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THE INFLUENCE OF TOOL WEAR ON THE CHIP-FORMING MECHANISM AND TOOL VIBRATIONS

VPLIV OBRABE ORODJA NA MEHANIZEM NASTANKA ODREZKA IN VIBRACIJE ORODJA

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In this paper we review an experimental investigation of the influence of tool wear on the chip-forming mechanism and the type of segmentation while turning. A direct microscopic analysis of the chip was used to determine the correlation between the tool-wear degree and the morphology of the chip cross-section. During the machining process the vibrations on the tool carrier were measured in the vicinity of the cutting zone. An analysis of the generated chip and vibration signals during the machining confirmed the hypothesis that changes in the tool-wear degree directly impacts on the chip form and the type of segmentation. This investigation contributes to a better understanding of the chip-forming mechanism and the type of segmentation, allowing us to collect high-quality input information that could be used for the subsequent development of a system for tool-wear identification.

Keywords: tool wear, chip-forming mechanism, turning, tool vibrations

Prispevek prikazuje način eksperimentalnega določanja stopnje obrabe orodja na mehanizem nastanka in tip segmentacije odrezka pri struženju. Na podlagi neposredne mikroskopske analize odrezka je določena korelacija med stopnjo obrabljenosti orodja in morfologijo prečnega prereza odrezka. Med procesom obdelave so bile merjene vibracije nosilca orodja v neposredni bližini cone rezanja. Analizi eksperimentalnih rezultatov pri nastanku odrezka in signalov vibracij, izmerjenih v procesu obdelave, potrjujeta hipotezo, da sprememba stopnje obrabe orodja neposredno vpliva na obliko in tip segmentacije odrezka. Raziskava, opisana v tem delu, je prispevek k boljšemu razumevanju mehanizma in tipa segmentacije odrezka za kvalitetnejše definiranje vhodnih informacij za razvoj sistema za klasifikacijo stopnje obrabljenosti orodja.

Ključne besede: obraba orodja, mehanizem nastanka odrezka, struženje, vibracije orodja

1 INTRODUCTION

The timely detection and replacement of worn tools is one of the key research areas in the domain of optimizing cost-effectiveness and productivity in modern, automated manufacturing. It is estimated that an accurate and reliable system for tool-wear monitoring and identification can contribute to an increase of the cutting speed by 1–50 %. The reduction of manufacturing downtime by timely tool replacement contributes to a reduction of the total manufacturing costs by 10 % to 40 %[1]. Investigations related to an increase of the reliability and performance of systems for tool-wear monitoring are directed towards an experimental determination of the chip-forming mechanism and its influence on the machine-tool–tool–workpiece system, as well as a FEM simulation of the cutting process.[2–4] The chip-forming mechanism and the chip morphology are characteristics that provide key information about the machining process and the quality of the machined surface. The chip-forming mechanism and the type of chip segmentation exert a primary influence on both the tool life and the quality of the machined surface.[5,6] A proper identification and understanding of the chip-forming mechanism can help us to detect tool wear in the machining of harder materials and special steels.[7,8] The chip-forming mechanism, as well as its form and flow over the tool rake surface, significantly impact the tool wear and machined-surface quality. Recent investigations emphasize the importance of a parametric analysis of the mutual influence between the tool-wear degree and the chip-forming mechanism.[9,10]

The analysis of tool-wear parameters established that the most important are as follows: the crater wear on the rake face, the flank wear, and the cutting-edge wear. The chip formed in conditions of intensified cutting speeds causes increased pressure and friction on the tool rake surface, while within the tool/chip interface it directly promotes tool wear, i.e., crater wear. Dutta[11] investigated the influence of the cutting parameters on the various types of composites used in tool materials, and how they affect the quality of the machined surface and the tool-wear mechanism during machining. Among other parameters, he analyzed the macroscopic and microscopic chip structure formed under the influence of various machining regimes. The results were presented in a diagram of cutting-force components and cutting-speed dependence, tool-wear degree, and their influence on the quality of the machined surface and the tool life. Ozcatalbas[12] analyzed the macroscopic and microscopic chip form depending on the cutting regime, also taking into consideration the tool-wear degree, as a secondary parameter. He analyzed the influence of cutting speed on the chip-cutting ratio, as well as the change of the tool-wedge geometry due to the cutting-edge build-up.

Based on "type and form" criteria, the chip is most often classified as continuous, segmented, or lamellar. **Figure 1** shows a typical image of a continuous chip, which exhibits no changes in the cross-sectional structure, with a flat upper side and no distinctive segments.

