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INFLUENCE OF TOOL WEAR ON THE MECHANISM OF CHIPS SEGMENTATION AND TOOL VIBRATION

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Original scientific paper

The tool wear has a significant impact on the cutting process and therefore tool wear monitoring is especially important for building intelligent machine tools which are capable of assessing their own states and reacting to important changes. This approach is based on the assumption that there exists a relationship between the spectrum of high-frequency vibrations measured on tool holder, in immediate vicinity of the cutting zone, and the tool wear degree. The wear causes changes in tool tip geometry, which has significant influence on the process of chip forming. At the same time, the erratic nature of chip forming process excites the cutting zone, generating a very broad spectrum of vibrations. Due to high input energy, these vibrations are very intensive, and spread through the entire machining system. In the paper, experimental results are shown which pertain to the relationship between the power spectral density (PSD) within 5 kHz to 50 kHz interval.

Keywords: *chip forming, tool wear, tool vibrations, turning*

Utjecaj trošenja alata na mehanizam segmentacije odvojenih čestica i vibracije alata

Izvorni znanstveni rad

Proces trošenja reznog alata ima značajan utjecaj na proces rezanja i stoga je praćenje stupnja potrošenosti alata od posebnog značaja za izgradnju inteligentnih alatnih strojeva koji imaju sposobnost pratiti svoja stanja i aktivno djelovati na njihovu promjenu. Ovaj pristup je zasnovan na pretpostavci da postoji određena korelacija između spektra visokofrekventnih vibracija mjerenih na držaču alata neposredno u blizini zone rezanja i stupnja potrošenosti alata. Trošenjem dolazi do promjene geometrije reznog alata što ima veliki utjecaj na proces formiranja strugotine. Istovremeno, diskontinuirana priroda procesa formiranja strugotine pobuđuje zonu rezanja, zbog čega se generira jedan vrlo širok spektar vibracija. Veliki intenzitet vibracija, koje se prostiru kroz cjelokupni obradni sustav, posljedica je unosa velike količine energije. U radu su prikazani rezultati eksperimentalnih istraživanja u cilju postavljanja korelacije između spektra vibracija ubrzanja (PSD) u intervalu od 5 kHz do 50 kHz i parametara trošenja alata.

Ključne riječi: *formiranje odvojenih čestica, trošenje alata, vibracije alata, tokarenje*

1 Introduction

Scientific approach and application of advanced information technology in the monitoring of machining processes can affect the product quality as well as increase productivity [1, 2]. Using various approaches, a number of researchers have dealt with the influence of machining conditions on chip morphology during machining of tempered steel. One of the approaches involves macroscopic and microscopic analysis of chip morphology, allowing insight into numerous pieces of information, including: mechanism of chip generation, dimensions, frequency of chip segmentation, shape, etc. In addition to better understanding of the chip forming mechanisms, chip morphology can be a clear indicator of tool wear and its general condition. Moreover, the knowledge of chip morphology contributes to higher machining productivity, dimension accuracy, and surface quality. During machining, the forming of lamellae, i.e. chip segmentation, generates energy impulses which are related to vibration.

Chip forming mechanism, and microscopic geometry of chip cross section at high-speed machining of steel are studied in [3, 4, 5]. The study examines: frequency of chip segmentation, dimensions of deformed and undeformed chip segments as well as their form. It is shown that the change in chip speed influences: form of segmentation, size of deformed and undeformed layer of lamellae. Higher cutting speeds influence thermal softening of material, which becomes a dominant mechanism of chip forming. Also, higher frequencies of chip lamellae generation decrease the area of deformed zone on chip cross section. Morehead et al. [6] investigated the influence of various machining regimes on the shape of the generated chip in hard materials. Included in their analysis was the change of tool wear level. They established that chip dimensions and frequency of lamellae generation depend on machining regime and tool wear degree, while the lamellae shear angle is approximately constant.

Dutta et al. [7] dealt with the influence of selected composite tool material on the macroscopic shape of formed chip. In addition, they examined the variation of chip shape and tool wear as the function of cutting regime. Previous analyses indicate that chip morphology changes with cutting speed. This change is caused by varying chip forming mechanism, and variations in location and flow of shear zone.

Chip morphology significantly influences thermo-mechanical characteristics in the tool/workpiece system, which directly impacts tool life. In order to increase productivity and tool life, simulations of influence of machinability, chip forming mechanism, and chip segmentation type on tool life have been performed [8, 9, 10, 11, 12].

Analytical and experimental research of the dynamic aspects of chip forming has so far employed numerous types of sensors and methods, which indicates the lack of a generally accepted method. It is, however, evident that indirect methods have gained popularity in the domain of monitoring of machining processes. Cotterell and Byrne [13] used high resolution cameras with high sampling rates to detect the character of chip formed at production cutting speeds.

Formation and spreading of cracks from the free chip surface towards the tool rake surface, forming mechanism of serrated chips, as well as the stress and strain phenomena related to thermoplastic instability were considered by Vyas and Shaw [14]. Sun et al. [15] established that frequencies of dynamic machining forces correspond to frequencies of chip segmentation during machining. Significant inconsistencies and controversy exist not only regarding the chip forming mechanism at high machining speeds, but also the metallurgical aspects of segmented chip.

