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INTEGRAL FFT ANALYSIS OF SIGNALS OF FORCES AND SURFACE PROFILES GENERATED IN CBN PRECISION HARD TURNING

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Summary

The paper presents an original approach to the prediction of deteriorations of the surface profiles produced on hardened steel parts using CBN tools. The experimental investigations involve recording of surface profiles and corresponding measurements of cutting forces resulting from variable feed rates of 0,05-0,1 mm/rev. As a result, machined surfaces with the Ra parameter ranging from 0,05 μm to 0,3 μm were produced. Both signals of recorded surface profiles and relevant cutting forces were processed using the FFT signal processing technique. The frequency characteristics including the signal amplitude and the wavelength were estimated from the power spectral density (PSD) spectra. A methodology for the prediction of surface profile deterioration based on the relation between the differences of the Rz (Ra) roughness parameter and signal amplitude is proposed.

Keywords: CBN precision hard turning, frequency characteristics, surface profile deterioration

Zintegrowana analiza FFT sygnałów sił skrawania i profili chropowatości powierzchni generowanych w precyzyjnym toczeniu ostrzami z CBN

Streszczenie

Artykuł przedstawia oryginalne rozwiązanie w przewidywaniu zniekształcenia profili powierzchni wytwarzanych elementów maszyn ze stali utwardzonej z użyciem narzędzi skrawających z PCBN. Badania doświadczalne obejmują pomiary profili powierzchni i określenia wartości składowych sił skrawania dla zmiany posuwu w zakresie 0,05-0,1 mm/obr. Powierzchnie po obróbce cechuje parametr chropowatości Ra od 0,05 µm do 0,3 µm. Zarówno sygnały zapisywanych profili powierzchni jak również i mierzonych składowych sił skrawania przetwarzano z użyciem techniki FFT. Także charakterystyki częstotliwościowe amplituda sygnału i długość fali były wyznaczane na podstawie gęstości widmowej mocy (GWM). Zaproponowano metodologię przewidywania zniekształcenia profili powierzchni uwzględniającą korelację zmiany parametru chropowatości powierzchni Rz i amplitudy sygnału.

Słowa kluczowe: toczenie precyzyjne, narzędzia skrawające PCBN, charakterystyki częstotliwościowe, zniekształcenie profili powierzchni

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1. Introduction

The prediction of the functional properties of machined parts belongs to the fundamental challenges of manufacturing engineering [1]. In general, the input data to this prediction are generated based on the measurements of 2D and 3D surface roughness produced in cutting and abrasive finishing operations.

The current knowledge on the constitution of surface roughness (SR) in the machining processes with defined cutting edges allows to predict the *Ra* and *Rz* parameters in terms of not only kinematic and geometric factors but also process variables such as plastic deformation in the surface layer, tribological effects from the cutting edge, side flow effect, elastic recovery of the machined surface or even cutting vibration [2-5]. Their quantification and separation from the entire distortion of the real surface profile is very difficult due to very complex physical phenomena involved [4,5]. As a result, the progress in the investigation of machined surfaces and surface topographies is still not satisfactory [3,5,6]. Typically, the distortions of SR profiles are quantified in relation to the theoretical surface profiles using well-known kinematical-geometrical models [1].

In general, the finishing operations are performed on the heat treated/hardened elements at low or very low feed rates (10-100 µm/rev) and also low depths of cut (0.05-0.15 mm) using superhard cutting tools (for instance CBN tools) [3]. For such extreme cutting conditions the deterioration of the machined surface is relatively high and predominant effects include side flow effect, elastic recovery (springback effect) and vertical and horizontal displacements of the surface profile peaks, which can also be related to cutting vibration.

In this research work, concurrent frequency analysis of the surface profile and corresponding three force components (F_c, F_f and F_p) is carried out based on the Fast Fourier Transform (FFT) technique. Based on the data obtained the signal amplitudes and associated wavelengths are compared [7]. In addition, the functional relations between the amplitudes of the surface profile and three force signals are derived. Based on the comparison of the theoretical and real surface profiles, the amount of the profile distortion resulting from the excessive profile peaks is determined using special computation algorithm.

