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Identification of the impact of tool coating on the surface microroughness in turning of hardened steel

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Abstract

This paper reports on the use of wavelets to identify the quality of tool coating. Both coated and uncoated tools were experienced in hard turning (PCBN tools).The idea is to assess the correlation between the changes in tool microtopography and the surface microroughness. The discrete wavelet transform and entropy coefficient were developed to extract the features of the quality of tool coating. Different form and size of tool coating change was exhibited in different dynamic components and created specific mark of the coating on the machined surface.

Keywords: machined surface, wavelet decomposition, PCBN tool.

Identyfikacja wpływu powłoki na ostrzu na mikrochropowatość powierzchni w toczeniu stali w stanie utwardzonym

Streszczenie

Artykuł poświęcony jest zagadnieniu zidentyfikowania jakości powlekanych narzędzi i ich wpływu na mikrochropowatość powierzchni obrobionej. Badania przeprowadzono dla stali hartowanej i narzędzi z polikrystalicznego azotku boru (PCBN) (rys. 1). Narzędzia tego typu posiadają dużą twardość i uniwersalność stosowania [1-10]. Charakteryzują się jednak dużą kruchością, która sprawia, że krawędź skrawająca ostrzy PCBN ma duży promień zaokrąglenia, a narzędzia powlekane są cienkimi warstwami w celu identyfikacji zużycia. W badaniach pomierzono krawędź skrawającą (rys. 2) oraz jakość powierzchni obrobionej (rys. 3). W badaniach zastosowano dyskretną transformatę falkową (DWT) w celu dekompozycji sygnału podstawowego kształtu profilu powierzchni na składowe aproksymacji i szczegółów (rys. 4 i rys. 5) [11-12]. Zaproponowano metodykę oceny jakości krawędzi skrawającej (i stanu powłoki) ostrza współczynnikiem entropii [13], wyliczonym dla wybranych składowych dekompozycji w ujęciu całościowym oraz cząstkowym. Wyniki zestawionych współczynników entropii dla powierzchni stali hartowanej uzyskanej dla ostrzy bez powłoki, powlekanych niezużytych i o znacznym stopniu zużycia zestawiono na rysunkach 6 i 7. Wynika z nich, że nakładanie powłoki na ostrze nie tylko pozwala łatwiej zidentyfikować jego zużycie, ale zmienia też właściwości kontaktu ostrze-powierzchnia. Powierzchnia obrobiona ostrzem powlekanym o pewnym stopniu zużycia zmienia kształt podstawowy mikronierówności, co wynika z odwzorowania zarysu ostrza. Natomiast zawartość informacyjna sygnału w zakresie mikrochropowatości, zmierzona współczynnikiem entropii, zawierała się dla wszystkich przypadków ostrza zużytego w przedziale między ostrzem nowym powlekanym i niepowlekanym.

Słowa kluczowe: powierzchnia obrobiona, dekompozycja falkowa, narzędzie z polikrystalicznego azotku boru (PCBN).

1. Introduction

In recent years, hard turning with polycrystalline cubic boron nitride (PCBN) tools has proven to be a good alternative to the grinding processes [1, 2]. Machining of hardened steels using geometrically defined tools has a lot of benefits. PCBN cutting tools decrease machining time, offer process flexibility and reduce energy consumption.

Because of the advantages of PCBN tools, the literature reports on their different applications for a wide range of materials [3]. Since tool life directly influences the machining cost, considerable effort has been focused on CBN content, binder composition [4]. It was shown that low-CBN content ceramic binder tools give longer life and better surface finish. Lower CBN content tools with a ceramic binder guarantee more resistance to abrasive wear due to increased bonding strength. Nevertheless, abrasive wear and adhesion still exist during the cutting process. Additionally, the brittle nature of PCBN tools makes them prone to chipping at the cutting edge.