As part of creating an intelligent machine tool, Tangjitsitcharoen [16] developed a system for monitoring of turning machining processes on CNC lathes with the aim to increase stability of cutting process. The method was based on the calculation of power spectral density (PSD), and measurement of dynamic cutting force during machining. Relationship was established between the calculated PSD and the macro geometry of generated chip. The proposed method exploits the relationship between the three calculated parameters of dynamic cutting force components. Parameter values were obtained from the cumulative relationship between PSD for a particular frequency range which corresponds to the components of dynamic cutting force.

Petrovic et al. [17] used accelerometers to monitor various dynamic chip forming phenomena. Vibration signal was measured during machining, while discrete wavelet transformations (DWT) were used to filter information to allow forming of a robust input vector for a tool wear monitoring fuzzy system. Ding and He [18] developed a model of tool wear monitoring based on monitoring and analysis of the vibration signal in the time and frequency domains. Signal processing allowed extraction of features such as: root mean square, covariance, and kurtosis, which allowed subsequent analysis of tool wear. Antic et al. [19] proposed a multi sensor, force-based tool monitoring system supported by analysis based on neural network concept. Considered in this paper was the relationship between tool wear and cutting forces during machining.

There are a small number of investigations which deal with the correlation between vibration signal and tool wear, on the one side, and the type of chip formed, on the other. This speaks in favor of the effort to further investigate chip forming mechanisms and their relationship with tool wear.

Contribution of this paper lies in identification and assessment of the influence of varying tool edge geometry - especially in the zone near the cutting edge – on the type of generated chip. Furthermore, the influence of tool edge degradation, and tool wear degree, on the character of generated vibrations during machining is also investigated. The basic approach used in this paper is based on the following:

- verification of the influence of tool wear degree on chip segmentation process by the use of direct microscopic analysis of the generated chip,
- assessment of correlation between the tool wear degree, and tool vibrations, induced by non-linear mechanisms of chip segmentation – which shall be used for development of the system for on-line tool wear identification.

2 Chip forming - modelling and measurement

The process of chip forming and chip classification was approached from various aspects: microstructure of material, cutting speed, feed rate, depth of cut, shear angle, etc. One of the first classifications of chip types in orthogonal cutting model made distinctions between: serrated and continuous chip. The mechanism of chip forming at high cutting speeds differs from that of conventional machining [20]. At high cutting speeds, the adiabatic shear is the dominant deformation process which takes place in the primary cutting zone [21]. Its basic feature is a thin band of pronounced deformation in the shear zone. The emergence of adiabatic shear band at high cutting speeds increases the tool wear, thus influencing surface quality of workpiece. On the other hand, this phenomenon is useful because it generates discontinuous chip, as one of the requirements of highly automated machining. To allow efficient control of the high speed cutting process, critical moments in the generation of adiabatic shear band were studied, in order to define the exact moment of its emergence. The studies showed that the critical velocity of deformation, i.e. cutting speed, plays an important role. However, the identification of parameters differs in various materials. Also, the influence of tool edge geometry is of key importance in the process of chip forming and segmentation, which transforms a static process into a dynamic one [22]. Abrasive wear on tool rake surface causes severe plastic deformations of material, as well as the formation of serrated chip.

2.1 Chip forming models and types of segmentation

In the process of machining with a rigidly fixed tool, continuous chip is formed without the dominant model of oscillation, in which: stress, shear, shear rate, and temperature profile remain constant in time, Fig. 1(a). Discontinuous or segmented chip is characterized by an oscillating profile with prominent lamellae tips at the free end, Fig. 1(b). Chip type and method of generation, as well as the method of chip evacuation over rake surface influence important machining process parameters such as tool life and workpiece surface quality. It is, therefore, important to establish the models which are able to predict the transition of chip from continuous into segmented form under various cutting conditions and for various materials. Such model of chip forming and segmentation was in the focus of numerous authors. The model of chip segmentation is presented in Fig. 2.

One of the induction mechanisms causing the vibrations in the machining process is the creation of chip lamellae. Generation of internal stresses within material structure due to material shear and lamellae generation excites complete system into dynamic oscillations at the frequency which corresponds to lamellae generation frequency. Chip morphology and segmentation is characterized by its dimensional values in terms of: saw-tooth height p_{sb}, height of the chip part h'_{ch}, chip height of continuous portion (h'), shear band spacing (d_c), angle in the direction of the initial crack (Φ_{seg}), the lamella formation steps p_c, cutting depth $a_p=h$, average height of the deformed chip part $\bar{h}_{ch}$ and cutting speed v_c.

Burns and Davies [23] presented a comparative analysis of orthogonal and torsional chip forming model. The authors showed by numerical simulations that there is a difference between generation of continuous and discontinuous chip.