2. Selection of machining conditions in the experimental program

The experimental program includes four series of precision hard turning (PHT) tests with variable feed rate. Cylindrical workpieces made of 41Cr4 alloy steel of about 55 HRC hardness was machined at defined cutting conditions. The turning tests were carried out on a CNC lathe Okuma Genos L200 using CBN cutting tools keeping constant cutting speed of 150 m/min, four feed rates of 0.025, 0.05, 0.075 and 0.1 mm/rev (with the constant increment of Δf = 0.025 mm/rev) in order to produce surfaces with the roughness parameter *Ra* in the range of 0.05-0.3 µm (equivalently the *Rz* parameter of 0.2-1.3 µm). The depth of cut was kept not higher than 0.15 mm but for lowest feeds it was decreased to 0.05/0.03 mm. The selected cutting parameters are typical for PHT [1, 8].

3. Measurements of cutting forces and surface roughness

In the first stage of the experimental study three components of the resultant cutting force (F_c, F_f and F_p) were measured using Kistler 9129A piezoelectric dynamometer and 5070A amplifier. After each machining test, surface profiles were recorded on the machined surfaces and surface roughness (*SR*) parameters were determined using a 2D portable profilometer Mahr profilometer. Both the recorded force spectra (Fig. 1) and the selected surface profiles (Fig. 4) were subsequently analyzed using a FFT technique (appropriately the FFT modules available in Matlab and Mountains Map packages).

Figure 1 shows the spectra of the three forces recorded for the lowest and medium feed rates of 0.025 mm/rev and 0.1 mm/rev respectively. All obtained data are specified in Table 1. It was confirmed in Fig. 1 that in hard turning operations the highest force is the passive (thrust) component F_p with the broadest dynamic spectrum. This mechanical evidence suggests that the strong elastic interaction between the cutting edge and the machined surface occurs leading to the springback effect, material squeezing and causing cutting vibration.

Table 1. Measured and computed values of cutting characteristics

F mm/rev	$F_c(Fz)$ N	$F_p(Fy)$ N	$F_f(Fx)$ N	e_c J/m^3	e_p J/m^3	k_c MPa	h_m µm
0.025	16.07	32.41	2.53	21.43	43.21	21426.7	3.4
0.05	26.40	57.36	10.13	10.56	22.94	10560	6.2
0.075	76.79	122.92	35.55	6.83	10.93	6825.8	8.8
0.1	94.36	146.32	41.40	6.29	9.75	6290.7	18.1

Moreover, the energetic characteristics and the relationship between the specific cutting energy (SCE) and the average uncut chip thickness (UCT) are shown in Fig. 2 and 3 respectively. The values of e_c, k_c and e_p are determined based on formulas given in Refs. [1, 8]. As shown in Fig. 2 the specific ploughing energy e_p overestimated the specific cutting energy e_c and this fact is more pronounced for lower feed rates (in particular for $f = 0.025$ mm/rev the ratio e_p/e_c is about 2 but for the highest feed rate of 0.1 mm/rev it decreases down to about 1.5). Correspondingly, the specific cutting pressure (SCP) increases up to 21500 MPa. Otherwise, it decreases down to about 6300 MPa when the feed rate of 0,1 mm/rev is applied. Moreover, it can be observed in Fig. 3 that the localization of PHT in terms of the energy consumption (represented by values of the SCE) corresponds rather with grinding than conventional cutting operations performed for hardened alloy steels.

