 20, and for recesses it is 40. This is visible in the graph showing the roughness profile - the peaks are sharp, while the recesses are softer, which results from the correct mapping of the tool geometry, close to the theoretical assumptions.

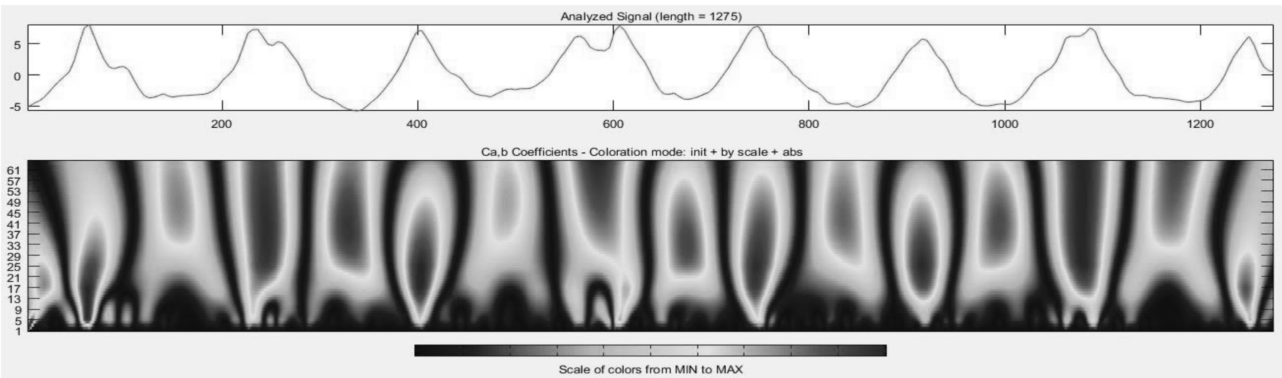

Fig. 10 *Continuous wavelet analysis using the "Mexican Hat" wavelet for a feed of f = 0.17* $mm.rev^{-1}$

Fig. 11 shows the Morlet wavelet analysis of the tested signal. Analysing the obtained image, we can see that the wavelet correlation for low-scale values occurs only for the profile peaks. There is also a noticeable irregularity in the profile in the section for samples 450-550, where the correlation for a scale value of 100 disappears. This can be a place where the cutting process has been disturbed (the chip curled under the material, the chip wrapped around the turned item, etc.).

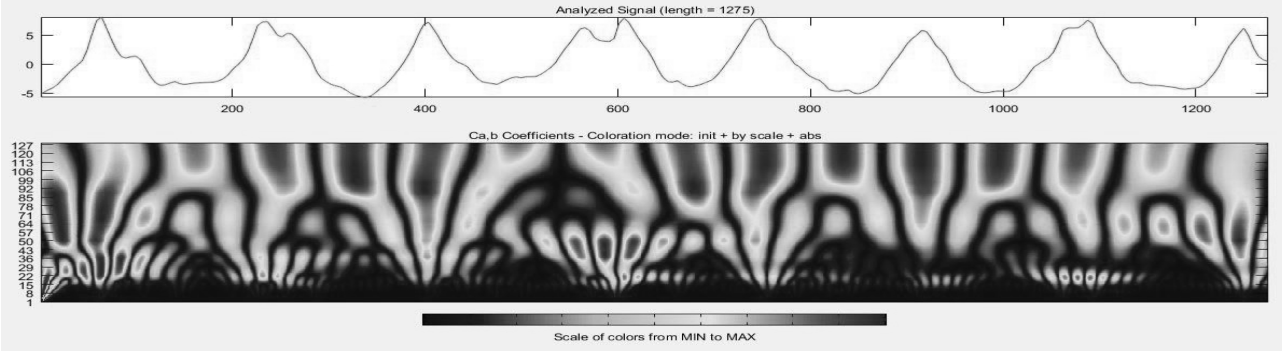

***Fig. 11** Continuous wavelet analysis using the Morlet wavelet for a feed of f = 0.17 mm.rev^{-1}*

The analysis with the Daubechies wavelet (Fig. 12) shows little correlation at the local signal scale. Points with high correlation occur from a scale parameter of 50. Signal dips correlate for a lower scale parameter than for sections where the signal value increases. Analysis of a very regular profile, with a repeating trace of feed and Daubechies wavelet, allows the detection of even small irregularities in the signal. The section for samples in the range of 500 - 600 is characterised by the lack of correlation for high values of the scale, while correlation points for the scale of 15 - 30 are visible, corresponding to (indicating) irregularities at the peak of the signal (double roughness peak near sample 600). Analogous places in the profile occur for samples 250 and 1070.

