

CONTINUOUS WAVELET APPROACH TO SURFACE PROFILE CHARACTERIZATION AFTER FINISH TURNING OF THREE DIFFERENT WORKPIECE MATERIALS

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Summary

In this paper the surface profiles generated in longitudinal turning operations were characterized using continuous wavelet transform (CWT). In the comparative analysis, some characteristic roughness profiles after the turning of three different workpiece materials, such as C45 medium carbon steel, nodular cast iron and hardened (55 HRC) high-strength ($R_m = 1000$ MPa) alloy steel were selected. For wavelet characterization, both Morlet and "mexican hat" analyzing wavelets, which allow the assessment of extrema and frequency distribution, were utilized. The results of the CWT as a function of profile and momentary wavelet length are presented. It is concluded that CWT can be useful for the analysis of the roughness profiles generated by cutting processes.

Keywords: surface roughness, continuous wavelet transform

Podjęcie falkowe do charakteryzacji profilu chropowatości powierzchni po toczeniu wykańczającym różnych materiałów konstrukcyjnych

Streszczenie

Opracowano charakterystyki profili chropowatości powierzchni generowanych w operacjach toczenia wzdłużnego za pomocą ciągłej transformacji falkowej (CWT). W prowadzonej analizie porównawczej, wykonano selekcję charakterystycznych profili powierzchni po toczeniu różnych materiałów: stali niestopowej C45, żeliwa sferoidalnego EN-GJS500-7 i stali stopowej 41Cr4 utwardzonej (55 HRC), o wytrzymałości na rozciąganie ($R_m = 1000$ MPa). W analizie fraktalnej stosowano zarówno falkę Morleta, jak i falkę „meksykański kapelusz”, umożliwiające ocenę rozkładu ekstremów i częstotliwości. Przedstawiono wyniki transformacji falkowej funkcji długości profilu i chwilowej długości falki. Stwierdzono, że CWT jest przydatna do analizy profili powierzchni generowanych w procesie skrawania.

Słowa kluczowe: chropowatość powierzchni, ciągłe przekształcenie falkowe

1. Introduction

The form of each roughness profile after finish turning strictly depends on the shape of the tool nose, cutting parameters and mechanical properties of the

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workpiece material used. It is obviously known that turning generates a broad spectrum of surface profiles and their features change from periodic to aperiodic. Moreover, in some cases they are partially random (chaotic) with lesser or higher coefficient of profile randomness [1]. Besides the use of standardized roughness parameters and less frequently fractal characteristics, the surface profiles can be analyzed in wavelength-amplitude domain based on discrete Fourier transform, especially using the power spectra density (PSD) and short time Fourier transform (STFT). It is well known that this type of spectral analysis is well applicable only to stationary signals.

Unfortunately, the roughness profiles in many cases are partially or completely non-stationary [2] and, as a consequence, special processing techniques are required for proper analysis of such profiles and the determination of their parameters. This is due to the fact that real surface profiles contain numerous non-stationary characteristics such as drifts, trends, and abrupt changes, which cannot be detected by means of classical Fourier analysis.

One of these possible techniques is previously mentioned continuous wavelet transform (CWT) [3-5]. The WT has been developed as an alternative to FT in order to overcome problems with the frequency resolution. The WT is described in a fashion similar to the short time Fourier transform (STFT) but instead of using periodic functions in the transformation Kernel, it uses a waveform function, so-called wavelet function. The transformation is based on a procedure in which the analyzed wavelet is scaled and translated along the recorded signal according to Eqn. (1), provided in similar form in Ref. [6, 7]. As a result, the scaling and translation gives the scalar product of wavelet and signal.

$$CWT_f(s, u) = \langle f(t), \psi_{s,u}(t) \rangle = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} f(t) \psi\left(\frac{t-u}{s}\right) dt \quad (1)$$

where: $f(t)$ is analyzed signal, $\psi_{\tau,s}(t)$ is wavelet basis function, s and u represent the dilation and translation parameters, $\psi(t)$ is referred to as the mother wavelet.