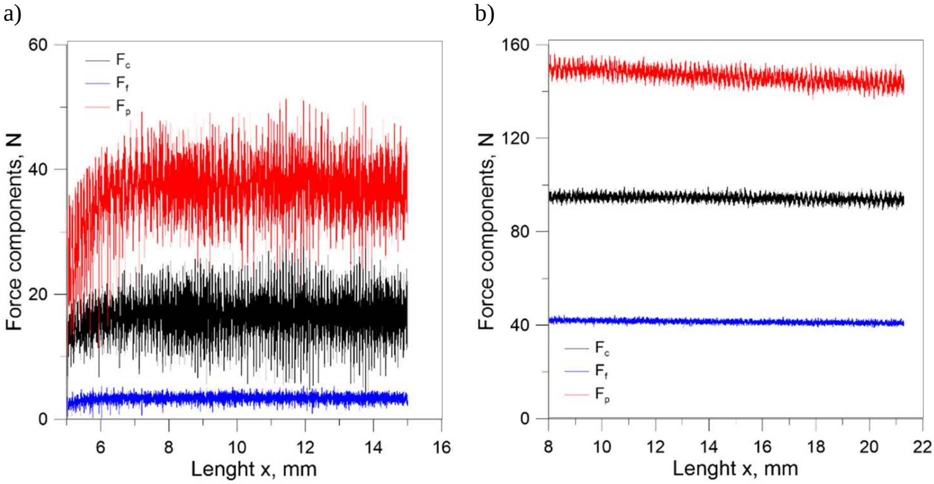


Fig. 1. Exemplary force spectra generated at feed rate of 0.025 (a) and 0.1 mm/rev (b)

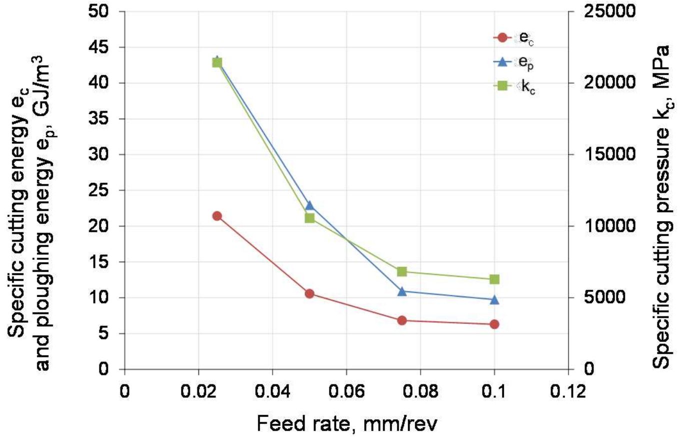


Fig. 2. Energetic relationships in PHT with variable feed rate (v_c = 150 m/min)

Figure 4 presents a set of magnified surface profiles generated at four feed rates of 0.025 (a), 0.05 (b), 0.075 (c) and 0.1 (d) mm/rev showing horizontal and vertical displacements of the profile irregularities. Apart from the surface roughness (*R*) parameters also surface waviness (*W*) parameters were estimated in order to control the dimensional accuracy in precision hard turning. It was revealed that the *Wz* parameter is several times lower than *Rz* parameter for all feed rates applied (*Wz* = 0.03-0.08 µm *vs*. *Rz* = 0.2-1.3 µm). Fig. 4 shows that the distinct distortion of feed marks within surface profiles is observed for the lowest feed rate of 0.025 mm/rev.

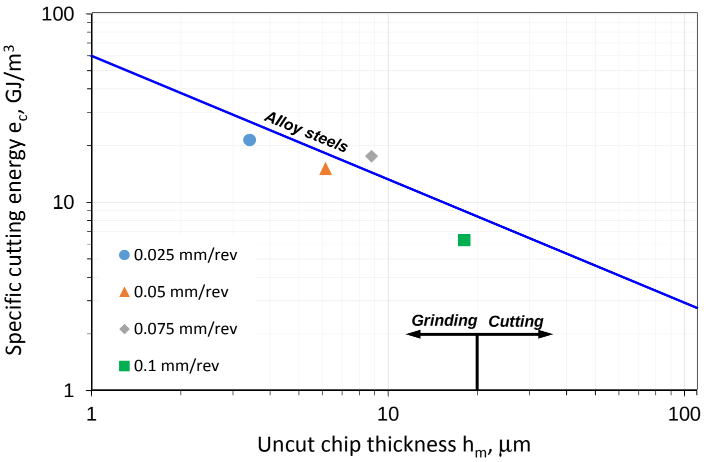
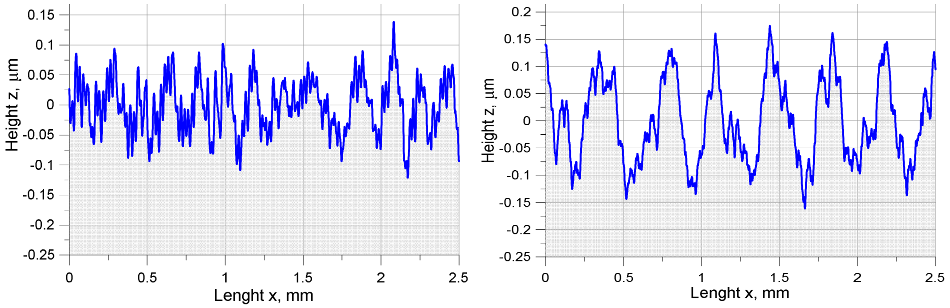