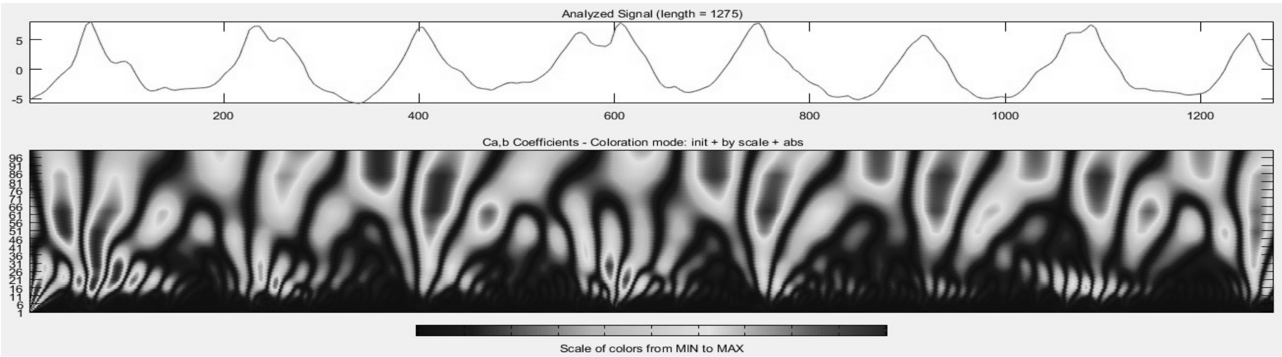

***Fig. 12** Continuous wavelet analysis using Daubechies wavelet 6 for a feed of f = 0.17 mm.rev^{-1}*

The next significant changes in the nature of the profile were observed when the feed was *f* = 0.375 mm.rev^{-1}. A small radius of rounding the cutting edge tip combined with the use of high feed rates generated surfaces with a significant share of "flat-valley" zones. The formation of such structures can be the result not only of increased feed, but also of an increase in process temperature. The heat generated in the cutting zone caused the material to flow and created characteristic roughness structures, as shown in Figs. 13-15. By obtaining such a structure, it is possible to examine how individual wavelets react to long zones of flat depressions. In the case of profile analysis using the "Mexican Hat" wavelet, correlation bands can be seen only in places where the tool generated peaks separating subsequent "flat-bottom" zones. This correlation is greatest for the peaks where most material has accumulated. The flat nature of the depressions resulted in a small correlation parameter, visible in the spectrum (Fig. 13), even for higher-scale parameters.

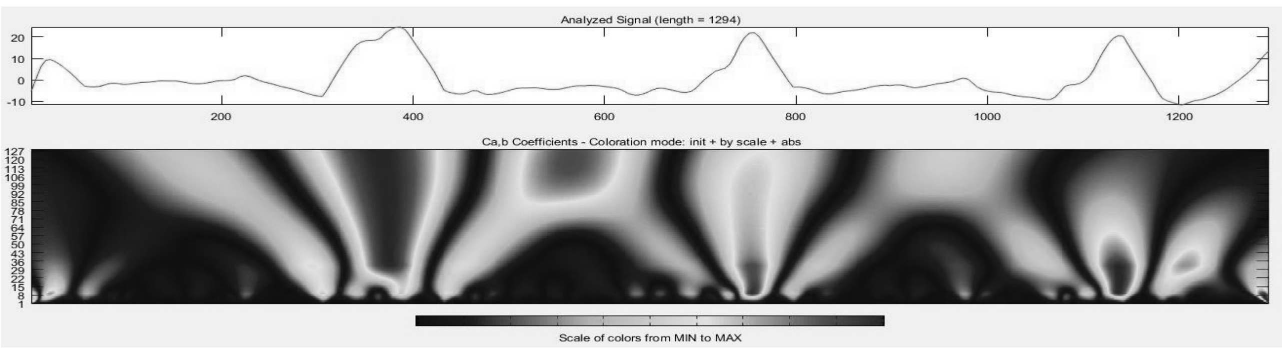

***Fig. 13** Continuous wavelet analysis using the "Mexican Hat" wavelet for a feed of f = 0.375 mm.rev^{-1}*

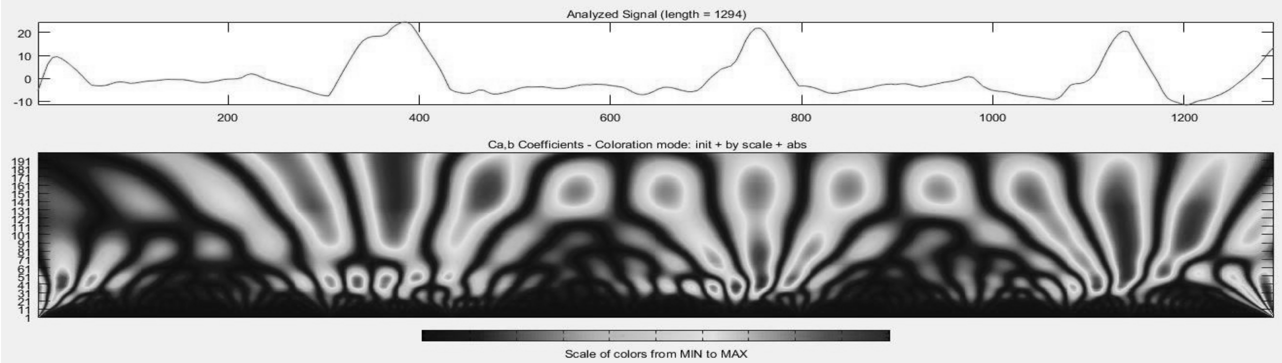

Fig. 14 *Continuous wavelet analysis using the Morlet wavelet for a feed of f = 0.375 mm.rev*$^{-1}$

