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SEBASTIAN BROL [*], *WIT GRZESIK* [**]

APPLICATION OF CONTINUOUS WAVELET TRANSFORM FOR ASSESSMENT OF SURFACE ROUGHNESS PROFILE AFTER MACHINING OF HARDENED AISI 52100 STEEL

In this paper, the authors present surface roughness profile assessment using continuous wavelet transform (CWT). Roughness profiles after turning and rough and finish belt grinding of hardened (62HRC) AISI 52100 steel are analyzed. Both Morlet and “Mexican hat” analyzing wavelets are used for the assessment of extrema and frequency distribution. 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 and abrasive machining processes.

1. Introduction

Nowadays, apart from classic roughness parameters, surface roughness profiles are analyzed by means of spectral analysis based on discrete Fourier transform. Especially, the power spectral density (PSD) and short time Fourier transform (STFT) are used. Their most common flaw is that they are well applicable only to stationary signals. Unfortunately, the roughness profiles in many cases are nonstationary. Specifically, the investigations show that profiles after machining can be partially nonstationary or nonstationary [5], [9], [10]. This situation leads to the conclusion that other tools must be used for proper analysis of nonstationary profiles.

One of these tools is continuous wavelet transform (CWT) [1], [2], [3]. The transformation is based on a scheme where the analyzing wavelet is scaled and shifted along the analyzed signal according to equation (1). The scaling and shifting result is scalar product of wavelet and signal.

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[*] *ul. Mikołajczyka 5, 45-271 Opole, Poland; E-mail: sbrol@po.opole.pl*

[**] *ul. Mikołajczyka 5, 45-271 Opole, Poland; E-mail: w.grzesik@po.opole.pl*

$$CTF_f(\tau, s) = \langle f(t), \psi_{\tau,s}(t) \rangle = \frac{1}{\left|\sqrt{s}\right|} \int_{-\infty}^{\infty} f(t)\psi\left(\frac{t-\tau}{s}\right)dt \qquad (1)$$

where:
$\psi(t)$ – analyzing wavelet,
s – scale,
τ – time,
s and τ – are domain of wavelet transform.

The result of one dimensional wavelet transform is a half-plane arranged in time-scale coordinates. The s variable is equal to the scale of analyzing wavelet on every step of transform calculation and its reciprocal is equal to frequency [1], [2], [3].

The analyzed wavelet must match some criteria. It should have finite energy and mean value equal to zero. These requirements make the wavelet form short duration dumped oscillation. Currently, many wavelets are used, such as Meyer's, Morlet's, Daubechie's, Haar's or "Mexican hat" [13]. Signal feature, which should be determined by (CWT), depends on the analyzing wavelet used [7], [8]. Mexican hat wavelet is suitable for extrema, and Morlet's for frequency distribution analysis [11].

2. Investigation conditions and methodology

The main goal of the investigation was to achieve the lowest roughness after hard turning and belt grinding. All machining processes used in research are shown in Table 1.

Table 1.

Parameters, tools and machines used for surface roughness generation

	Turning (T)	Rough belt grinding (BG30)	Finish belt grinding (BG9)
Parameters	Feed rate f=0.1 mm/rev, Depth of cut a_p=0.3 mm, Cutting speed v_c =100 m/min.	Specimen rot. speed n = 900 rev/min, Belt feed f = 0.3 mm/s, Belt oscilation frq. f_t = 12 Hz, Belt oscilation amplitude A_t = 0.5 mm, Machining time t_o = 9 s. Cooling – MQL	
Tool	TNGA 160408 S01020-7020	Grain 30 µm, Al_2O_3	Grain 9 µm, Al_2O_3
Machine	PRECIMAB SP	ENISE Saint Etienne	
Number of samples	3	3	3

Hard turning and belt grinding was done in ENISE in Saint Etienne in France, and roughness measurements at Opole University of Technology in the Department of Manufacturing Engineering and Production Automation [6].