Fig. 3. The envelope SCE vs. UCT for PHT tests with variable feed rate [1, 8]

a) *Rz* = 0,20 µm, *Ra* = 0,04 µm b) *Rz* = 0,32 µm, *Ra* = 0,07 µm



c) *Rz* = 0,95 µm, *Ra* = 0,26 µm d) *Rz* = 1,31 µm, *Ra* = 0,32 µm

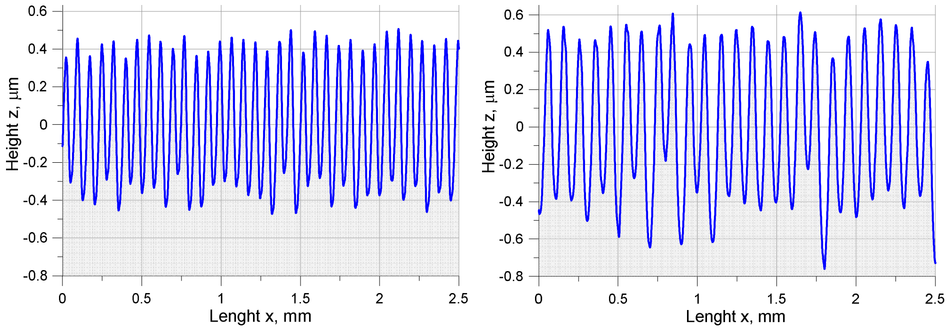


Fig. 4. Characteristic surface profiles recorded for variable feed rate of 0,025 (a), 0,05 (b), 0,075 (c) and 0,1 (d) mm/rev

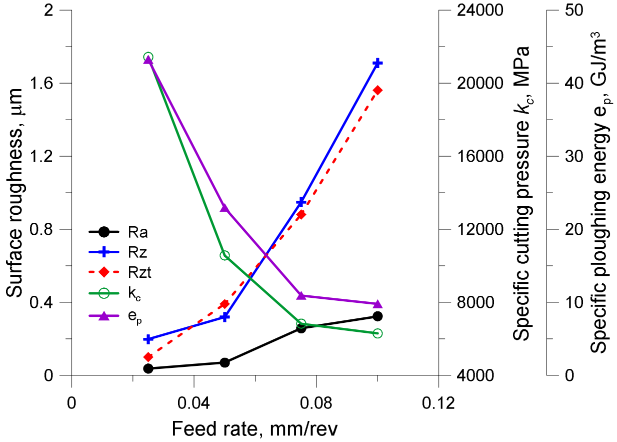
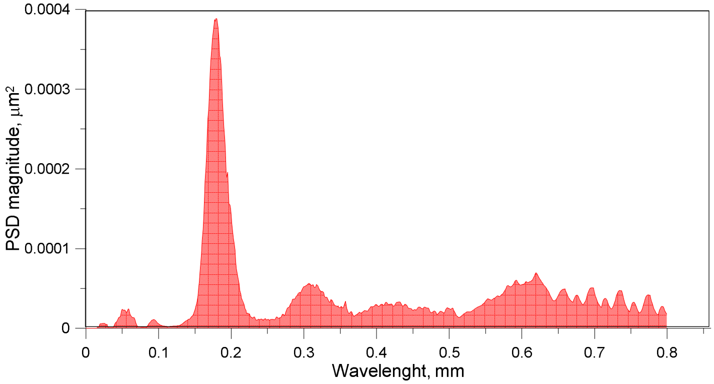