One of the possibilities to preserve the cutting edge from chipping and premature tool failure is to apply not only the ceramic binder but also to cover the tool with a coating [5]. On the cutting tool market, the PCBN tools are coated with a thin TiN coating. The coating is softer than the substrate and in hard turning the abrasive particles rapidly eliminate the thin layer of TiN coating. However, despite the lack of coating on the tip of the tool in a certain phase of wear the coated inserts behave better than the uncoated ones [6].

Research done by Poulachon et al. [7] demonstrated the longer life of the coated PCBN tools. The use of TiN coating on PCBN tools improved indeed their wear resistance by reducing the diffusion phenomenon between the workpiece and the tool rake face. Zimmermann et al. [8] showed moreover that the TiN layer reduces a chemical reaction between the tool and the chip. The role of TiN layer is then to delay the diffusion and chemical wear [9]. Thus by the process of coating, wear of PCBN tools in hard turning can be reduced significantly if we make sure that the coating materials do not react chemically with the atmosphere or workpiece. Suffice it to say that, when the full amount of wear is not eliminated (especially, when studying hard turning process), the extreme precision of surface finish become something of an embarrassment, and overload for its quality assessment.

The aim of this research is to find the wear pattern of coatings in the investigation of PCBN hard turning. It enables the identification of mechanism of wear and location of the surface modification caused by edge wear.

2. Experimental procedure and results

Machining was performed on EN 41Cr4 steel rods. Specimen diameter and length were, respectively, 26 and 90 mm. The steel hardness was increased to 58 HRC using a quenching treatment at 850 °C. The chemical composition of steel was 0.44% carbon, max 0,3% nickel, 0.8-1.1% chromium, 0.5-0.8% manganese, and 0.17-0.37% silicon.

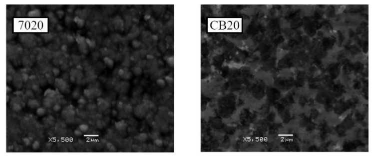

Fig. 1. Microstructures of CBN tool materials
Rys. 1. Mikrostruktury materiałów narzędziowych CBN

The chosen PCBN tool is commercially known as 7020 (coated) and CB20 (uncoated). 7020 is essentially made of 57% CBN and 35% Ti(C,N). EDS analysis of the TiN coating revealed - Ti

(75%) and N (25%). EDS analysis of the new uncoated wedge reveled such elements as B, N, C, Ti (88%) in it and Al, Co and W (12%) in smaller quantities. Insert ISO designation is TNGA16 04 08 S01020 and was manufactured by Sandvik. The physical properties of the 7020 and CB20 tools are summarized in several papers [7, 10].The forecasted tool life is 23 minutes for a normal work of the tool. The failure of the tool is supposed to appear when the cutting speed exceeds 200 m/min.

Microstructures of CBN materials are compared in Fig. 1. For 7020 cutting tool material, the TiN coating thoroughly covers the CBN structure. The visible grains have a diameter of 0.5 to 2 µm. Dark particles of the size of 1 to 2 µm, are CBN grains; the grey phase is identified as TiCN. The glowing points are Co, W and Al.

The cutting tests in hard turning configuration were performed using high rigidity CNC NEF 400. Tool holder was codified as DTGNR 2525 M 16. The attempts of continuous cutting were realized for cutting speed of 165 m/min, feed rate of 0.15 mm/rot and cutting depth of 0.2 mm.

3. Tool wear analysis

Cutting tools underwent analysis in the initial phase of their work. The cutting length was 48 m, which corresponded to 18 seconds of cutting time. Notice that after this time the wear rate occurred only on the main flank. Figure 2 compares SEM photos taken from the tip of the rounding. Examination of the wedges confirmed progressive wear-off processes. In case of CB20 wedge, EDS examination of the work part showed changes within component analysis. Fe and O – 30% weight units, appeared. Wearing-off is mainly of the abrasive nature. Scratches resulting from abrasion on the hard surfaced material are visible. Value of abrasion is low and fits within the rounding of the cutting edge.