The generation of a segmented chip during machining causes impulse forces, which, in turn, generate tool vibrations. Investigations related to the registration of dynamic parameters of lamellae forming during machining encompass the acquisition and processing of various sensor signals. Antić[13] used power spectral density (PSD) sensors and a dynamometer to monitor the various dynamic parameters during machining. The obtained results were used as prerequisites for the development of an artificial neural network (ANN) for tool-wear monitoring. The development of the system for real-time signal acquisition and processing allowed the application of direct methods and techniques based on high-res, high-speed cameras in order to determine the chip parameters during machining.[14]

The simultaneous effect of high temperatures and shear stresses on the tool-rake surface cause thermal softening within the cutting zone and the generation of a segmented chip. During machining, the chip lamellae slip along a narrow zone of thermal softening, generating pronounced chip segments. The generated chip features excessive roughness on the free surface, which indicates the presence of adiabatic shear during chip generation. Pronounced chip segments most often appear during the high-speed machining of hard materials. **Figure 2** shows a segmented chip with pronounced lamellae tips on the free surface.

Beri and Gerald[15] considered the chip-forming mechanisms in the machining of tempering steels, concluding that a saw-tooth chip is generated due to thermal softening and adiabatic shear in the narrow zone.

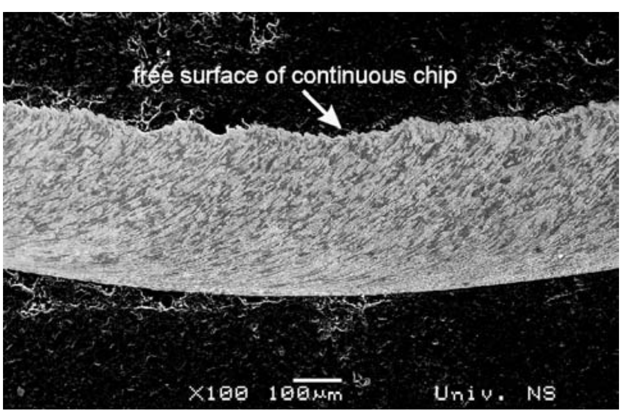

Figure 1: Continuous chip
Slika 1: Kontinuirani ostružek

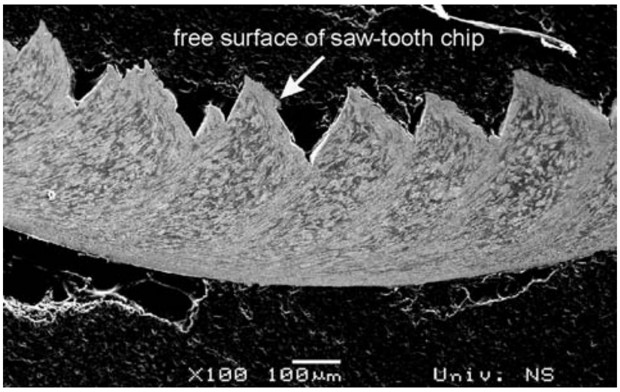

Figure 2: Segmented chip
Slika 2: Segmentiran ostružek

The goal of this investigation was to determine the dependence between the type of generated chip and the tool-wear degree during turning. Direct microscopic measurements were performed to analyze the chip cross-section. In addition, during the experiment, characteristic chip parameters were analyzed to establish a correlation with the tool wear, i.e., tool-wedge degradation.

Reviewed in the introductory section of this paper are the investigations focused on the relationship between the tool-wear degree and the chip-forming mechanism. The experiment was setup based on an analysis of previous investigations. The remaining sections review the experimental results obtained for the correlation between the tool-wear degree and the chip-forming mechanism. The final part presents some conclusions and recommendations for future investigations aimed at a better understanding of the chip-formation mechanism and the creation of requisites for the development of an intelligent system for tool-wear monitoring.