The Morlet wavelet, similarly to the "Mexican Hat", shows the highest correlation bands with the examined profile at the places of peaks occurring in the profile. However, it can be observed that this correlation depends less on the quantity (volume) of the material collected at this place of the profile. Additionally, one band is noticeable for the scale value of 160, in which areas with a high correlation coefficient also occur for flat sections of the profile, but it does not occur along the entire length of the measurement section. The best correlation band occurs in the range of samples 450-950, i.e. in the zone of valleys with the greatest depth and greatest flatness.

For the Daubechies 6 wavelet, similarly to the "Mexican Hat" wavelet, there are bands of increased correlation for peaks that clearly differ in height from the rest of the signal. An important difference is that the Db6 wavelet correlates better with peaks with steeper slopes where less workpiece material has accumulated. For the profile valley zones, characterised by a flat course, the spectrum generated using the Db6 wavelet does not show any places with significant correlation values.

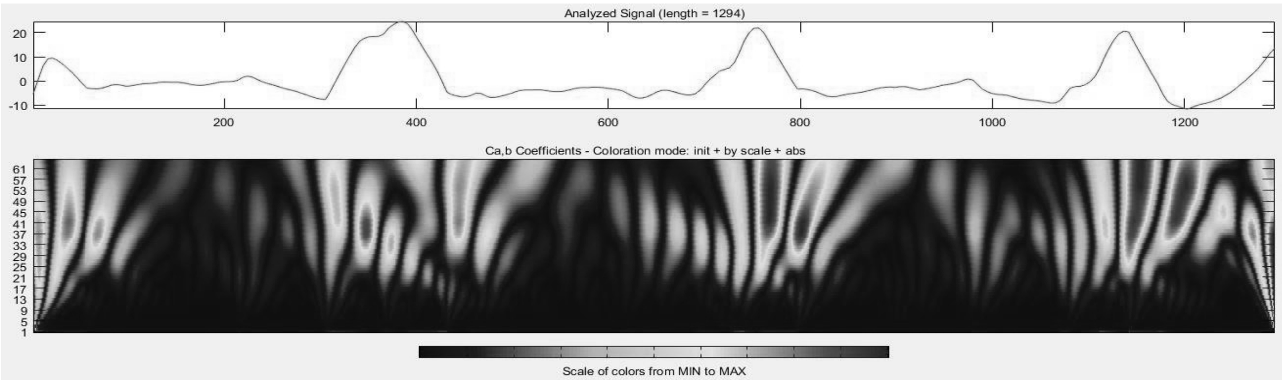

Fig. 15 *Continuous wavelet analysis using Daubechies wavelet 6 for a feed of f = 0.375 mm.rev*$^{-1}$

5.2 Fourier Transform FFT Analysis

In order to expand the scope of the analysis and collect more information about the nature of the structures obtained after turning polypropylene, it was decided to also analyse the tested signal using the Fourier transform (FFT) for selected profiles. This transform is one of the tools that allows us to evaluate the measurement results obtained after filtering out interference related to measurement errors or accidental process disturbances that make it difficult to obtain a real picture of the situation. As filtering tools, Fourier analysis and wavelet analysis are very similar. Both are based on using the scalar product of a given signal and a part called a transformation kernel. This kernel is where the fundamental difference lies between these filtering tools. The Fourier transform uses a sinusoidal function as the kernel, which means that each function will be represented constantly by a selected frequency. However, in the wavelet transform, the kernel is a function called a wavelet, which meets the requirements of time-frequency analysis.

Frequency spectra resulting from the use of FFT analysis was obtained using the TalyMap Gold programme. Results are shown for the same variable feed values for which continuous profiles were analysed using wavelet analysis (f = 0.04; 0.095; 0.17; 0.375 mm.rev^{-1}). The vertical black lines visible in the graphs are marked for those frequencies where the amplitude is the highest. A description of the values characteristic of the highest amplitudes is given under each graph and shows: the wavelength, the magnitude of the amplitude and the phase of the frequency component.

The result of the Fourier transform for a profile after turning with a feed of f = 0.04 mm.rev^{-1} (Fig. 16) proves that the signal consists of many sinusoidal functions with predominant, longer wavelengths. The higher amplitude bands are clustered and are on the left side of the graph; i.e. they have low frequencies, which means high wavelength values. The main band marked with a black line reaches an amplitude value of A = 3.72 µm for a wavelength of 0.144 mm. Since the length of the dominant wave does not correspond to the applied feed *f*, it can be assumed that there are many additional disturbances in the structure of the generated profile, indicating deteriorating material decohesion conditions for such a selected feed.