The result of one-dimensional wavelet transform is a half plane arranged in the time-scale coordinate system and, what is very important, scale corresponds to the frequency band. The variable is equal to the scale of analyzed wavelet on every step of transform calculations and its reciprocal is frequency [2-6]. In application to the roughness profile, the CWT matrix is arranged at a scale-profile length and in this investigation it is composed as the matrix in which every cell is colored according to assigned color map (Fig. 1).

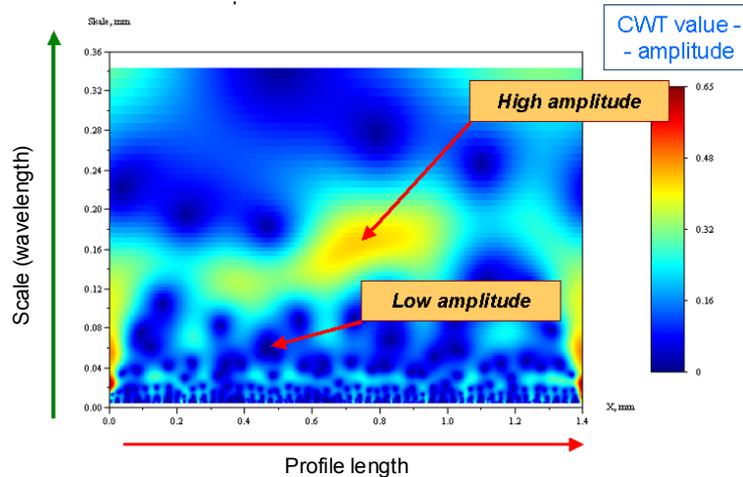


Fig. 1. CWT matrix arrangement – Morlet wavelet for the roughness profile analysis

Currently, many wavelets such as Meyer's, Morlet's, Daubechie's, Haar's or "mexican hat" wavelets [8] are used. On the other hand, discrete wavelet transform can be effectively performed using Coiflet's or biorthogonal wavelets [9]. The extracted signal features, which should be determined by (CWT), depend on analyzing wavelet used. In particular, "mexican hat" wavelet type is predominantly suitable for extrema and Morlet wavelet seems to more appropriate for frequency distribution analysis [8, 10].

From an intuitive point of view, the wavelet decomposition is based on the calculation of a "resemblance index" between the signal and the wavelet. If this index is large, the resemblance is strong, otherwise it is slight. The indices are equal to the wavelet coefficients [8]. On the other hand, if a signal is similar to itself at different scales, the "resemblance index" or wavelet coefficient also will be similar to each other at different scales. In the plot of these coefficients with the scale measured on the vertical axis, this self-similarity generates a characteristic, self-replicable patterns like those exemplarily shown in Fig. 2.

The WT is localized in the frequency-length space, therefore can yield frequency information at different frequency scales and allow a multiscale description of surface morphology. Probably, Pandit [11] was the first propose to estimate wavelength components of machined surfaces by the wavelength decomposition of Green's function, after turning, grinding and EDM, with respect to cutting conditions used and the physical mechanisms generating the surfaces. The main finding was the increasing contribution of feed wavelength with increasing feed for turned surfaces, which is self-evident from the dynamics of turning process.

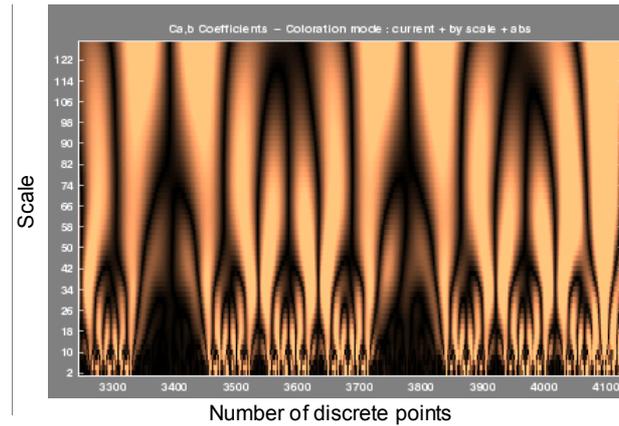


Fig. 2. Koch curve for a CWT with self-replicable patterns [8]