Roughness measurement was performed by means of Hommel Tester T-1000E profilometer and *Autopomiar* PC software [4]. The sample length was set to 0.8 mm and measurement length to 4.8 mm. For every sample 12 measurements were done. The mean values of roughness parameters were calculated and distribution deviations using Students t statistics with probability $\alpha = 0.05$.

Surface roughness was analyzed using selected vertical, horizontal and hybrid parameters (Table 2). One additional parameter Rλq (root mean square wavelength of roughness profile) outside PN-EN-ISO 4287 standard was used for comparison with RSm parameter.

Table 2.

Parameters and analyzing wavelets used for surface roughness profile analysis.

Roughness parameters			CWT	
Vertical	Horizontal	Hybrid		
Ra, Rq, Rz	RSm, Rλq*	RΔq	Morlet	“Mexican hat”

* Roughness parameter which is not selected in PN-EN-ISO 4287.

As the next step, CWT was calculated by means of both “Mexican hat” and Morlet’s analyzing wavelets. Values of CWT coefficients were shown in profile length – wavelet scale coordinate system. Calculations were made with Scilab software.

3. Investigation results

Mean values of selected roughness parameters are shown in Table 3. Mean values and confidence intervals of vertical and hybrid parameters values are decreasing with every step of technological process, but the horizontal parameters change their values in a different way. Surprisingly, the lowest values were received after rough belt grinding.

Table 3.

Mean values of selected roughness parameters

Machining	Roughness parameters				
	Ra [μm]	Rz [μm]	RSm [μm]	Rλq [μm]	RΔq [°]
T	0.27 ±0.022	1.99 ±0.16	79.91 ±6.08	32.42 ±2.92	4.81 ±0.64
BG-30	0.13 ±0.010	1.24 ±0.10	**29.29 ±1.85**	**18.42 ±0.96**	3.91 ±0.28
BG-9	0.05 ±0.008	0.46 ±0.05	48.53 ±9.13	25.22 ±2.89	1.42 ±0.04

In the same way, values of confidence intervals change. This rule is not maintained for the changes of values of horizontal roughness parameters. The lowest mean values of RSm and Rλq parameters and appropriate confidence intervals were obtained after rough belt grinding. The lowest mean values of horizontal roughness parameters after rough belt grinding differ from the expected ones. Rough belt grinding with abrasive grain diameter ca. 9 μm should form surface with lower spacing than these after grinding with grain diameter of 30 μm.

One could put forward a thesis that mean values of these parameters depend on wavelengths and amplitude distribution in profiles.

In Figure 2a, CWT – "Mexican hat" is shown. Based on it, a scale dependent extrema distribution of analyzed roughness profile (Fig 1a det. 1 and 2) can be determined. Local extrema position relative to scale axis depends on wavelet lengths, which are a part of the profile. Short-length waves' extrema can be found on high scales (Fig. 1b, det. 5) and long length on low scales (Fig. 1b, det 3).