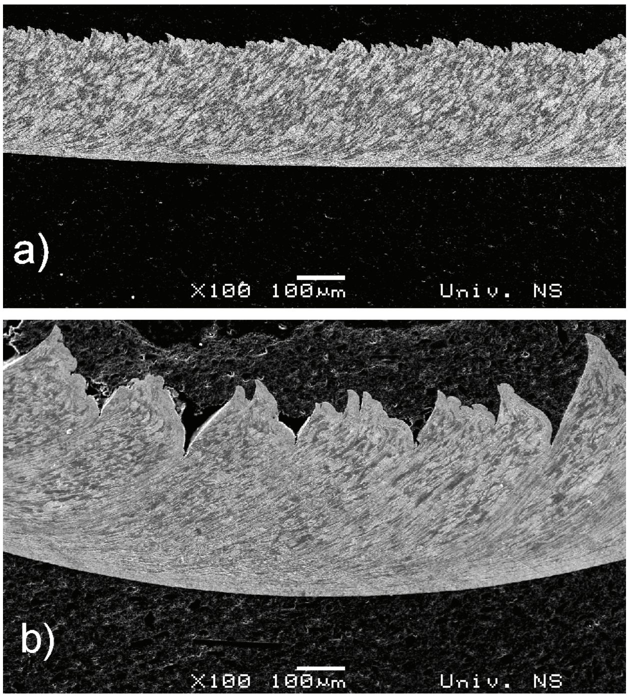

Figure 1 Types of chip formation and segmentation for tempered steel, a) continuous chip, b) discontinuous chip

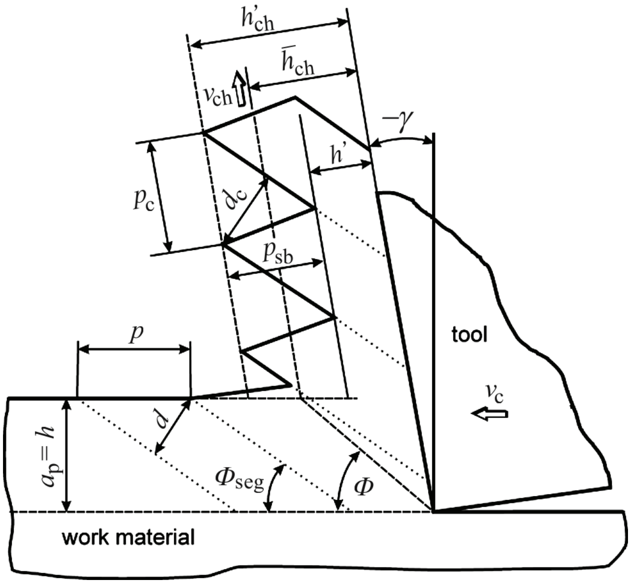

Figure 2 Chip formation model and geometry

2.2 Tool wear process and chip segmentation

Tool wear mechanisms have various impacts on tool. One of the most important impacts is on the tool rake surface, which changes the tool edge geometry. This is directly related to the mechanism of chip forming and its form. Generation of various types and forms of chip influences inhomogeneous and non-stationary changes in the contact zone between the tool and chip, i.e. the friction at tool-chip interface. Such changes generate various forms of tool vibrations, influence work surface quality, and intensify tool wear.

After the penetration of chip lamellae into the base material of tool insert it begins to intensify. The crater which appears weakens the cutting edge and, in conjunction with high temperatures, leads to breakage of insert tip. The growth of the crater on tool rake surface has an influence on the mechanism of chip forming as well as on the frequency of chip segmentation and its form. Crater wear directly impacts the initial phase of chip formation which always tends to keep a continuous form.

This type of chip causes increased tool wear, i.e. decreased tool life and work surface quality. Thus, better work surface quality, increased tool life, and favourable chip form, are a matter of compromise. Successful realization of such compromise requires analyses to establish influence of machining parameters and tool geometry on vibrations and forces which emerge during the machining process. Furthermore, comprehensive analyses are also required to study stress and temperature distribution during the chip forming process.

2.3 Measurement of vibrations

Acceleration vibrations carry information directly related to the machining process. The problem is that the information changes and superimposes on other vibrations in a dynamic interaction with the tool and the machining system. Within this research, initial assumption was that some part of frequency spectrum contains information which can be extracted to allow unambiguous detection of the current state of tool cutting edge wear.

For that purpose, the dynamic system, i.e. cutting tool (turning knife), was equipped with an accelerometer of required measuring performances, which turned it into a sensor system that collected information on vibrations, and, after signal conditioning, transferred them into acquisition system.

Due to their dynamic properties the tool and tool edge prevent the linear flow of information. Energy impulses caused by chip segmentation, and destruction of cut material on the crystalline lattice level, excite the elasto-viscous structure of tool. All natural frequencies of tool and tool support mechanical structures are located within the lower spectrum of vibrations, whose upper boundary is 5 to 10 kHz. Due to this, the excitations from the cutting zone are distorted in this part of spectrum, so that the accelerometer gets 'coloured' signal, which is amplified at some frequencies, while suppressed at others. There is also a special situation when the frequency of discrete excitation coincides with some of the tool's natural frequencies or some of its higher harmonics. This is when resonance takes place, which adds even more distortion of excitation signal. The mechanical structure of tool acts in lower spectrum as a non-linear filter which alters the information coming from the cutting zone where the tool edge interfaces work material.