For the roughness profile after cutting with a feed of $f = 0.095$ mm.rev^{-1}, the component with the highest amplitude reaches a lower value of A = 2.98 µm, for a wavelength of 0.216 mm, which - similarly to turning with a feed of f = 0.04 mm.rev^{-1} - does not correspond to the feed value. Fig. 17 shows other components with similar amplitude values, such as the component with amplitude A = 2.6 µm for the 12th frequency point, which comes from the shaping of the surface by the tool. This result of the spectrum indicates the presence of dominant low- and very low-frequency vibrations in the measured signal. This may indicate a gradual change in the nature of the generated surface and a transition from isotropic to anisotropic structures, which should be characterised by correct turning.

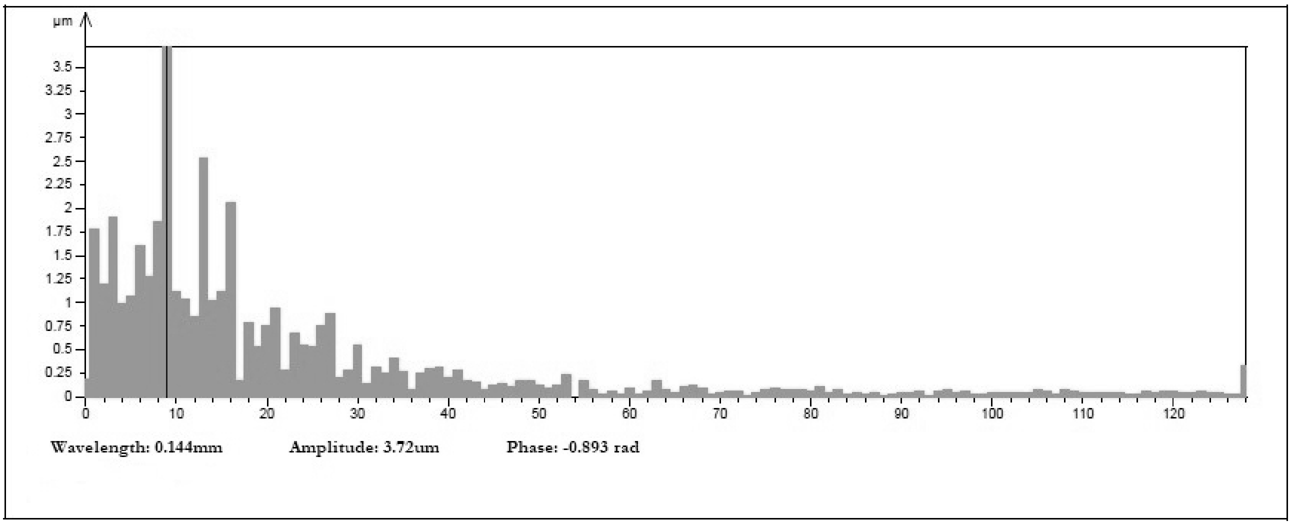

***Fig. 16** Frequency spectrum obtained after FFT analysis of the profile obtained after turning polyethylene with a feed rate of f = 0.04 mm.rev^{-1}*