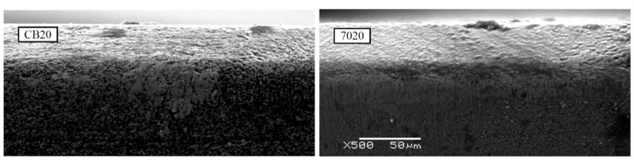

Fig. 2. Tool edge wear
Rys. 2. Zużycie krawędzi narzędzia

Wear on 7020 wedge can be observed better as apart from the change in the outside shaping of the wear-off traces, abrasion of the layer and border between the layer and CBN substrate is also visible. EDS analysis confirmed presence of Fe and O on the abraded TiN layer - 11%, and where the substrate was exposed B – 9%, C – 27%, N – 29%, 0 – 11%, Ti– 16%, Fe – 6%.

Analysis of the scanning microscope images of the cutting edge proves the complex texture of the cutting edge. Micro-geometry of the rounded cutting edge is the sum of changes from micro-geometry of machined surface, the phenomena of internal and contact frictions, reversibility of resilient deformation and plastic deformation processes. The rounding radius' value changes along the cutting edge. In this way, the active part of the cutting edge is featuring a great randomness. The stochastic and dynamical nature of the cutting edge roughness is one of the reasons for changes in the dynamics of cutting process.

4. Machined surface analysis

Machined surface was considered as the main source of information of the cutting process. It was evaluated in the 2D and 3D arrangements with the use of coherence correlation interferometry technique. Two- and three-dimensional surface data were collected using Talysurf CCI 6000 profilemeter. The measured roughness, presented in Figure 3, turned out to be higher than the theoretical value - 0.807 µm, theoretical Ra calculated for the cutting conditions.

Theoretical research of surface roughness focuses on kinematic-geometric mapping of the tool nose with an unchangeable cutting edge. Basing on geometric and kinematic values, it can be determined that the wedge scratches the same fragment of surface time after the time. In this way, the material machined in the cutting area is exposed to temperature and pressure so high that they cause full plasticization. Feed rate value influences the area where thickness of the cut layer is lower than the minimal. This result in a great part of the material being moved in a direction opposite to the feed rate direction rather than the material being properly cut, which leads to side flow of the material, eventually leaving its trace in geometry and roughness.

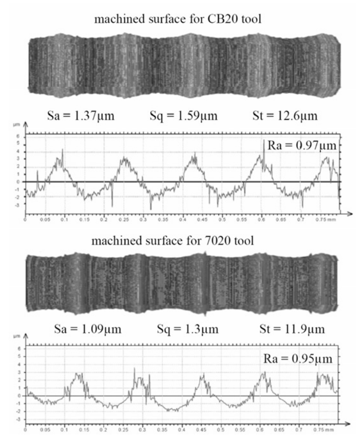

Fig. 3. Plastic side flow generated by cutting edge in turning, parameters of the machined surface for CB20 and 7020 cutting tool
Rys. 3. Płynięcie plastyczne boczne powstające przy toczeniu, parametry obrabianej powierzchni dla narzędzi tnących CB20 i 7020

The wear of the tool causes the changes in tool nose radius determining wider flat section parallel to the surface causing the intensification of side flow phenomenon. It also makes the cutting edge to be blunter and rougher affecting the increase of uncut chip thickness and growth of microcutting, scratching and ploughing.

5. Discussion on the signature of the tool coating on the cut surface

Observation of the topography of both machined surfaces does not show any considerable differences. Both of the surfaces, presented in Figure 3, are smooth, even, and uniform. Increase of observation resolution allows for distinction of changes within a single micrometer (Fig. 4). The averaged profiles in two perpendicular directions for surface created by the coated wedge 7020 and the uncoated wedge CB20 show considerable differences. The grey field surrounding the averaged profiles suggests that surfaces created by coated wedges are more determined. Probability of profile changeability is lower (less grey color) than in case of surface created by the uncoated wedge. Changeability of value of a few micrometers occurs along the whole profile and has various amplitude and frequency.