Fig. 5. Relationship between roughness parameters and specific cutting pressure/ploughing energy

a) *f* = 0.025 mm/rev, *Ap* = 0.0197 µm, *WL* = 0.17 mm



b) *f* = 0.05 mm/rev, *Ap* = 0.0473 µm, *WL* = 0.36 mm

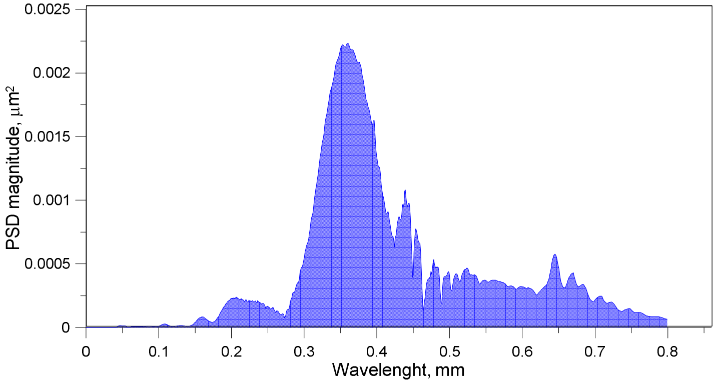
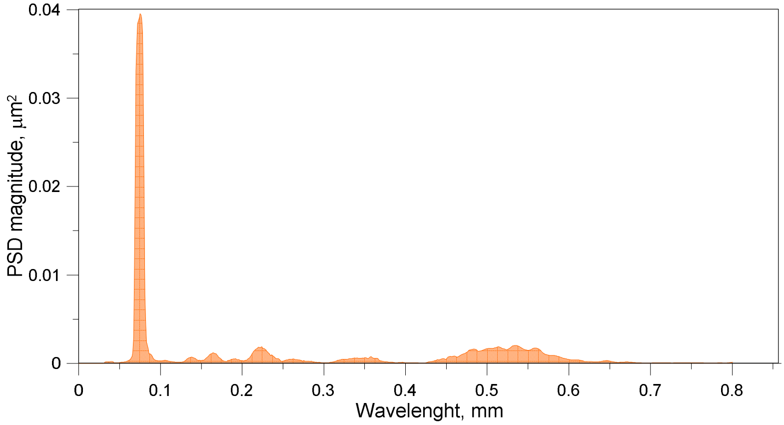


Fig. 6. PSD spectra obtained for surface profiles produced with different feed rates (see surface profiles in Fig. 2) A_f = 449 µm, *WL* = 0.17 mm [9]

c) f = 0.075 mm/rev, Ap = 0.199 μm, WL = 0.075 mm



d) f = 0.1 mm/rev, Ap = 0.315 μm, WL = 0.099 mm

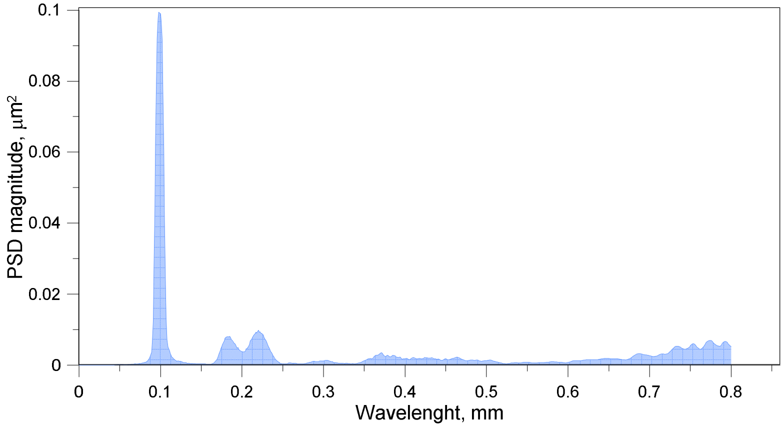


Fig. 6 (continued). PSD spectra obtained for surface profiles produced with different feed rates (see surface profiles in Fig. 2) A_f = 449 μm, WL = 0.17 mm [9]