Lee *et. al* [6] used wavelet transform to explore the multi-scale roughness features of various engineered surfaces to find a link between manufacturing process and their service functions. After two-stage decomposition using inverse wavelet transform, the wavelets were normalized in order to characterize the local morphology of roughness in the space-frequency domain. The modulus and the sign change of the phase of the WT were used for the detection of the singularities of the roughness. The local maxima of the modulus of WT corresponded to the position of the singularities of the signal, which correspond to the peak and valley positions.

This paper is intended to explore capabilities of the wavelets for surface profile characterization and analysis, which enhance standard profile description.

2. Objectives and conditions of investigation

In this investigation, the main objective was to compare surface roughness profiles after turning operations on different workpiece materials using continuous wavelet transform technique. The second objective was to compare some representative roughness parameters produced after hard turning using optionally standard and wiper ceramic inserts. The two shapes of cutting tool corners are shown in Fig. 3. The workpiece materials with different mechanical properties and machinability ratings were used in order to examine different cutting mechanisms and as the feedback- differently distributed and shaped roughness profiles.

In the first stage, an experiment was carried out on C45 medium carbon steel (equivalent to AISI 1045 grade) specimens with multi-layer coated inserts. Then, the obtained reference profiles were compared to the profiles after turning

of nodular cast iron EN-GJS500-7 (NCI) and hardened high-strength alloy steel 41Cr4 of 55 HRC hardness (equivalent to AISI 5140) respectively.

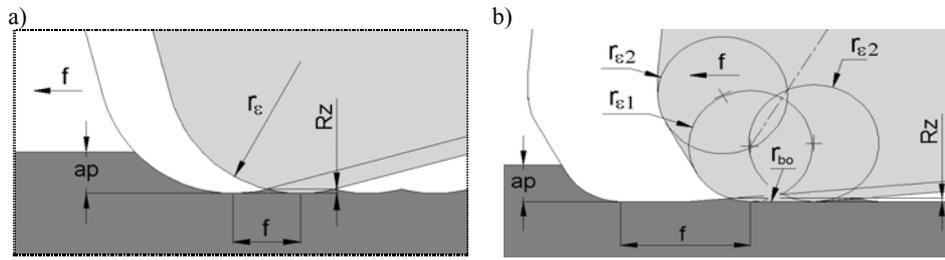


Fig. 3. Surface roughness generation when cutting with: standard (a) and wiper (b) inserts. Symbols: f – feed; a_p – depth of cut; r_ϵ – radius of the cutting edge; $r_{\epsilon 1}$ and $r_{\epsilon 2}$ – radii of wiper curvature; r_{bo} – radius of smoothing part; Rz – valley-to-peak height

In the second stage of investigation, the profiles produced in hard turning operations by standard and wiper ceramic inserts were compared. The standard geometry (Fig. 3a) is simple but the wiper geometry (Fig. 3b) is more sophisticated because it is composed of a few arcs of different radii to obtain the final smoothing effect. Roughly, when the same federate is used, cutting tool insert with wiper geometry generates two times lower surface roughness Ra (Fig. 3b) in comparison to the standard-shaped insert. On the contrary, turning with wiper insert with two times higher federate allows the surface roughness to be equal to this produced after turning with the standard insert. This feature allows to increase substantially the productivity, but according to machine shop practice the wiper inserts require stiffer lathes than conventional machine tools [12].

All tools and workpiece materials along with machining conditions employed are given in Table 1.