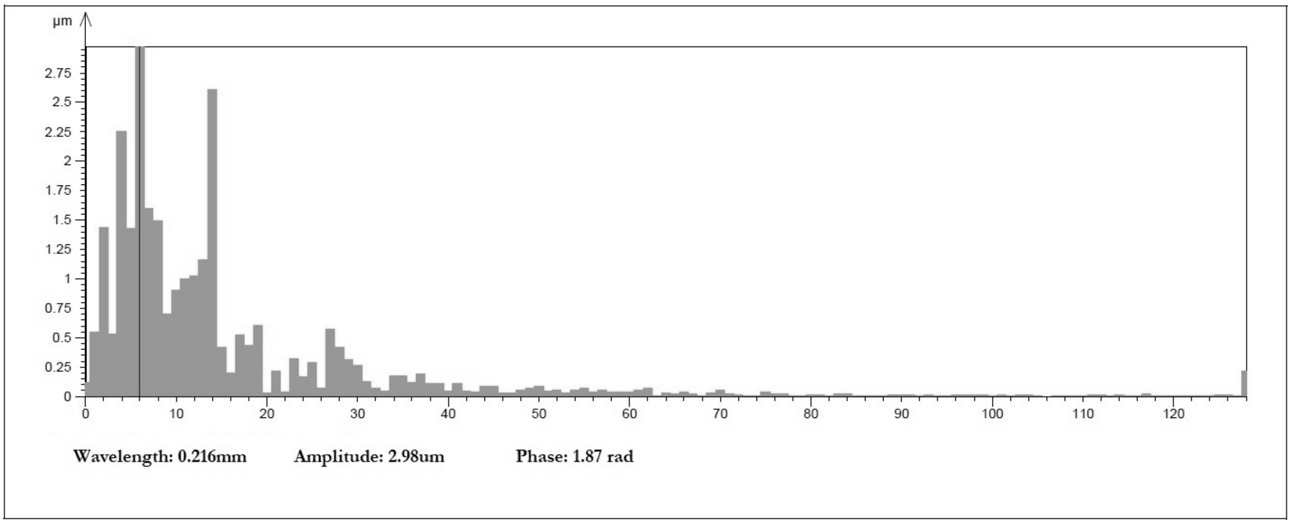

***Fig. 17** Frequency spectrum obtained after FFT analysis of the profile obtained after turning polyethylene with a feed rate of f = 0.095 mm.rev^{-1}*

The profile obtained after turning with a feed of $f = 0.17$ mm.rev^{-1} is characterised by the most stable course, repeatability, and visible periodicity (Fig. 10-12). The frequency spectrum obtained as a result of Fourier analysis also confirms this - in Fig. 18, a band with a large amplitude A = 4.28 µm and a wavelength of 0.162 mm is clearly visible. It is the main frequency component of the tested signal. The wavelength of this component is equivalent to the applied feed *f*. It can therefore be concluded that this profile was not significantly disturbed by additional vibrations of the system - the process was stable under such selected conditions. Higher frequency bands are almost absent from the profile.

Fig. 19 shows the frequency spectrum obtained after performing the FFT analysis for a sample turned with a feed of $f = 0.375$ mm.rev^{-1}. In this case, there is a significant increase in the amplitude of the main harmonic component and the occurrence of subsequent harmonic frequencies in its vicinity, which indicates a high probability of generating not only roughness, but also higher order components on the surface, especially waviness. Increased feed values generate greater loads acting on the tool, which, under conditions of high probability of high temperatures at the point of contact between the tool and the material, causes local material flow. The harmonic component of the signal with the highest amplitude differs in wavelength from the applied feed. This shows the great influence of external factors on profile disturbances. The surface begins to lose the characteristic turning directional pattern of traces. The use of FFT analysis allowed, in the above cases, to determine the size and frequency of harmonic vibrations for disturbances occurring during the turning of polyethylene, but it did not allow one to indicate the exact places on the profile where such changes will occur.

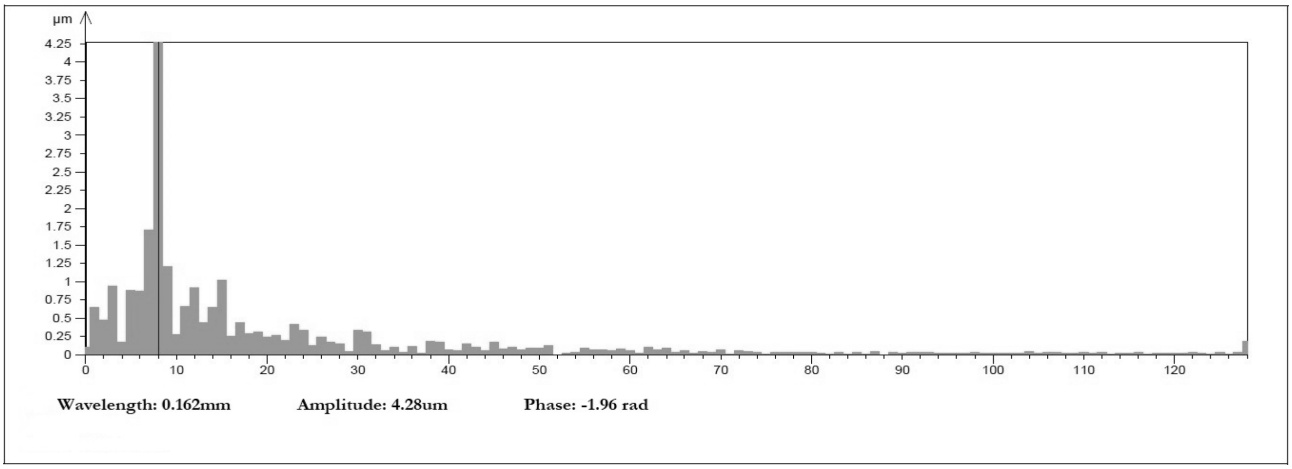

Fig. 18 *Frequency spectrum obtained after FFT analysis of the profile obtained after turning polyethylene with a feed rate of f = 0.17 mm.rev^{-1}*