The other response component takes place in the higher part of the frequency spectrum, i.e. in the interval whose lower boundary is 5 kHz ÷ 10 kHz. In that part of the spectrum stress waves propagate through the homogenous mechanical structure of tool. These stress waves are little changed, i.e. compared to the excitation signal, their distortion is relatively small. The information content thus gathered is in a quasi-linear correlation with the state of tool edge geometry, as well as with the phenomenon of material separation and chip segmentation, which takes place on a microscopic level. In the higher part of spectrum (up to 100 kHz), tool mechanical structure acts as a quasi-linear filter which has very little influence on information content coming from the cutting zone. The part of the spectrum above 100 kHz - which is also convenient from the aspect of distortion of information from the cutting zone – cannot be monitored by accelerometers. Instead, AE sensors can be used, as they are able to register extremely high frequencies, the magnitude of MHz. However, this technology is severely limited by the technical problems of acquisition and processing of signals of extremely high frequencies, as well as the presence of signal attenuation, especially in the case of inclusions.

3 Experimental setup

The experiments of longitudinal turning were conducted in order to investigate tool wear (type of wear, wear mechanism, tool life, wear band), and its influence on tool vibrations. Sensor placement on tool holder and experimental setup scheme is shown in Fig. 3. Experimental machining was performed on a CNC lathe, INDEX GU 600. Cutting speed varied between 180 m/min and 250 m/min, feed ranged from 0,1 mm/rev to 0,3 mm/rev.

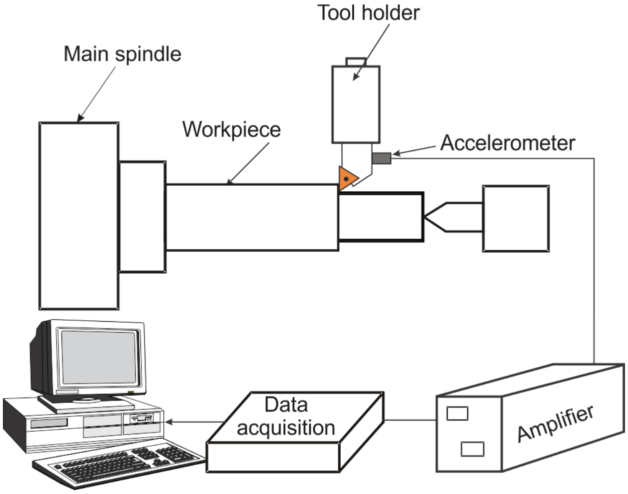

Figure 3 Experimental setup

Two dimensions of tool holder were used during experiment, 20×20 mm and 25×25 mm, while the insert tip was P25, TNMM 220408. Accelerometer Kistler 8002 was fixed onto the tool holder, and used to measure acceleration of vibrations. This signal was sampled at 625 kHz, using A/D converter NI 625 USB, National Instruments. Workpiece material was steel 42CrMo4, hardness 48 (±2) HRC, with guaranteed mechanical and chemical properties.

After the length of 500 mm was machined, the cutting process was stopped, tool insert was removed from tool holder and taken for measurement of wear band (VB), and wear crater (KT). Assessment of chip morphology was done by examination on an optical microscope. Maximum wear band width and wear crater depth were measured on a tool microscope. Tool insert was then carefully repositioned on the tool holder, and the cutting process was resumed until the wear band reached the wear criterion. During the experiment, vibration accelerations were measured at each cutting pass, for the duration of 1s.

Wear band width *VB* (μm), cutting time *t* (s), and cutting length l_c (m) were measured and recorded throughout the experiment. The recorded signals were analysed to assess the influence of tool wear on vibration signal, and PSD was calculated. Morphology and microstructure were examined on an electronic microscope (SEM).

4 Experimental results and discussion

4.1 Microscopic analysis of chip

Microscopic analysis of chip cross section geometry allows one to establish direct relationship between the mechanism of chip forming and tool wear degree.

Under a 500 times microscopic magnification, shown in Fig. 4, the difference is even more visible. Fig. 4(a) shows the chip type generated by a new tool insert, with the dominant continuous form, without pronounced discontinuous pattern. Fig. 4(b) shows the chip generated by the worn tool insert, where, in contrast to the new tool insert case, the chip generation mechanism features thermal softening, and a pronounced shear in the primary cutting zone. Komanduri and Hou [24] presented similar models of chip segmentation due to shear - when the thermal softening is dominant over stress strengthening during material separation.