Table 1. Cutting parameters employed and tools and inserts used in investigations

Material	Cutting speed, m/min	Feed rate f , mm/rev	Depth of cut, mm	Tool holder	Insert type	Tool geometry
C45 steel	130	0.1	1.5	TGNR 2020-16	TNMG 160408-12	$\kappa_r=90^\circ, \alpha_o=5^\circ, \gamma_o=-5^\circ, \lambda_s=-6^\circ$
Ductile iron EN-GJS 500-7	270	0.1	2	TGNR 2020-16	TNMA 160408	
Hardened 41Cr4 steel	100	0.1 0.2	0.2	CSRNR 2525M 12-IC WIPER	SNGN 120408 T01020 WIPER	

3. Investigation methodology

The registration of surface profiles and measurement of surface roughness parameters were performed by means of Hommel Tester T-1000E profilometer with the assistance of a special PC software called *Autopomiar* [13]. The sample length and measurement length were set to 0.8 mm to 4.8 mm respectively. For every sample, 12 individual measurements were carried out and based on these data, the mean values of roughness parameters were calculated. Surface roughness was analyzed using horizontal and vertical roughness parameters as well as fractal dimension and continuous wavelet transform. The mean values of measured roughness parameters are listed in Tab. 2.

Table 2. Values of surface roughness parameters for feed rate of 0.1 mm/ref for standard (S) and $f = 0.2$ mm/rev for wiper (W) inserts

Roughness parameter	Material grade			
	C45(S)	41Cr4(S)	41Cr4(W)	EN-GJS500-7(S)
Ra	1.07	1.16	0.56	0.86
Rz	5.27	2.26	2.51	6.25
Rsm	90.59	98.13	214.40	136.09
RΔq	11.8	7.34	2.47	9.13
Rku	2.53	2.47	2.48	4.03
Rsk	0.89	1.25	1.44	-0.18

As mentioned in Section 1, CWT was calculated by means of both „mexican hat” and Morlet’s analyzing wavelets. Values of CWT coefficients were presented in the profile length–wavelet scale coordinate system. With the use of CWT, two profile features were analyzed, namely the extreme and frequency distribution along the profile length. All calculations were performed using *Scilab* software.

4. Computation results

4.1. Roughness profiles

In general, roughness profiles obtained after turning of selected workpiece materials contain periodically distributed micro-irregularities, except those produced by turning on the pieces made of nodular cast iron (Fig 4b). In all following cases, the mean spacing between roughness elements characterized by the Rsm parameter is close to the feed rate value used (it ranges from 90.59 μm to 98.13 μm depending on steel grade for standard geometry and up to 214.4 μm for wiper geometry). After turning of nodular cast iron with small feed rates,

Rsm values were significantly greater ($R_{sm} = 136.09 \mu\text{m}$). These higher values can be explained by specific profile shapes, which were irregular and contained significant amount of low frequency waves. On the other hand, the Rsm calculation method, which counts the mean value of the distance between crossing points of reference horizontal line and profile (in this case the reference line was assumed to be at height $c = 0$) leads to achieving these values.

The acquired roughness profiles produced by the standard cutting inserts also differ in the height of local peaks. The highest value of Rz parameter, which is good estimation of the heights of local profile peaks, was the greatest after turning of the nodular cast iron ($R_z = 6.25 \mu\text{m}$) and, in turn, the lowest value of $R_z = 2.26 \mu\text{m}$ was obtained after hard turning. Turning with wiper geometry generates a little bit higher Rz values of about 10% and not the same values in comparison to machining with standard insert. It could be due to the fact that the cutting was performed with two times higher feed rate and obviously the cutting forces were greater than in machining with standard inserts. This situation leads to increasing the cutting tool displacements relative to workpiece during machining [14]. One of the symptoms of this phenomenon is the vertical relative displacement of cutting edge traces, which are well visible in Fig. 4d.

The cutting edge traces within the appropriate surface profiles are well recognizable in both cases of hard turning (details 1 and 2 in Fig. 4c). Particularly, after machining of C45 steel, the traces resulting from the cutting edge shape could not be found due to large amount of disturbances caused by plastic deformation. For the cutting insert with nose radius of $r_\epsilon = 0.8 \text{ mm}$ and for the feed rate of $f = 0.1 \text{ mm/rev}$ the machining produces the lowest roughness height of all feed rates applied. This phenomenon, originating from the side flow of plastically deformed chip, was characterized by Brammertz and in Ref. [15] the author pointed out that in the surface profiles produced on C45 steel workpieces with feed rates lower than $f = 0.1 \text{ mm/rev}$ cutting edge traces were not distinguished.