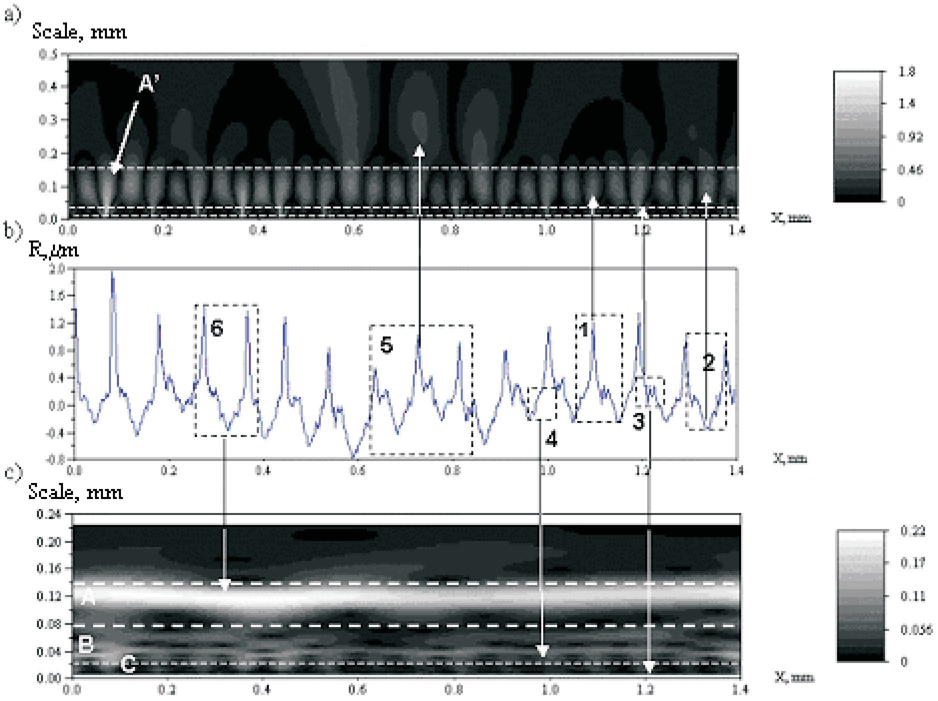

Fig. 1. Surface roughness profile after hard turning and its continuous wavelets transforms: CWT-with use of "Mexican hat" wavelet a), roughness profile b), CWT-with the use of Morlet wavelet

Based on CWT in Figure 1a, one can conclude that the roughness profile after turning consists of many waves with different amplitudes. Well recognizable are extrema related to cutter marks (Fig. 1b, det 1 and 2) and those existing in cutter mark area (Fig. 1b, det. 3). First ones appear frequently and their values change slightly, and the others appear irregularly in scale from 0.005 to 0.05 mm and their values are different for every cutter mark.

In matrix CWT, obtained by Morlet wavelet shown in Fig. 1c, three bands can be distinguished.

- band A from scale ranging from 0.08 to 0.13 mm,
- band B from scale ranging from 0.02 to 0.08 mm,
- band C from scale ranging from 0.007 to 0.02 mm.

In band A, wavy ribbon is visible, and its parameter values are the highest in the whole CWT matrix. Its maximum occurs approximately for scale equal to 0.1 mm, which is adequate to feed rate of f=0.1 mm/rev, with which surface was formed.