2 EXPERIMENTAL SETUP

Machining experiments were performed on a CNC GU 600 lathe manufactured by INDEX and installed in the laboratory of the Faculty of Technical Sciences in Novi Sad. The investigation of the tool-wear process encompassed the monitoring of the dominant wear mechanism through the following parameters: wear band, crater wear and tool life. In the course of the turning process, the vibration signal and the cutting force were registered at the tool shank. For each tool pass the generated chip segments were sampled. The setup of the tool sensors, as well as the dimension of workpiece used in this experiment, is shown in **Figure 3**. During the experiment two cutting speeds were employed, 180 m/min to 250 m/min, in conjunction with 0.15 mm and 0.3 mm feed rates. The cross-section of the tool shank used in the experiment was 20 mm × 20 mm. The machining was performed with P25 tool inserts designated TNMM 110408. The vibration and force signals were sampled at 625 kHz, with A/D converter

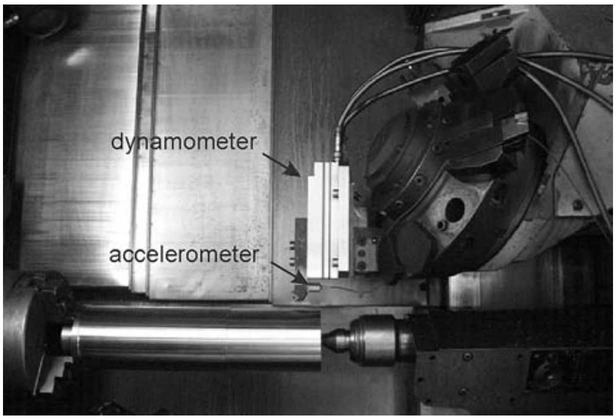

Figure 3: Experimental setup
Slika 3: Postavitev eksperimentalnega mesta

NI625 USB "National Instruments". The workpiece material, 42CrMo4, was of guaranteed mechanical and chemical properties, with a 290 HB hardness.

3 EXPERIMENTAL RESULTS

The experimental results were obtained through a combination of direct measurements of the chip characteristic dimensions on an electronic microscope, and indirect sensor measurements of the forces and vibrations. Variations in the tool-wear degree were monitored through a measurement of the wear band width (VB), which defines the tool flank wear. This measurement was performed periodically on a tool microscope. The results of the VB measurements are shown in **Figure 4** for different cutting speeds during the experiment.

The progression of the tool wear directly impacted the chip-forming mechanism and its form. The results of a direct microscopic analysis provided an insight into the relationship between the lamellae form and the geometric characteristics of the generated chip and

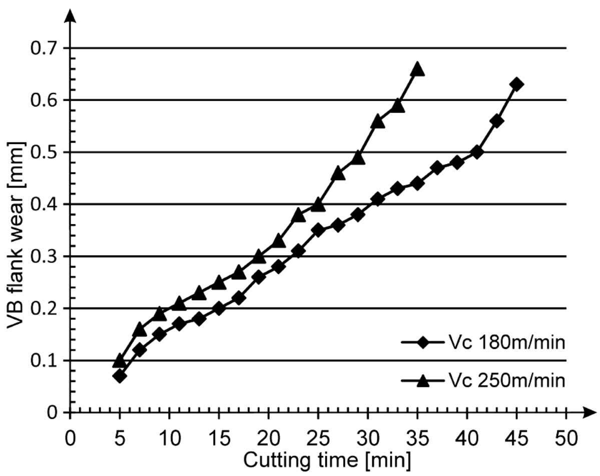

Figure 4: Change of flank wear in time
Slika 4: Potek obrabe proste ploskve

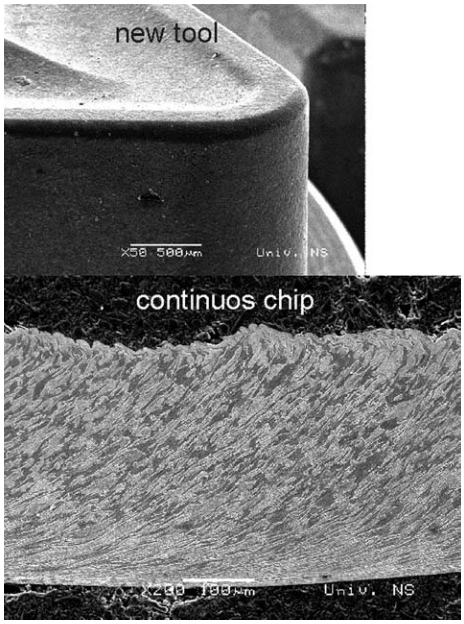

Figure 5: Continuous chip generated by a new tool insert
Slika 5: Kontinuirani ostružek, oblikovan z novim orodjem

tool-wear degree. In most of the cases a saw-tooth chip is a consequence of the adiabatic shear of the lamellae, which is visible from the cross-section of the generated chip.

3.1 Forming of a continuous chip

A continuous chip form is generated through material shear in the primary cutting zone without clearly observable segment borders in the cross-section, and without distinctive segment tips on the free chip surface. The height of the segments on the free-chip surface is very small and corresponds to the width of a single segment. The upper chip zone, closer to the free surface, is mildly wrinkled with only a slight indication of incipient lamellae, as shown in **Figure 5** (right).