In this investigation, the profiles of turned surfaces on nodular cast iron pieces were highly disturbed. The nodular cast iron is, in general, brittle material due to its specific structure containing graphite particles even of $16 \mu\text{m}$ in size. During cutting, the tool partially pulls out small fragments of workpiece material. This phenomena contributes to the generation of roughness profiles with unrecognizable cutting edge traces leading to highly disturbed and stochastically distributed peaks, which can be easy seen in Fig. 4d.

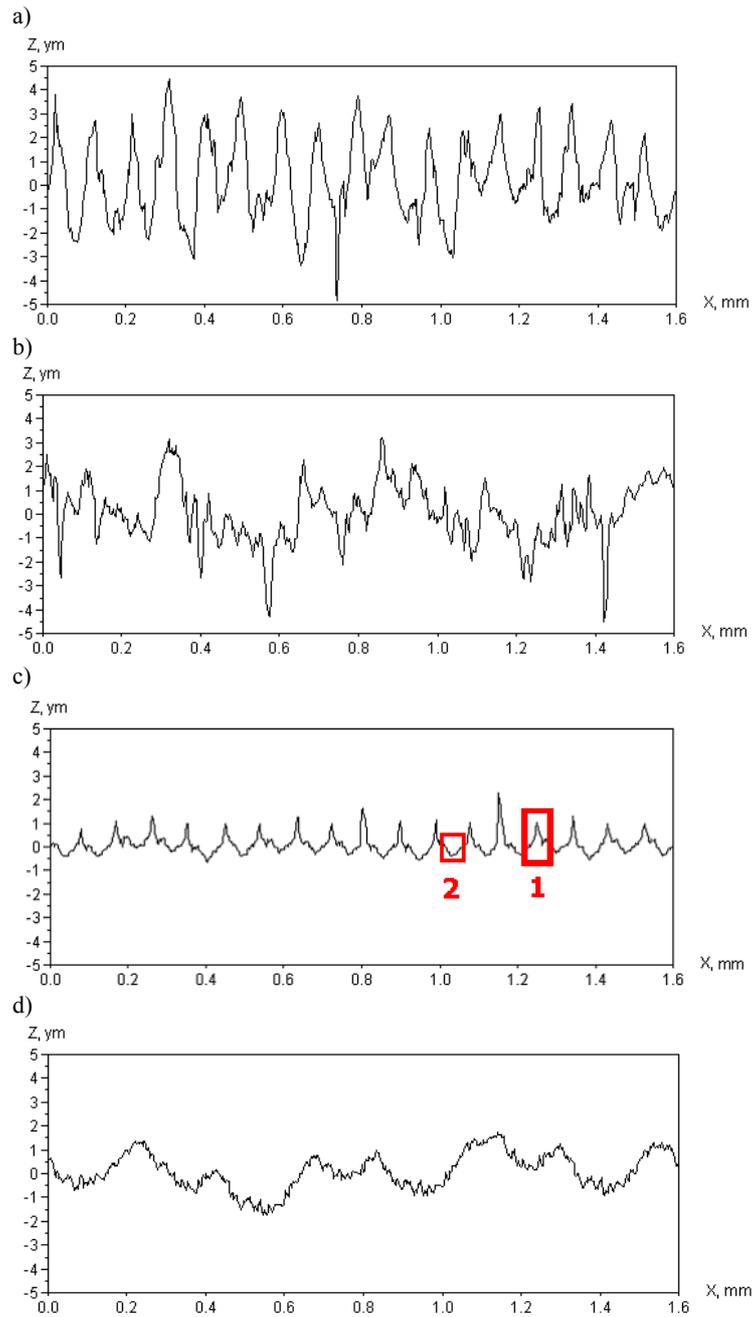


Fig. 4. Examples of roughness profiles obtained after turning of: C45 steel (a), nodular cast iron (b) hardened 41Cr4 steel with standard (c) and wiper (d) insert

4.2. CWT using “mexican hat” wavelet

The CWT performed with “Mexican hat” analyzing wavelet allows the distribution of profile extrema to be assessed along the defined profile length. The position of local extrema relative to the scale axis depends on wavelet lengths, which are a part of the profile. Extrema with short length waves can be found on upper scales and those with long length waves on lower scales.