The influence of feed rate on the *Rz* (*Ra*) roughness parameter and its theoretical value, and the mechanical loads exerted by the cutting edge is shown in Fig. 5. It is evident that in both cases the trends are similar. It can also be noticed in Fig. 5 that the real *Rz* value depends on the contact conditions between the cutting edge and the generated surface. In particular, the effect of side flow causing lateral flashes close to the high irregularities occurs (see Fig. 4b). Otherwise, they consist of more regularly spaced feed marks when the feed rate increases up to 0,1 mm/rev. The correlation between the SCP and the ploughing energy is visibly stronger for the P-V height (*Rz* parameter) than for the *Ra* roughness parameter.

4. Comparison of frequency characteristics for surface profiles and force signals

Figures 6 and 7 show representative frequency spectra for the surface profiles recorded for the selected feed rates (two force records and SR profiles are presented in Figs. 1 and 2 respectively). The digitalized input data were implemented into Mountains Map software in order to perform FFT analysis thoroughly. The amplitude of the predominant peaks (A_f, A_p) and corresponding wavelength (WL) were selected for further analysis [9]. It should be noted in Figs. 6 and 7 that the amplitude of profile peaks A_p in each PSD spectrum is squared.

It can be seen in Fig. 6 that the profile peak amplitude increases when feed rate increases but it is localized in the medium wavelength range for lower feed rates (0,025 and 0,05 mm/rev) and in the shorter wavelength range for higher feed rates (0,075 and 0,1 mm/rev). This fact agrees with the general rule that periodic signals (or profiles) with lager wavelength λ (see for instance Fig. 4d) correspond to spectral lines at the left side of the spectrum.

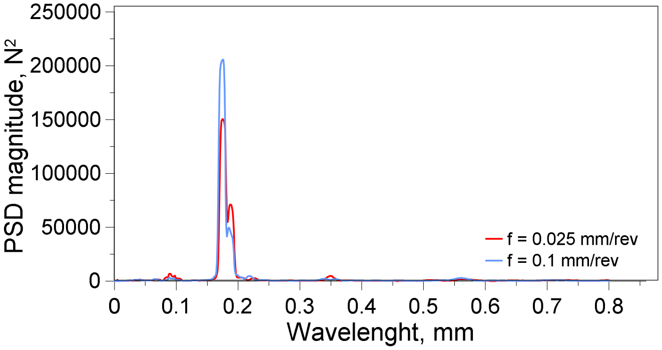


Fig. 7. PSD spectra of Fc force signals obtained for the lowest (f = 0.025 mm/rev) and highest (f = 0.1 mm/rev) feed rates

In the case of force components the frequency amplitudes determined for both cutting F_c (Fig. 7) and feed force F_f change linearly with the increase of feed rate and the amplitude of F_c signal was selected for further analysis [9]. It was documented in Ref. [9] that the functional relations between force and profile amplitudes are linear in the range of feed rates selected in this study. Figure 7 presents two exemplary distributions of spectral amplitudes determined from the force signals recorded for the lowest and highest feed rates respectively.

In order to compare the differences between real and theoretical surface profiles (ΔA_p) in the frequency (PSD) domain all real surface profiles were modified by eliminating sharp peaks above Rz_t value (it was equal to 0.1, 0.39, 0.88 and 1.56 μm) [9].