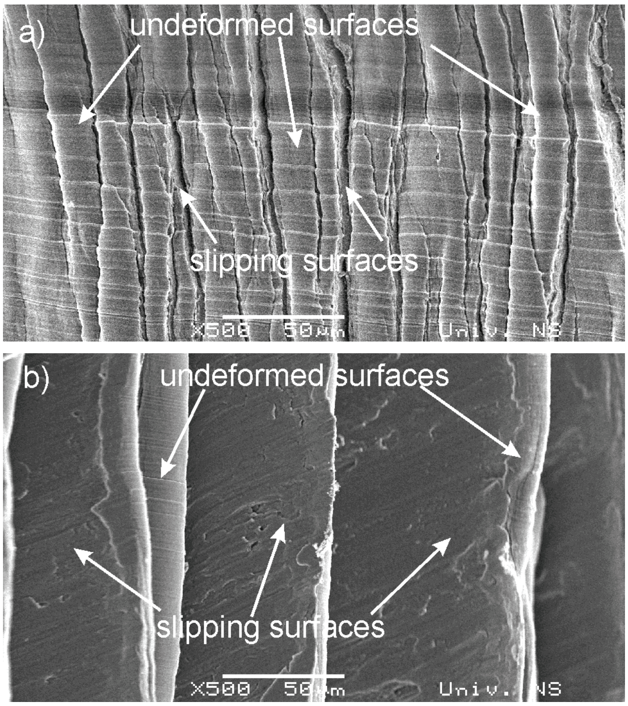

Figure 4 Images of free chip surface at 500 times magnification on SEM, generated with tool inserts of different wear state, at 180 m/min cutting speed, feed rate 0,2 mm/rev, depth of cut 1,5 mm: a) new tool insert, b) worn tool insert

Such conclusion is supported by Fig. 5 which shows the cross section of chips generated by new and worn tool inserts. The different micro-geometric structures of these cross sections indicate different chip forming mechanisms. The cross section of chip has shown in Fig. 5(a) features periodic initiations of segmentation, while the formed segments are irregular in shape. The free surface of chip exhibits undeformed surfaces of small and irregular heights, with small interstices and sporadic shear initiations, which are also visible in Fig. 5(a). Continuous forming and overlapping of lamellae is clearly visible, with the slipping at 40 degrees angle across the entire chip cross section, without pronounced zones of extensive material deformation. The change of tool wear, i.e. tool edge geometry, also influences variations in chip forming mechanism.

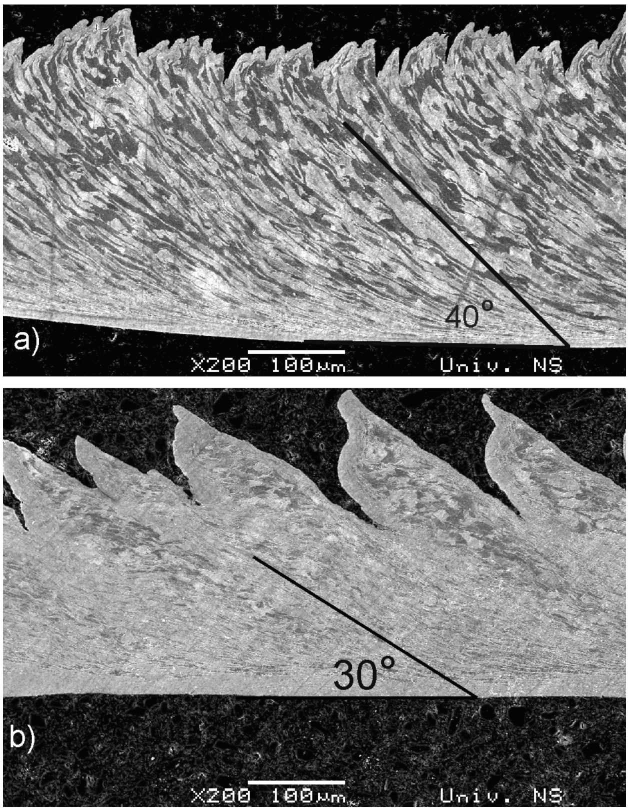

Figure 5 Chip cross section formed at the cutting speed of 180 m/min, feed rate 0,2 mm/rev, depth of cut 1,5 mm: a) new tool insert, b) worn tool insert

Typical form of discontinuous chip is shown in Fig. 5(b). Speaking of a single chip segment, its geometric features are: tooth height, tooth pitch, length of undeformed surface, and shear angle (*Φ*). In [14] it is pointed out that, due to material stiffness in the area of primary shear, there is a periodic occurrence of segmentation and micro cracks, initiated in front of the shear zone, on the free chip surface, which contribute to chip segmentation. The shear phenomenon, i.e. the initiation of cracks, occurs in the material prior to the forming of primary shear zone. This is visible in Fig. 5(b), where the standard discontinuous lamellae on the free chip surface were generated by adiabatic shear in the primary cutting zone at a 30 degrees shear angle.

Sun et al. [15] claim that the ratio of chip segments generated by adiabatic shear in the total chip mass, increases with the cutting speed, reaching 100 % at 75 m/min. Furthermore, they point out that the frequency of dynamic cutting force generated by emergence of discontinuous chip, as well as the length of the undeformed surface of discontinuous chip, do not depend on the depth of cut, but increase with the feed rate. This causes the dynamical force frequency to be directly proportional to the cutting speed, while being inversely proportional to the feed rate. Variations in dynamic force frequency amplitude are related to discontinuous chip forming and increase with the depth of cut, and feed rate.