It can be concluded based on Fig. 5 that the roughness profile after turning consists of many waves with different amplitudes. Well recognizable are dominant, regularly distributed extrema which were determined as the components of the tool marks (window in Fig. 5a). They can be easily recognized in Fig. 5c at scale of 0.1 mm. On the other hand, other small maxima appear irregularly at scale lower than 0.1 mm (or lower than feed rate) and their values are different for every tool mark (Figs. 5a and windows in Figs. 5c and 5d).

Apart from profiles produced by turning of nodular cast iron, the maximums of wavelet coefficient appear on the scale close to the feed rate with which the analyzed surface was created. This is: scale = 0.1 mm for profiles after cutting of C45 and hardened 41Cr4 steels (Fig. 5a and 5c) and scale = 0.2 mm for hard turning with wiper insert (Fig. 5d). In all afore-mentioned cases, the localizations of maximums of wavelet coefficients are relatively shifted along scale axis and also the areas of maxima are not equally wide along the profile length (see window in Fig. 5a). If vertical shift of maximums is present at the scale corresponding to the feed rate, this fact implicates relative vertical displacements of the cutting edge traces. On scales lower than feed rate used, the profile disturbances can be detected, especially these ones which appear in the area of individual cutting edge trace (see windows in Figs. 5c and 5d), which was previously discussed in [10].

4.3 CWT using Morlet wavelet

The CWT performed by means of Morlet analyzing wavelet allows the amplitude and frequency distribution along the profile length to be determined.

Apart from profiles generated during turning of nodular cast iron, main wavy ribbons of maximum coefficient values are visible in Fig. 6. Relevant values of wavelet coefficients are the highest in the whole CWT matrix. Their local maximums can be selected in regions belonging to the above-mentioned ribbons where the scale is equal to feed rate (line inside band *A* denoted by *f* in Fig. 6c). For defined length of the profile, changes of the highest CWT coefficient values in the band are very distinct, and they correspond to changes of the local profile amplitude.