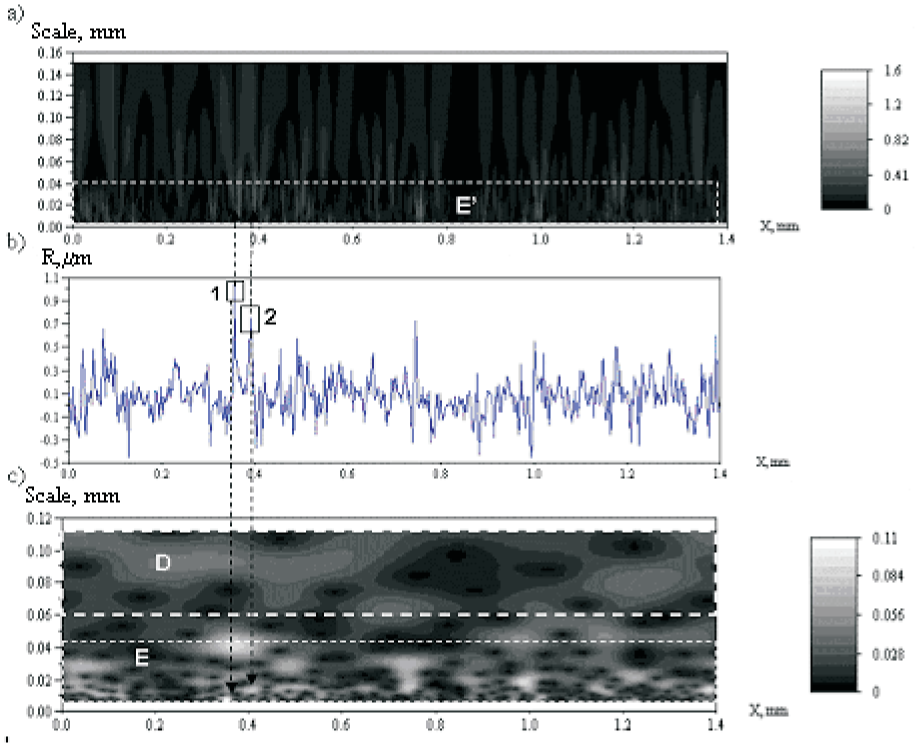

Fig. 2. Surface roughness profile after rough belt grinding and its continuous wavelets transforms: CWT-with use of "Mexican hat" wavelet a), roughness profile b), CWT-with use of Morlet wavelet

For specified length of profile X, changes of the highest CWT coefficient values in the band are very distinct, they correspond to the changes of local profile amplitude.

The scale, in which there is a maximum in band A, varies in profile length. It allows us to conclude that roughness spacing corresponding to cutter marks along the whole profile length is not constant and varies from 0.08 to 0.095 mm. Comparing figure 1a and 1c, one can say that changes of the highest values in a band (Fig. 2c band A) change according to values of maximums CWT – "Mexican hat" (Fig. 1c band A') for scale equal to 0.1 mm (Fig. 1c, detail 6).

As shown in Fig. 3c, the highest values of CWT – Morlet coefficients appear in the band from scale equal to 0.012 to 0.04 mm (Fig. 2c, band E), which occur irregularly along whole profile length. It is also confirmed by CWT matrix with the use of wavelet "Mexican hat". In this case, the highest amplitude extremum can be observed (Fig. 2a, band E').

In the band from 0.06 to 0.12 mm (Fig. 2c, band D), there are irregular bands dividing and uniting according to profile length, which can be the effect of permanent growth and reduction of wavelets length in the profile. The highest values of CWT coefficients in band D concentrate in the vicinity of scale equal to 0.06 mm.

In band B, a wavy ribbon is visible, too. It corresponds to irregularity shown in Fig. 2b, detail 4. In band C, under the scale 0.02 mm, an increase of CWT values associated to grain marks is visible, and these marks correspond to wavelets' marks in Fig. 2b, detail 2. After rough belt grinding, the profiles obtained are characterized by roughness height (Ra = 0.13 μm, Rz = 1.24 μm) about two times lower and more thickly spaced and sharper local roughness (Fig. 2b) than in profiles obtained after turning.

Another characteristic of these profiles is also the appearance of local, sharp peaks, about two times higher than the rest of the peaks. There is an adequate distinct increase of coefficient values in both CWT (Fig. 2b, details 1 and 2).

After finishing belt grinding, surfaces of about two times lower roughness height (Table 3) relative to pretreatment (Fig. 3b) were obtained. As shown in Fig. 3a, the biggest part of the profile takes waves shorter than 0.07 mm (Fig. 3c, band F), they occur along the whole profile length in the same way as in pretreatment (Fig. 2c). It is confirmed by transformation by means of "Mexican hat" wavelet. In this case, minima and maxima of CWT coefficients – "Mexican hat" (Fig. 3a, band F') in the same band can also be observed.

Comparing pretreatment and finishing belt grinding, one could emphasize the fact that after pretreatment the band obtained was narrower with the highest values of coefficients for shorter wave lengths (from 0.002 to 0.04 mm) than after finishing (from 0.002 to 0.07 mm).