Regarding the mechanism of chip forming, and chip form, and its relation to tool wear, identical results were obtained for the cutting speed of 250 m/min. Fig. 6 presents images of the free surface of chip generated by a new tool insert. Due to higher cutting speed, it is visible in Fig. 6(a) that lamellae are more frequent, compared to those generated by machining at the 180 m/min cutting speed.

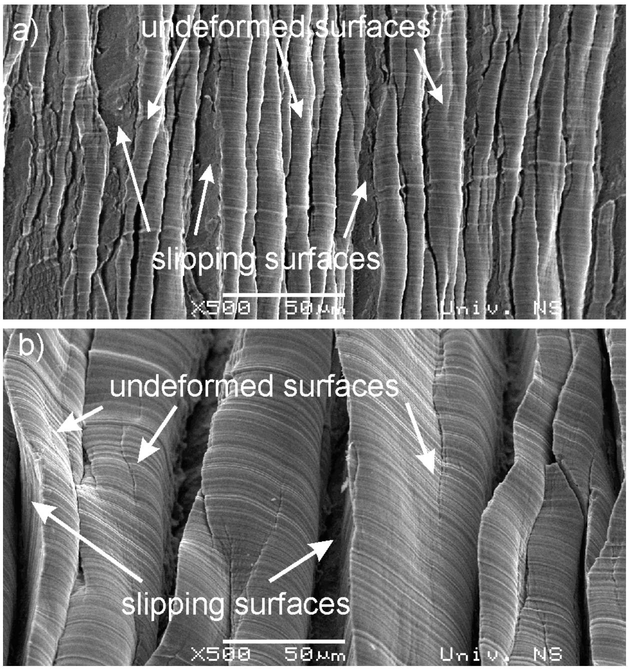

Figure 6 Images of free surface of chip generated by insert tips of various wear degree, at the cutting speed of 250 m/min, feed rate 0,3 mm/rev, depth of cut 2,5 mm: a) new tool insert, b) worn tool insert

Higher cutting speeds were related to more frequent occurrence of lamellae shear, while the continuous chip form remained dominant. This can be documented by Fig. 7(a). Due to higher cutting speed, the shear angle also increased in the primary cutting zone. In addition, similar to the case of 180 m/min cutting speed, the chip cross section exhibits clear change of chip forming mechanism. However, continuous chip forming is still prevalent. Fig. 6(b), and 7(b) show changes in the mechanism of chip forming for a worn tool insert and at the cutting speed of 250 m/min.

Due to higher cutting speed the shear angle also increased with new tool inserts. The discontinuous chip consisted of segments which were slightly deformed in the middle, and were connected by narrow, severely deformed zones alongside which the shear occurred. The highly deformed material layer was formed in the primary and secondary shear zones. SEM examination of the chip cross section generated by machining at 250 m/min also revealed great deformations in the primary and secondary cutting zones which can be attributed to changed cutting geometry due to wear, i.e. due to the change of rake angle with the increase of crater wear, similar to the machining at lower cutting speeds.

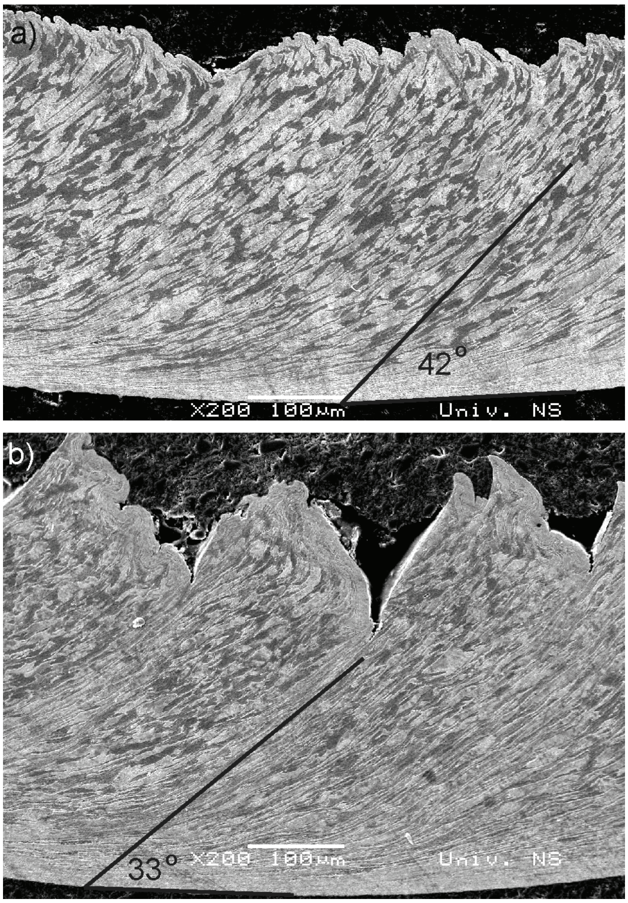

Figure 7 Chip cross section generated at 250 m/min cutting speed, feed rate 0,3 mm/rev, depth of cut 2,5 mm: a) new tool insert, b) worn tool insert