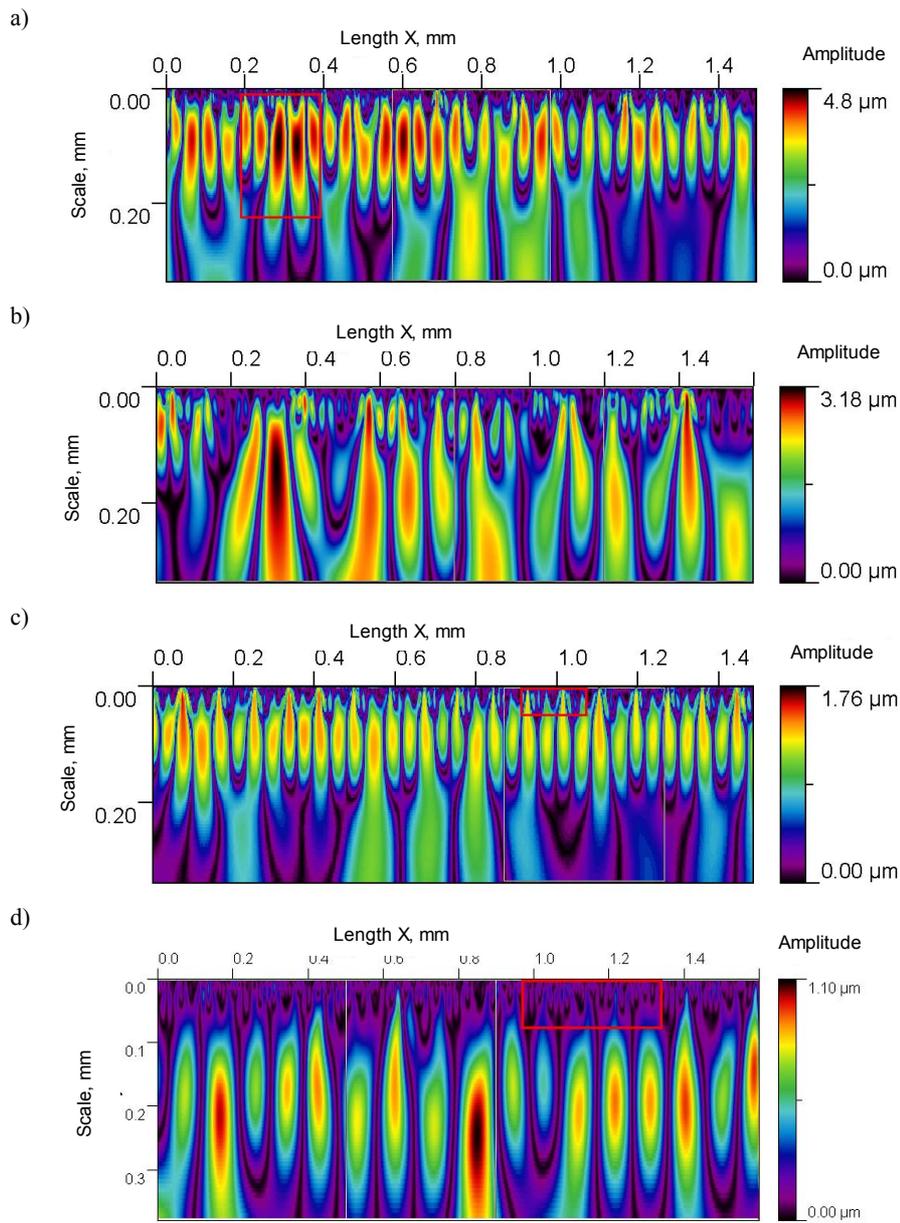


Fig. 5. CWT using "Mexican hat" wavelet obtained for profiles after turning of C45 steel (a), nodular cast iron (b) hardened 41Cr4 steel with standard (c) and wiper (d) inserts