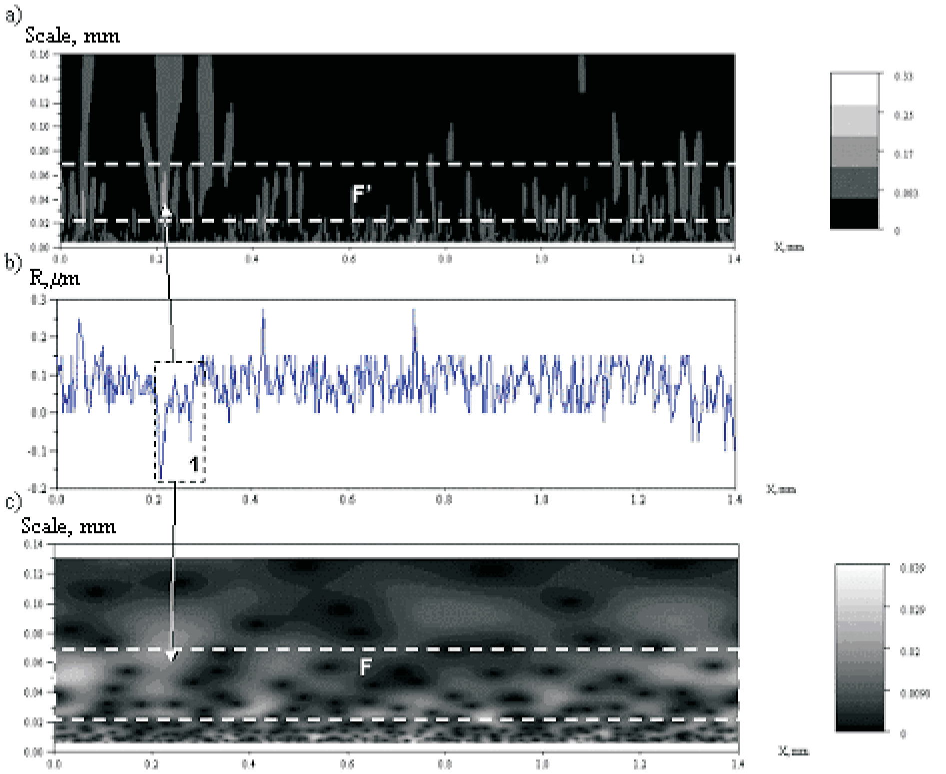

Fig. 3. Surface roughness profile after finish belt grinding and its continuous wavelets transforms: CWT-with use of “Mexican hat” wavelet a), roughness profile b), CWT-with use of Morlet wavelet

However, relative amplitude distribution for scales from 0.01 to 0.03 mm in both cases are similar, and it allows us to claim that belt grinding with abrasive grain diameter ca. 9 µm smoothed roughness formed earlier but did not remove it completely.

4. Conclusions

1. CWT using basic wavelet “Mexican hat” gives information about profile extrema distribution and values but does not allow precise evaluation of proper wave length.
2. CWT using basic Morlet wavelet allows evaluation of the length of profile constituent wavelets but information about their amplitudes is not precise.
3. On the basis of points 1. and 2. we can state that for receiving the most complete information about amplitudes and lengths of profile constituents

distribution the analysis of at least two CWT by means of different wavelets is necessary.

4. CWT using Morlet wavelet, in the case of profiles after turning, allows finding and evaluating disturbance intensity in cutting edge trace area and also to represent changes of main roughness spacing occurring on whole profile length.

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Zastosowanie ciągłej transformacji falkowej do oceny profili powierzchni po obróbce utwardzonej stali AISI 52100

Streszczenie

W artykule autorzy przedstawili sposób oceny profili chropowatości powierzchni z wykorzystaniem ciągłego przekształcenia falkowego (CPF). Przedmiotem analizy falkowej były profile po toczeniu na twardo oraz wstępnym i wykańczającym szlifowaniu taśmowym stali AISI 52100 w stanie utwardzonym. Wykorzystano dwie falki analizujące: „Meksykański kapelusz" i falkę Morleta do oceny odpowiednio: rozkładu ekstremów oraz częstotliwości i amplitudy falek składowych. Wyniki przekształcenia falkowego przedstawiono w funkcji długości profilu i chwilowej długości falki analizującej. Stwierdzono, że CPF może być wykorzystywane do analizy profili chropowatości powierzchni zarówno po obróbce ostrzem o określonej geometrii, jak i po obróbce ściernej.