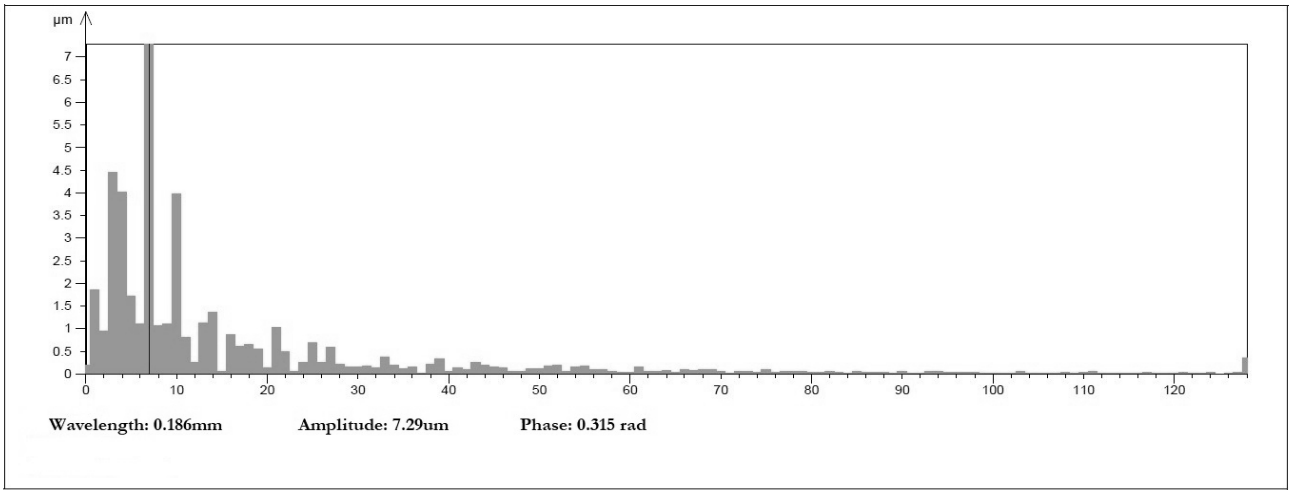

Fig. 19 *Frequency spectrum obtained after FFT analysis of the profile obtained after turning polyethylene with a feed rate of f = 0.375 mm.rev^{-1}*

6 Conclusions

Based on the research carried out and presented in the article, it can be concluded that the use of wavelet analysis to evaluate the structures formed on the surface after machining with a defined blade geometry tool allows for finding and observing roughness profile elements with different properties.

One of the most important factors influencing the result of the continuous wavelet transform is the selection of the base wavelet. The selected wavelet will indicate points with characteristic features, and so the

"Mexican Hat" wavelet indicates local extremes occurring in the signal and their distribution. This wavelet does not allow for the indication of the wavelengths present in the roughness profile. Hence, the Morlet wavelet was selected, which shows frequency bands on the spectrum that correspond to the wavelengths that are the components of the signal. The addition of the 6th-order Daubechies wavelet to the previous two made it possible to identify those sections of the profile that are characterised by the greatest gradient in the change in the roughness height.

By analysing the obtained spectra, we can identify irregularities in the roughness profile generated during cutting and show the place where these irregularities occur. As the stability of the cutting process increased, spectra were obtained in which it was easier to indicate where interference occurred.

It is problematic to use wavelets to find places where single, random disturbances occur in the case of unstable processes, i.e. those for which - in a controlled manner - too low or too high a feed was used. At the same time, it can be stated that flat or almost flat sections of the signal for the roughness profile obtained by turning with the highest feed should not be subjected to wavelet analysis because they are not described by this mathematical tool.

An additional mathematical tool that complements information about the tested roughness profile is the Fourier transform. It allows you to obtain information about the frequency and amplitude of vibrations that disturb the ideal course of the generated profile, as well as the number of harmonic components present in the signal.

The wavelet transform can be a useful tool that enables additional analysis of the roughness profile in terms of searching for other signal properties than the classic methods of its filtration, such as the Gaussian filter, strong Gaussian regression or 2CR. It seems that the greatest limitation in the use of this method is the proper selection of the wavelet for the assessment and observation of individual groups of features occurring on real surfaces. Another significant disadvantage of this tool is that the wavelet transformation, using each of the wavelets used in this work, does not fully meet the expectations we set for it in the case of the analysis of profiles very similar to theoretical waveforms and those in which we observe hills or depressions characterised by small changes in height on long fragments of the examined profile. In such cases, it may be necessary to select a different wavelet whose properties and shape will better match the nature of the analysed signal.

References

[1] SOORI, M., JOUGH, F. K. G., DASTRES, R., & AREZOO, B. (2024). Robotical automation in CNC machine tools: a review. *acta mechanica et* automatica, *18*(3).

[2] LAURO, C. H., et al. "Monitoring and processing signal applied in machining processes–A review." *Measurement 58* (2014): 73-86.

[3] GEISLER J. (edit.): Low-density polyethylene: properties and applications. *Nova Science Publishers*, New York 2020 (157pages). ISBN : 1-5361-8273-7.

[4] KARANIA R., KAZMER D.: Low volume plastics manufacturing strategies. American Society of Mechanical Engineers. *Design Engineering Division*, 118 A (2005) 1, 265–274.

[5] CIENKA A., CIECIŃSKA B.: Optimization of laser cutting conditions of polypropylene and polypropylene with talc. *Physics for Economy. Oficyna Wydawnicza Politechniki Rzeszowskiej. Rzeszów* 4/2021, pp.5-15.