4.2 Analysis of power spectral density (PSD)

Shown in Fig. 8 is the PSD obtained in eight consecutive experiments, run with new tool inserts. From Fig. 8 it is obvious that at frequencies below 5 kHz, high intensity is present, which is attributed to vibrations of the machining system. It is supposed that, at the considered cutting speeds, the segmentation of lamellae is performed at higher frequencies, and it represents one of the dominant sources of vibrations during machining. Also visible from Fig. 8 is overall stability of the system, because the spectrum remains unchanged throughout the whole series of experiments with the new tool insert. Since the PSD was obtained with new tool insert, the influence of vibrations is clearly distinguishable for particular frequencies. Fig. 8 shows obvious peaks at frequencies between 6 kHz and 14 kHz, 20 kHz and 25 kHz, as well as at frequencies around 30 kHz, which is attributed to initial stages of chip segmentation.

Fig. 9 shows machining with severely worn tool insert, and the tool edge damaged by micro cracks. This most probably lead to the "sharpening" of cutting edge, which caused the occurrence of peaks at the same frequencies as with the new tool insert. The main difference with this worn tool insert, compared to the new one, is a significantly higher spectral leakage around the peaks, which indicates important changes in the process of chip forming. The change in the wear level leads to increased slipping friction between the tool rake surface and the chip which is evacuated during cutting, which caused additional vibrations of the machine-tool-workpiece system.

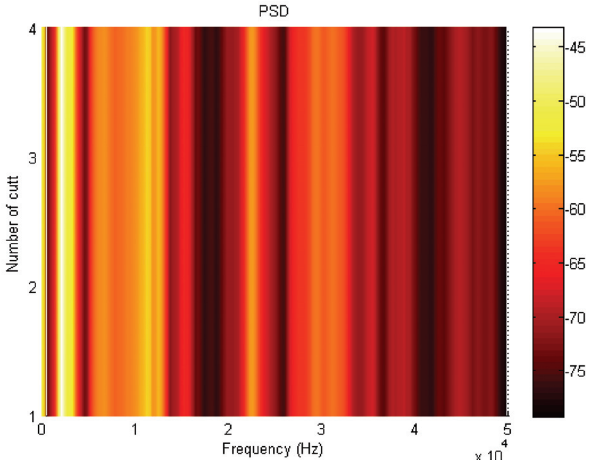

Figure 8 PSD vibrations signal for the new tool insert

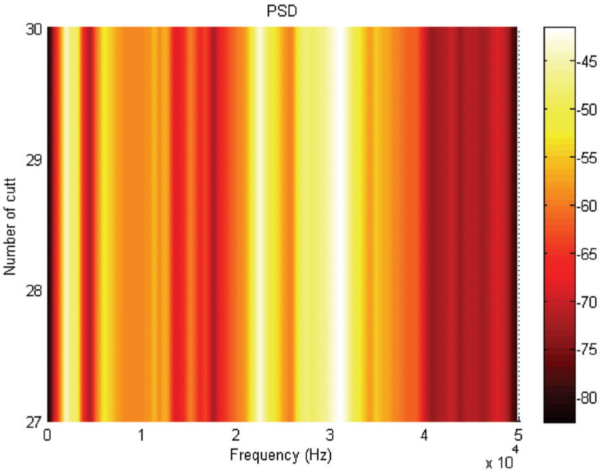

Figure 9 PSD vibrations signal for machining with worn tool insert

Considering the PSD for several measurements with different tool wear degrees, there is a visible change in the spectrum, as shown in Fig. 10. It is obvious that, at higher frequencies (over 6 kHz) the influence of the tool insert degree of wear has more influence on the spectral composition than at the lower frequencies. The peaks at lower frequencies, especially up to 5 kHz, are pronounced and stable, which means that they originate from the machine tool, and not from the machining process. This justifies the approach which is based on using the higher part of the spectrum to define the state of tool edge, i.e. to define the state of tool wear during machining. At higher frequencies, from 50 kHz to 500 kHz, one should expect an even more pronounced dependence between tool geometry state, and the frequency response of the machining system.

The analysis of results from the images clearly reveals the change of PSD at higher frequencies, which indicates that tool wear, i.e. the change in tool edge geometry, suppresses the peaks at higher frequencies, and boosts signal strength. The spectral leakage around the peaks at characteristic frequencies is significantly higher for the worn tool insert, which indicates significant changes in the process of chip forming. Also notable is a multiple energy and power boost at these frequencies. The images show that, at some frequencies, the signal boost from the worn tool reaches up to 10 dB. This eight-fold increase of signal power indicates a very good correlation between the spectrum of dynamic response of the machining system, and the state of the tool cutting geometry.