Due to repeatability of the profile at the distance of the feed rate's value, part of the profile of a feed rate length was distinguished in such a way that 'outline of the wedge' – the basic shape of unevenness, was obtained. Comparing proportions of heights of the unevenness with length of the basic shape of unevenness - 5 µm of height to 150 µm of length of the feed rate - it can be noticed that it is a tiny, almost flat part of the wedge. This part is printed on the surface and remains unchanged for a long time – despite the change of the wedge's geometry of the main flank and rake face.

In case of the surface created by the coated wedge a tiny development of the surface can be seen on the left side of the valley. Areas of geometrically similar micro-unevenness can be noticed. The wedge is in perfect condition and cuts the work material easier than the uncoated wedge for which the side is far more developed. The upper part of the left side is a place where torn traces after side flow of the material can be distinguished. For this reason, a trail of grey lines in this area is depicted. Greater randomness of the profile caused by side flow of the hard work material is visible especially in case of the first profile (uncoated wedge). The phenomenon is more intense in this case.

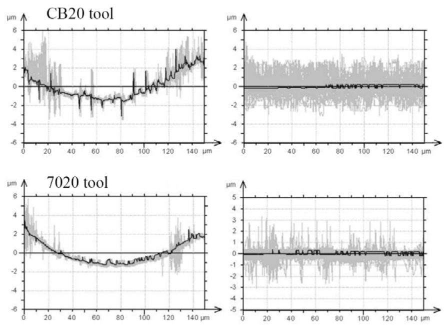

Fig. 4. Averaged surface profiles toward the greatest and smallest surface roughness
Rys. 4. Uśrednione profile powierzchni w kierunku największej i najmniejszej chropowatości powierzchni

The right side, on the other hand, is retracement of the cutting edge on the wedge's side towards the minor flank. This time the wedge scratches the surface freely. The observed averaged line of the profile (Fig. 4) displays certain stability and uniformity within the profile's outline for both, the first and the second surface. The upper part of the right profile shows greater randomness due to change in a direction of the tangent cutting force. Part of the material is pushed away and a flow-out is created – side flow of the material.

Analysis of surfaces created by CB20 and 7020 cutting tool makes observation of differences, whose evaluation is still difficult due to their nature, possible. Each of the surfaces is characterized by small characteristic autonomic layout of the unevenness. When analyzing structure of this unevenness, their layout within the basic unevenness shape, an attempt can be made to perform a quantity distinction of the change source observed on the surface.

6. Signal processing

Machined surface data gathered with the use of optical profilometer constitute the source of information on condition that they are properly processed. Traditionally they are filtered and then the 2D and 3D parameters are evaluated. In this paper, the machined surface data are decomposed into the time-frequency components and then analyzed. Such an analysis is called wavelet analysis.

Wavelet analysis is similar to Fourier analysis. Nevertheless, the wavelet analysis enables the data to be examined both in space and in frequency. The selection of filters for the decomposition means the selection of the main wavelet from a bank of wavelet families and offers the possibility to match them with the specific surface data. The research performed in [11] and [12] with a bank of wavelets from different families in surface roughness decomposition confirmed the usefulness of Coiflet wavelets. The preferred tree for the decomposition of machined surface data was the tree of discrete wavelet transform (DWT) with the best decomposition level as 5 [12].

The algorithm of discrete wavelet transform divides the signal into two parts. After the division, an approximation and detail vectors are obtained. Both vectors are in a rough scale. The information lost between the signal and approximation vectors is collected in the details vector. The next stage is division of the approximation vector into approximation and details vectors. The detail vector is not divided any further. Next, the approximation vector is further divided and in this way, a discreet wavelet transform decomposition tree is obtained.

Figure 5 presents an exemplary wavelet decomposition of the basic unevenness' shape. The decomposition was performed using discrete wavelet transform with Coiflet as a basic wavelet. The decomposition allowed for division of the measurement data into approximation signal and five detail signals of various scale. An initial analysis can be made during comparison of particular components of figure 5. In case of both surfaces, strong similarity was observed within the area of approximation component vector. The approximation vector determines the dominant component, trend. In this case, it resembles the basic shape of unevenness. The greatest differences were observed for D1, D2 and D3 detail component vectors. While in case of uncoated wedge the surface is characterized by relatively evenly spread values in components of the higher scale, on the surface shaped by a coated wedge the values in components of the higher scales are laid out in a more determined manner.