[6] LAZAREVIĆ D., MADIĆ M., JANKOVIĆ P., LAZAREVIĆ A.: Cutting parameters optimization for surface roughness in turning operation of polyethylene using Taguchi method. *Tribology in Industry*, 2012, 34(2): pp. 68÷73.

[7] ABDUL SHUKOR J., SAID S., HARUN R., HUSIN S., KADIR AB.: Optimising of machining parameters of plastic material using Taguchi method. *Advances in Materials and Processing Technologies* (Abingdon, England), 2016-01, Vol.2 (1), p.50-56. https://doi.org/10.1080/2374068X.2016.1143216

[8] SALLES J., GONCALVES M.: Effects of Machining Parameters on Surface Quality of the Ultra High Molecular Weight Polyethylene. (2003) *Materia*, 8 (1), pp. 1÷10.

[9] MOŠORINSKI, P., PRVULOVIC, S., JOSIMOVIC, L.: Determination of the optimal cutting parameters for machining technical plastics. *Materiali in Tehnologije*, 2020-01, Vol.54 (1), p.11-15.

[10] OLEKSY M., ZABORNIAK M. , KOŁCZYK L.: Selection of cutting process parameters for selected models made of polymer materials. Sieć Badawcza Łukasiewicz - Instytut Mechanizacji Budownictwa i Górnictwa Skalnego. Wydawnictwo SIGMA-NOT. *Przegląd Mechaniczny* 7-8/2018, pp. 57-60. (in Polish).

[11] HRBACKOVA L., SEDLAK J., CHROMJAKOVA F., MACUROVA L., JURICKOVA E., DOBROCKY D., SKERIK F.: Evaluation of the Effect of Machining Technologies on the Surface Texture Analysis

of Ertacetal C Polymer. *Manufacturing Technology* 2022, 22(6):679-692 DOI: 10.21062/mft.2022.083.

[12] HAMLAOUI N. AZZOUZ S. CHAOUI K. AZARI Z. YALLESE M.-A.: Machining of tough polyethylene pipe material: surface roughness and cutting temperature optimization. International Journal of Advanced *Manufacturing Technology*, 2017-09, vol.92 (5-8), p.2231-2245. https://doi.org/10.1007/s00170-017-0275-4

[13] UYSAL A.: Anova optimization of drill bit temperature in drilling of pure and carbon black reinforced high density polyethylene. *Journal of Engineering Studies and Research*, 2019-09, vol.25 (3), p.44-50.

[14] BADNARIK, M., MIZERA, A., OVSIK, M.: The Influence of Ionizing Beta Radiation on the Flammability Index and Ignition Temperature of Thermoplastic Materials. *Manufacturing Technology* 2019. vol. 19(6):907-911. DOI: 10.21062/ujep/394.2019/a/1213-2489/MT/19/6/907

[15] CEPOVA L., SOKOVA D., MALOTOVA S., GAPINSKI B., CEP R.: Evaluation of Cutting Forces and Surface Roughness after Machining of Selected Materials. *Manufacturing Technology* 2016, 16(1):45-48 DOI: 10.21062/ujep/x.2016/a/1213-2489/MT/16/1/45.

[16] MAJERÍK J., DUBOVSKÁ R., BAŠKA I., JAMBOR J.: Experimental Investigation and Measurement of Surface Roughness and Cutting Forces while Turning AlCu3MgMnPb Aluminium Alloy. *Manufacturing Technology* 2018, 18(1):66-71 DOI: 10.21062/ujep/55.2018/a/1213-2489/MT/18/1/66.

[17] MAJERÍK J., MAJERSKÝ J., CHOCHLÍKOVÁ H., BARÉNYI I., ESCHEROVÁ J., KUBASÁKOVÁ M.: Machining of M390 Microclean® and M398 Mircoclean® PM Steels – the Comparison of Cutting Forces and Surface Roughness. *Manufacturing Technology* 2023, 23(6):853-860 DOI: 10.21062/mft.2023.096

[18] BIN Y., HONGJIAN W., KUNKUN F., CHONGLEI W. Prediction of Cutting Force and Chip Formation from the True Stress-Strain Relation Using an Explicit FEM for Polymer Machining. *Polymers*, 2022-01, vol.14 (1), p.189. https://doi.org/10.3390/polym14010189

[19] BIRUK-URBAN K., JÓZWIK J., BERE P.: Cutting Forces and 3D Surface Analysis of CFRP Milling. Advances in Science and Technology. *Research Journal*, 2022, vol. 16, no 2, pp. 206-215. DOI: https://doi.org/10.12913/22998624/147338

[20] DUAN Z., LIU G., FAN X., TAO CHEN T.: Study on cutting force performance and cutting mechanism of Carbon Fiber Reinforced Polymer (CFRP) composites. Bulletin of the JSME. *Journal of Advanced Mechanical Design, Systems and Manufacturing*. vol.15, No.3, 2021. 10.1299/jamdsm.2021jamdsm0037