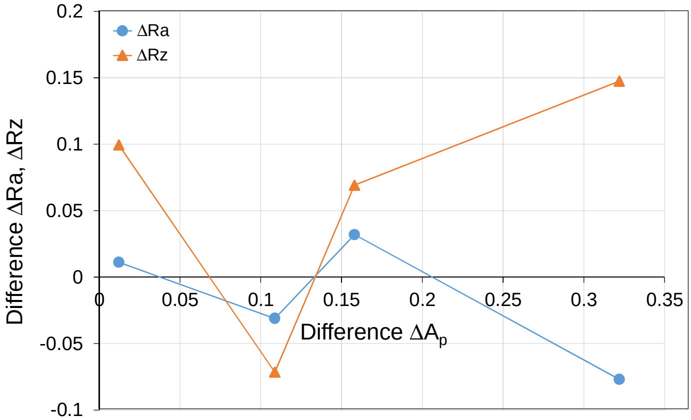


Fig. 8. The relationships between increments of surface roughness and signal amplitude for different feed rates

The effect of this modification resulting in changing the heights of amplitude peaks in the PDS spectrum is presented in Fig. 8. The differences vary from 0 to 0.06 μm depending on the feed rate employed. It can be observed in Fig. 8 that for the feed rate of 0.075 mm/rev the deterioration of the surface profile is marginal and the values of PSD amplitudes are comparable. For the lower feed rates this difference is equal to 0.006 and 0.01 μm which means that surface profile produced at the feed of 0.05 mm/rev is more random (see Fig. 4b). Due to high notches in the surface profiles (see Fig. 4d) the ΔA_p is the maximum one. In contrast, the profile amplitudes determined for the theoretical roughness profiles ($Rz_t = f^2/8r_\varepsilon$, $r_\varepsilon = 0.8$ mm) are distinctly higher especially at higher feed rates.

Summary

This paper presents a new methodology for the determination of the influence of peak displacements on the deterioration of surface profiles generated at variable feed rate using the Power Spectral Density (PSD) magnitude.

It was found out that the relations between amplitudes obtained by FFT analysis of the cutting and feed force signals and corresponding surface profile are linear.

When the theoretical and real surface profiles are compared in terms of the difference between PSD responses the magnitude e of profile deterioration due to cutting vibration can be predicted.

The comparison of the real and simulated surface profiles indicated that the higher amplitudes are generated for theoretical profiles due to lower number of spectral lines within the relevant PSD spectrum.

References

[1] W. GRZESIK: Advanced machining processes of metallic materials. Elsevier, Amsterdam 2017.

[2] J.P. DAVIM (ed.): Metal cutting. Recent advances, Nova, New York 2010, Chapter 6, W. GRZESIK, S. BROL: Generation and modeling of surface roughness in machining using geometrically defined cutting tools, 163-185.

[3] W. GRZESIK: Prediction of surface topography in precision hard machining based on modeling of the generation mechanisms resulting from a variable feed rate. *International Journal of Advanced Manufacturing Technology*, **94**(2018), 4115--4123.

[4] F. ANCIO, A.J. GAMEZ, M. MARCOS: Study of turned surfaces by principal component analysis. *Precision Engineering*, **43**(2016), 418-428.

[5] P.R. PROVENCHER, M. BALAZINSKI: Principal component idealization of the dominant modes of variability in the mechanics of the cutting process in metal turning. *International Journal of Advanced Manufacturing Technology*, **95**(2018), 1665-1676.

[6] J.P. COSTES, A predictive surface profile model for turning based on spectral analysis, *Journal of Materials Processing Technology*, **213**(2013), 94-100.

[7] Understanding the frequency spectrum, Mountains Map.v.6, User guide.

[8] W. GRZESIK, K. ŻAK: A new aspects of hard machining using CBN tools with variable tool corner radius and tool wear effect. *Advances in Manufacturing Science and Technology*, **41**(2017), 5-20.

[9] W. GRZESIK, K. ŻAK, P. NIESŁONY, R. CHUDY: Detection of the occurrence of cutting vibration in surface profiles generated in CBN precision hard turning, Proc. of 4th CIRP Conference on Surface Integrity (CIRP CSI). *Procedia CIRP* (2018), Reference No. PROCIR 394787.

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