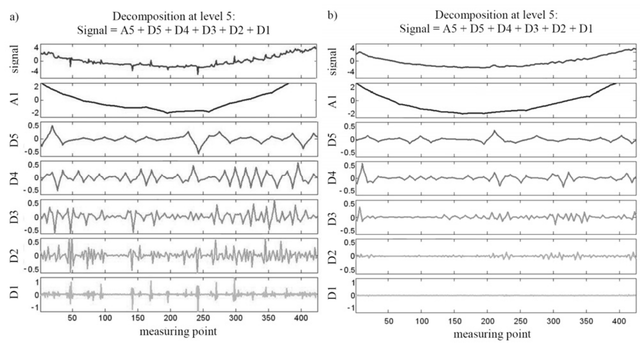

Fig. 5. Decomposition of the basic roughness' shape for cutting tool, a) CB20, b) 7020
Rys. 5. Dekompozycja kształtu chropowatości podstawowej dla narzędzi a) CB20, b) 7020

For a purpose of quantitative description of the signal components and then recognition the difference between the sets of data, the entropy coefficient was applied. Methodology of determining entropy coefficient for the basic shape of micro-unevenness consisted in averaging the scaled profile for 0.01mm (20 independent sets of data). For each of the averaged profile the quantization was performed and then the wavelet decomposition was completed.

Each of the wavelet components was divided into ten separate sets of data of the length of 0.015 mm (one tenth of the feed rate). Value of the entropy coefficient (equation 1 - 'Shannon's Entropy' [13]), as indicator of disarrangement of the signal, was calculated for each of the subcomponent. The entropy of a system (or a process) with the probability density q is represented as

$$H(q) = -\int_D q(y)\log q(y)dy \,. \tag{1}$$

The shape obtained after joining points of entropy coefficients for particular component indicates the amount of information produced by the process, or is a measure of uncertainty present in the cutting process. A larger value of entropy coefficient corresponds to greater amount of information (uncertainty) in the process. The entropy coefficient is only 0 if we are certain about the outcome. The entropy coefficient is maximal if all surface data have equal probability. Any change toward equalization of the probabilities increases the entropy.

7. Results and discussion

Layout of entropy coefficient along the basic shape of unevenness was applied as the indicator of the profile's dispersal. Results for both surfaces are compared in Figure 6. The entropy coefficient is calculated for the averaged ten elementary lengths. The location of entropy coefficient points along the profile enables for particular components' vectors of the wavelet decomposition to evaluate the deterministic part of surface's profile.

The approximation component vector describes the low-frequency component – trend. In this case, the entropy coefficient is calculated for the determined signal. Approximation component signal is similar for both surfaces and therefore layout of the entropy coefficient is alike (Fig 6 – A5). Layout of the entropy coefficient for the approximation vector corresponds with layout of the entropy coefficient for the original signal in shape and size.

For detail component vectors of the lower scales (Fig 6 - D4, D5) layouts of the entropy coefficient interweave in both cases of cutting. The resultant distributions of entropy coefficient are similar. This means that the probability of lower scales occurring in the profile of the component's surfaces is alike.

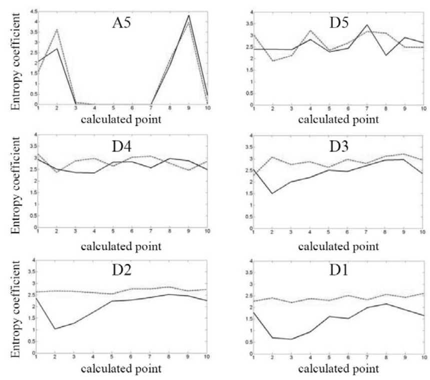

Fig. 6. Layout of the entropy coefficient along the basic shape of unevenness for particular component vectors of wavelet decomposition, for surface created by the cutting tool: a) CB20, dash line, b) 7020, continuous line