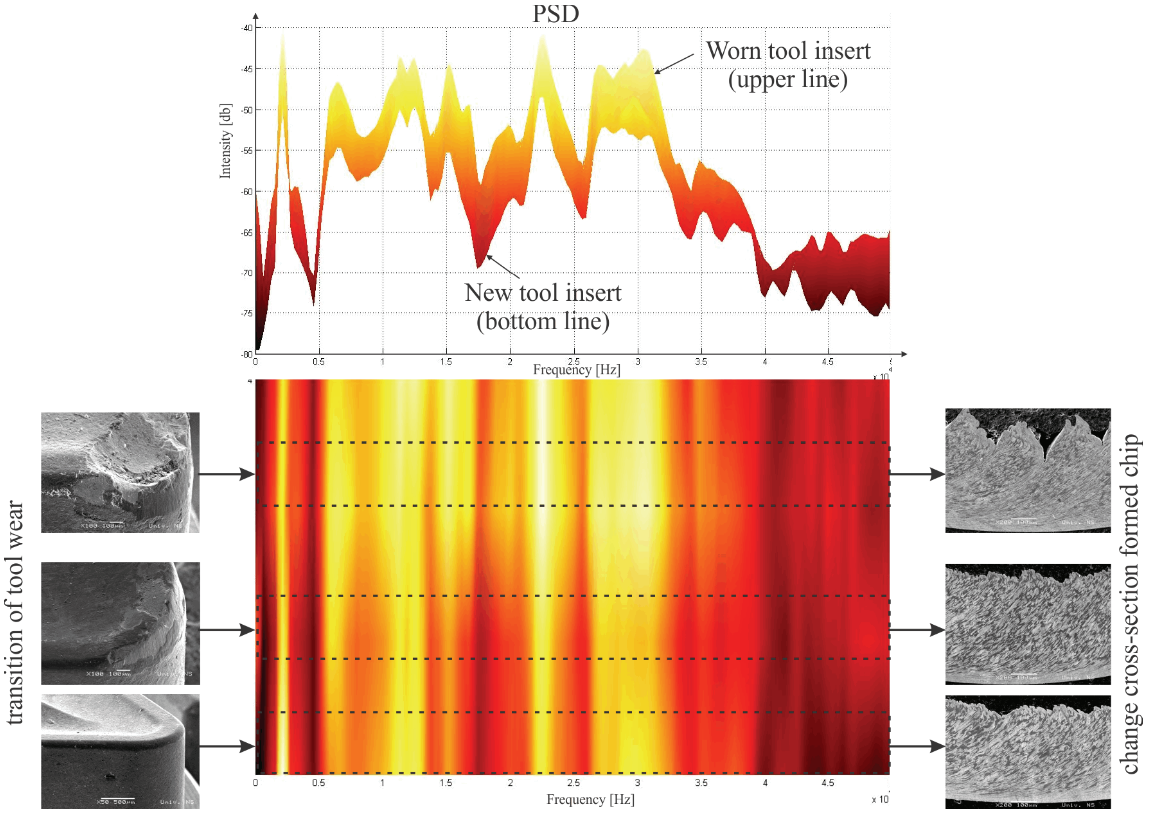

Figure 10 Changes of PSD intensity and chip segmentation for different tool wear degrees

Fig. 10 shows a comparative review of PSD intensity changes for the various degrees of tool wear and chip geometry. The upper part of Fig. 10 shows the change of PSD intensity with frequency throughout tool life. The lower band line corresponds to new tool insert, while the upper is related to the worn one. The bottom segments of Fig. 10 illustrate in parallel the PSD intensity changes and chip forming, depending on tool wear degree at various frequencies. As can be seen, at frequencies above 6 kHz the tool wear degree has more influence on the spectral content of the signal, while at lower frequencies the signal is relatively constant. This confirms the hypothesis that at higher frequencies tool vibrations are dominated by tool wear degree and chip forming mechanism, while at lower frequencies the influence of machining system is dominant.

5 Conclusions

Based on the results obtained by microscopic analysis of chip samples, strong correlation was established between the chip forming mechanism, chip morphology and tool wear degree. Moreover, at constant machining parameters, the change of tool wear degree influences the changes in chip form and type of segmentation. For the machining regimes used in this experiment, the machining with new tool inserts generated continuous, i.e., quasi-continuous chips. Once tool wear degree indicated by *VB* > 0,5 mm was reached, the generated chip was serrated, with distinctive lamellae at free surface. This type of chip is characteristic of thermal softening and adiabatic shear in the primary cutting zone, which is visible in the chip cross section images obtained on an electronic microscope.

Measurements of PSD intensity on tool holder in the immediate vicinity of the cutting zone allowed establishment of correlation with tool wear degree, chip forming mechanism and chip morphology.

Changes in PSD signal measured in the immediate vicinity of the cutting zone were caused by variations in tool/chip interface area on the rake surface, as well as the chip forming mechanism due to progressing tool wear degree. This was confirmed by SEM analysis of chip samples.

Variations of PSD signal measured on tool holder in the immediate vicinity of the cutting zone allow not only better understanding of chip forming mechanism and chip morphology, but can also serve as a good indicator of tool wear in difficult machining conditions, where indirect monitoring methods are applied, such as extraction of characteristic signal features by statistical analysis.

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