[21] LEE B. Y., TARNG Y. S.: Application of the Discrete Wavalet Transform to the Monitoring of Tool Failure in End Milling Using the Spindle Motor Current. *International Journal of Advanced Manufacturing Technology*, 15 (1999), pp: 238-243. https://doi.org/10.1007/s001700050062

[22] KOSICKA M.: Możliwości zastosowania falek Haara do analizy i optymalizacji układów napędowych. *Prace Instytutu Elektrotechniki*, Z. 214 (2002), 99–116. (in Polish)

[23] ZAWADA-TOMKIEWICZ A:. Analiza obrazu powierzchni obrobionej do celów estymacji parametrów tej powierzchni. *Acta Mechanica et Automatica*, vol. 1 (2007), nr 2, 79–84. (in Polish)

[24] TANGJITSITCHAROEN S., HARUETAI L.: Hybrid monitoring of chip formation and straightness in CNC turning by utilizing Daubechies Wavelet Transform. *Procedia Manufacturing* vol. 25 (2018) pp: 279-286. https://doi.org/10.1016/j.promfg.2018.06.084

[25] GARCIA PLAZA E., NUNEZ LOPEZ P. J.: Application of the wavelet packet transform to vibration signals for Surface roughness monitoring in CNC turning operations. *Mechanical Systems and Signal Processing*, vol. 98 (2018) pp.: 902-919. https://doi.org/10.1016/j.ymssp.2017.05.028

[26] JOSSO B., BURTON D., LALOR M. J.: Frequency normalised wavelet transform for Surface roughness analysis and characterisation. *Wear* 252/5-6 (2002) pp.: 491-500. https://doi.org/10.1016/S0043-1648(02)00006-6

[27] CHANG C.-C., YU C.-P., LIN Y.: Distinction between crack echoes and rebar echoes based on Morlet Wavelet Transform of impact echo

signals. *NDT&E International*, vol. 108 (2019), article number 102169.

[28] KARIMI H. R., PAWLUS W., ROBBERSMYR K. G.: Signal reconstruction, modeling and simulation of vehicle full-scale crash test based on Morlet wavelets. *Neurocomputing*, vol. 93 (2012), pp. 88-99. https://doi.org/10.1016/j.neucom.2012.04.010

[29] SABRI L., MEZGHANI S., MANSORI M., ZAHOUANI H.: Multiscale study of finish-honing proces in pass production of cylinder liner. *Wear*, vol. 271, issues 3-4 (2011), pp. 509-513. https://doi.org/10.1016/j.wear.2010.03.026

[30] GRZESIK W., BROL S.: Wavelet and fractal approach to surface roughness characterization after finish turning of different workpiece materials. *Journal of Materials Processing Technology*, vol.209, issue 5 (2009), pp. 2522-2531. https://doi.org/10.1016/j.jmatprotec.2008.06.009

[31] LIU W.Y., HAN J.G.: The optimal Mexican hat wavelet filter denoisig method based on cross-validation method. *Neurocomputing*, vol. 108 (2013), pp.31-35. 10.1016/j.neucom.2012.11.010

[32] PAHUJA R.: RAMULU, M.: Surface quality monitoring in abrasive water jet machining of Ti6Al4V–CFRP stacks through wavelet packet analysis of acoustic emission signals. *International Journal of Advanced Manufacturing Technology*, 2019-10, Vol.104 (9-12), p.4091-4104. 10.1007/s00170-019-04177-0

[33] GARCÍA PLAZA E., NÚÑEZ LÓPEZ P.J.: Analysis of cutting force signals by wavelet packet transform for surface roughness monitoring in CNC turning. *Mechanical Systems and Signal Processing*, 2018-01, Vol.98, p.634-651. https://doi.org/10.1016/j.ymssp.2017.05.006

[34] TIEN D.H., THOA P.T., DUY T. N.: Application of wavelet ratio between acoustic emission and cutting force signal decomposing in intelligent monitoring of cutting tool wear when turning SKD 61. *International Journal on Interactive Design and Manufacturing*, 2024, vol.18 (1), p.525-539. https://doi.org/10.1007/s12008-023-01571-7

[35] KAROLCZAK P.: Analysis of Cutting Forces with Application of the Discrete Wavelet Transform in Titanium Ti6Al4V Turning. *Manufacturing Technology* 2023, 23(4):449-460 DOI: 10.21062/mft.2023.062.

[36] CABRERA C. G., ARAUJO A. C., CASTELLO D. A.: On the wavelet analysis of cutting forces for chatter identification in milling. *Advances in Manufacturing*, 2017-06, vol.5 (2), p.130-142. https://doi.org/10.1007/s40436-017-0179-4

[37] BATKO W., ZIÓŁKO M.: Zastosowanie teorii falek w diagnostyce technicznej. *AGH Kraków* 2002. (in Polish).