Rys. 6. Wykres współczynnika entropii wzdłuż podstawowego kształtu nierówności dla poszczególnych wektorów składowych dekompozycji falkowej, dla powierzchni utworzonej przez narzędzie: a) CB20, linia kropkowa, b) 7020, linia ciągła

For detail component vectors of the higher scales (Fig. 6 - D1, D2, D3) layout of the entropy coefficient diverge in case of both surfaces. Layout of the entropy coefficient for surface created with a coated wedge assumes the lower value. This suggests that detail component vectors of the higher scales are more highly determined, and, consequently, that the surface is better arranged within higher frequencies.

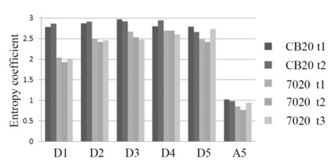

Fig. 7. Averaged entropy coefficient of wavelet components of basic shape of unevenness ($t1$=18s, $t2$=2 min, $t3$ (cutting speed 210 m/min)=18s)

Rys. 7. Uśredniony współczynnik entropii składowych falki podstawowego kształtu nierówności ($t1$=18s, $t2$=2 min, $t3$ (prędkość cięcia 210 m/min)=18s)

Layout of the entropy coefficient along the basic shape of the roughness for particular component vectors of the wavelet decomposition is the indicator of phenomena taking place on the wedge. Layout of the entropy coefficient is therefore a quantity indicator of the wedge's coating quality. Change of the coating's condition, and eventually its lack, leads to layout of the entropy coefficient like in the case of uncoated wedge. Within the space between decomposition for a coated and uncoated wedge, there are curves responsible for various conditions of the wedge's coating.

The averaged values of entropy coefficients for three cutting times are shown in Fig. 7. Cutting time $t1$ indicates the beginning of cutting. It means that the tool is fresh. Comparisons made for machined surface cut by CB20 and 7020 signify the difference of all the components. The difference is t most visible for D1, D2 and D3 components. For the cutting time was longer ($t2$ = 2 min), then the difference was even greater in all the components. The situation changed with the abrupt change in the tool geometry when the cutting speed was increased above the 200 m/min and wedge was broken up. For such a tool condition, the active part of the cutting edge was more developed. Interesting in the research results is that the coating on the tool was still present and changes concerned mainly the shape of the basic shape of the unevenness (and shortening of the tool) but not the submicroroughness. The increase of the entropy coefficient of A5 approximation component and D5 detail component testify for the hypothesis of the beneficial influence of the TiN coating on the machined surface quality.

8. Conclusions

Application of PCBN material on cutting wedges resulted in the possibility to cut various machined materials whose machined surface quality is approximate to grinding. Such determination of the purpose of application of PCBN in cutting wedges necessitated on one hand evaluation of properties of the machined surface as relate to the surface's micro-roughness and, on the other hand, determination of conditions in which the machined surface will have strictly predetermined geometric features.

The paper attempts to evaluate the influence of a thin TiN layer on surface's micro-roughness properties within a basic shape of micro-unevenness in hard turning. Discrete wavelet transform and entropy coefficients were applied in evaluation of the level of arrangement of particular frequency components of the profile. The general conclusions of this work are as follows:

The coating applied onto the wedge changes its properties, which positively influences condition of the cutting edge.

The wedge almost does not wear out on the minor flank, as multiple scratching of the same fragment of surface by the wedge (surface softened by the emitted heat) for PCBN wedge, does not cause any changes in the latter one.

Profile analysis within single wedge imaging allows for distinguishing of such elements as the profile's indentation, left and right side, prominence of the profile and phenomena occurring during their creation.

Layout of the entropy coefficient along the basic shape of the unevenness for particular component vectors of the wavelet decomposition enabled the evaluation of the profile's arrangement and, by extension, condition of quality of the cutting edge coating.

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