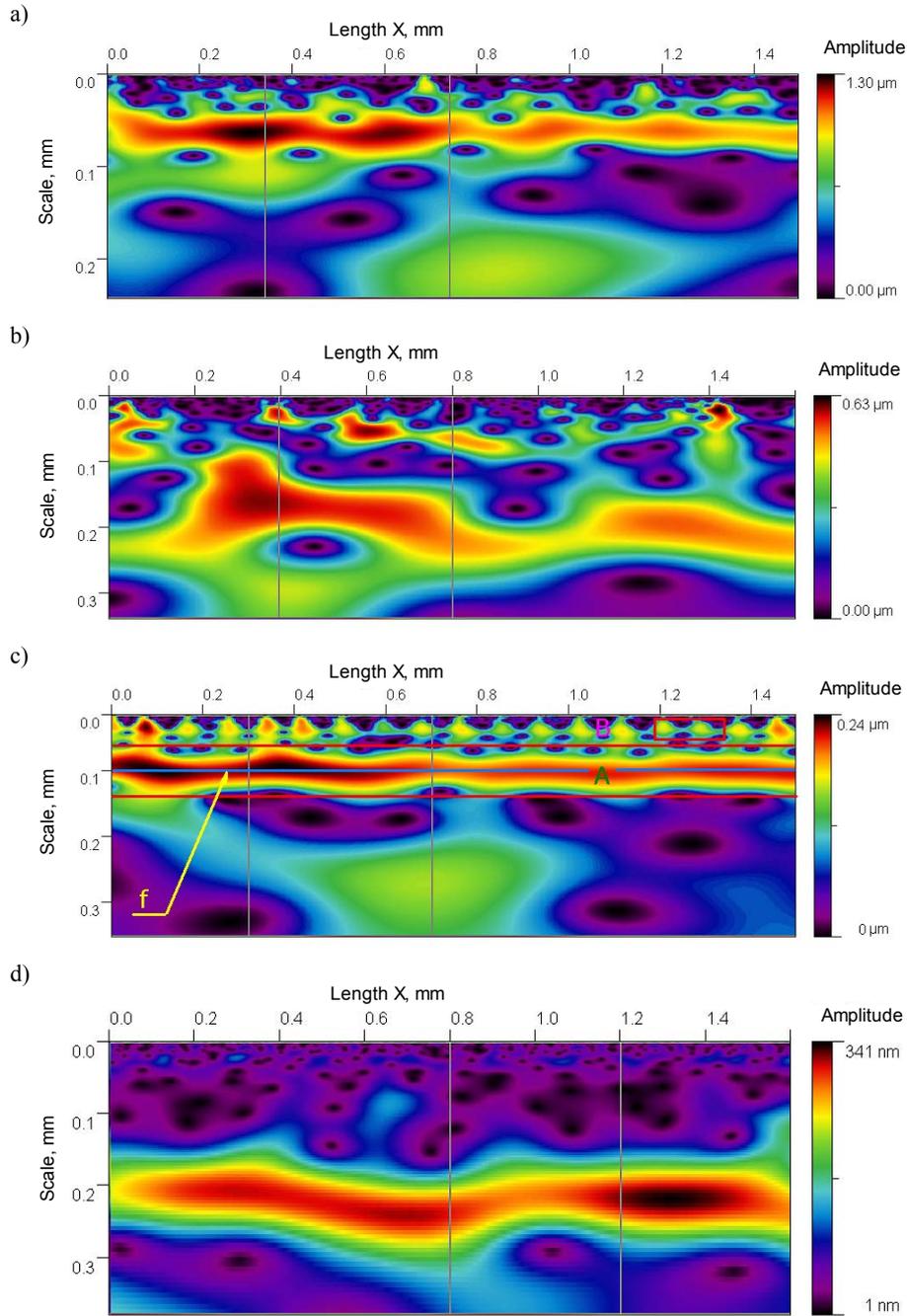


Fig. 6. CWT using Morlet wavelet obtained for profiles after turning of C45 steel (a), nodular cast iron (b) hardened 41Cr4 steel with standard (c) and wiper (d) insert

The scale in which a maximum in the dominant band (for example band A in Fig. 6c) appear varies within the profile length. It allows to conclude, that roughness spacing corresponding to tool marks is not constant along the whole profile length and varies from 0.075 to 0.11 mm for turning of C45 steel and also for hard turning with standard insert (Fig. 6a and band A in Fig. 6c). In contrast, for wiper tools it changes from 0.16 to 0.28 mm (Fig. 6d).

At the scale ranging from 0.02 to 0.04 mm (band B) for standard insert (Figs. 6a and 6c) and at the scale from 0.01 to 0.12 mm for wiper insert (Fig. 6d), aperiodically appeared maxima remain after hard turning. Their values are of one fourth of those present in the dominant ribbon (additional small window in Fig. 6a corresponding to detail 1 in Fig. 4c). They can be associated with wavelets observed in the tool marks, caused probably by copying of the micro-irregularities remaining on the cutting edge.

5. Conclusions

CWT using „Mexican hat” wavelet gives information about the distribution of profile extrema and their values but does not allow the wavelength to be precisely evaluated. On the other hand, CWT using Morlet wavelet allows the length of profile constituent wavelets to be evaluated but the information about their amplitudes is not precise. In order to aggregate information about amplitudes and lengths of profile constituent’s distribution, analysis of at least two CWT by means of different wavelets is necessary.

For profiles after turning, CWT-Morlet allows finding and evaluating the intensity of disturbances occurring in cutting edge trace and also to extract changes of the main line peak spacing in the entire profile length.

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