Investigations have shown that that the chip form is largely influenced by changes in the tool-wedge geometry, which progresses during the machining process. **Figure 5** shows a cross-section of a continuous chip generated by a fresh tool insert. Obviously, continuous segmentation is taking place, without distinctive separation between the chip segments.

3.2 Forming of a discontinuous chip

As the wear band and the wear crater on the tool rake surface progressively grow, i.e., the cutting geometry degrades, **Figure 6**, the chip form also changes. It is evident that the formed segments were generated through a cyclical process (from the first to the last segment). After a certain machining time, due to the change in tool-wear degree, i.e., cutting geometry, the chip form begins its transformation. From the macroscopic view-

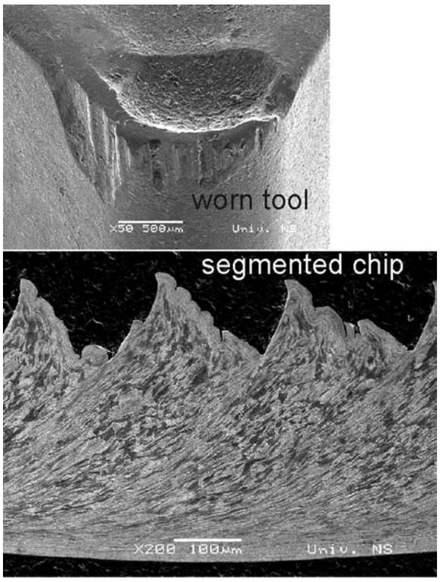

Figure 6: Saw-tooth chip generated by a worn tool
Slika 6: Nazobčana oblika ostružka, nastala pri močno obrabljenem orodju

point, the chip becomes more flat, with distinctive material slip along the basic plane. The tool side of the chip becomes wrinkled and uneven when compared to that generated by a fresh tool insert.

Grain lengthening in the material structure occurs rectilinearly within a narrow band, i.e., the primary cutting zone. It is visible on the cross-section of the generated chip, **Figure 7**. Rather than creating an initial crack and spreading the break towards the tool side of the chip through the primary cutting zone, chip segmentation occurs due to material deformation in the narrow band through thermal softening and adiabatic shear mechanisms. The absence of an initial crack and a distinctive separation of the material between segments in the upper part of the primary zone, indicates the existence of deformations and shear due to thermal softening of the basic material within a narrow zone.

With all the considered chip segments it is possible to clearly identify the change of chip-forming mechanism within the primary shear zone as well as the forming of tips on individual chip segments on the free end. The change of the chip form reflects on the vibration signal, the machined surface quality, and, consequently, the total cost of the machining energy.

4 FREQUENCY OF CHIP SEGMENTATION AND TOOL VIBRATION

Cutting-tool vibrations during machining occur due to friction on the rake and flank tool surfaces, chip segmentation, roughness of the machined surface, etc. The hypothesis of this investigation is that in the high-frequency spectrum there are warping and masking of the information content that is of interest to us. However, there are methods which allow us to extract the information content that can be used to unambiguously detect the current wear degree of the tool cutting edge.

The frequencies at which the forming of the chip lamellae occur can be calculated based on: lamellae pitch, p_c, depth of cut (thickness of undeformed chip segment), h, height of deformed chip segment, h_{ch} and cutting speed, v_c, by applying the following expression:

$$f_{lam} = \frac{v_{ch} \cdot h_{ch}}{h \cdot p_c} = \frac{v_{ch}}{\lambda \cdot p_c} \tag{1}$$

The analysis of the geometric features of the chip cross-section encompassed the following parameters: height of formed segment (tooth), distance between segments (teeth), i.e., segmentation pitch, length of undeformed tooth area, $L_{undeformed}$, length of machined tooth area, $L_{machined}$, and share angle, Φ_{seg}. A typical image of the segmented chip form with characteristic features is shown in **Figure 8**.

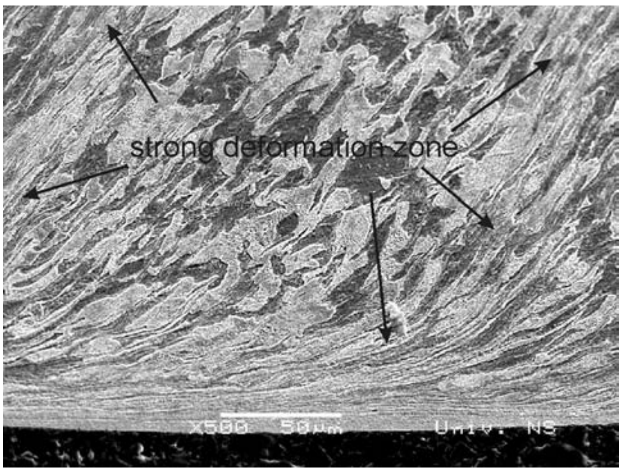

Figure 7: Coalescence of zones with intensive shear on the tool side of the chip
Slika 7: Spajanje con intenzivne deformacije (striga) na hrbtni strani ostružka

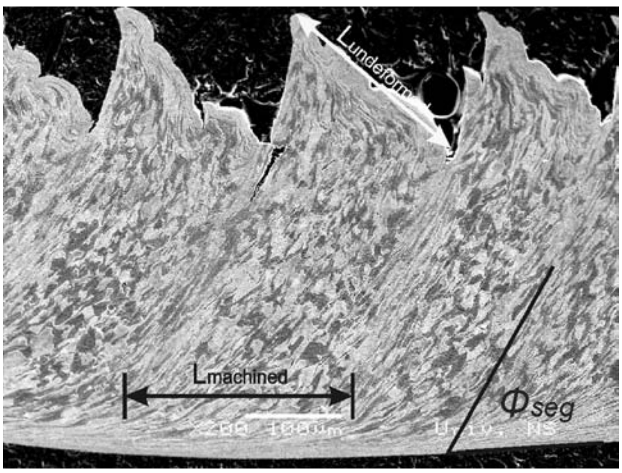

Figure 8: Geometric parameters of the chip segmentation
Slika 8: Geometrijski parametri segmentiranja ostružka

Geometric relationship between the length of the undeformed area and the length of the machined area of a single tooth is given by[16]:

$$r = \frac{L_{\text{undeformed}}}{L_{\text{machined}}} \quad (2)$$

In the case of an ideally continuous chip, this geometric relationship is $r = 1$ due to the lengths of the undeformed and machined areas being equal. In the case when $r < 1$, the newly formed segment is pushed forward along the slip plane, which causes the formation of wrinkling on the chip-free surface, while the machined segment area is elongated on the tool rake surface due to the friction coefficient. If $r > 1$, the newly formed segment is pushed forward along the slip plane towards the free surface and relieved of stresses resulting from the tool tip pressure, which results in a shorter tool-side chip area due to the lower pressure and the friction of the segment along the tool rake surface. The increase of cutting speed leads to a gradual decrease of the continuous shear and the chip becomes segmented in a periodical manner, showing very pronounced shear zones due to higher temperatures. In the shear zone, the material deformation is pronounced, while being much lower in the very segment, which can be seen in **Figure 9**. The degree of chip deformation during the cutting process can be calculated from $\varepsilon = (h_1 - h_2)/h_2$[17].

This degree of chip deformation was calculated for the five contiguous chip segments and the mean value was used as a relevant parameter. Shown in **Figure 9** are the parameters that were measured and used to calculate the degree of chip deformation.

Based on the measured parameters shown in **Figure 9**, and the calculated degrees of chip segmentation, a diagram was made that shows the correlation between tool-wear degree and chip-segmentation degree, shown in **Figure 10**.

The measurements showed that during the initial phase (fresh tool insert), for all cutting regimes, a continuous chip is generated. Once a particular tool-wear

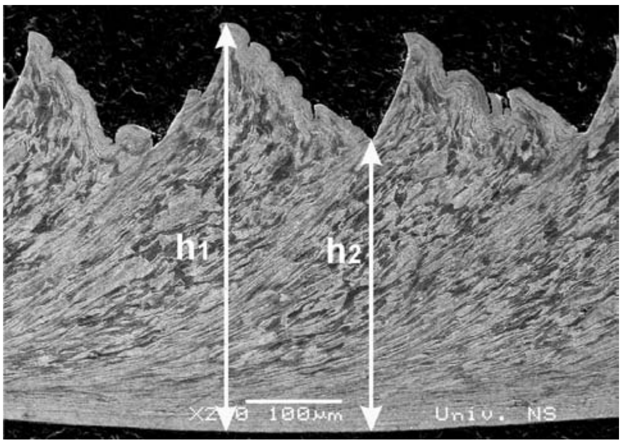

Figure 9: Parameters for calculation of the chip-deformation degree
Slika 9: Parametri za določanje stopnje deformacije ostružka

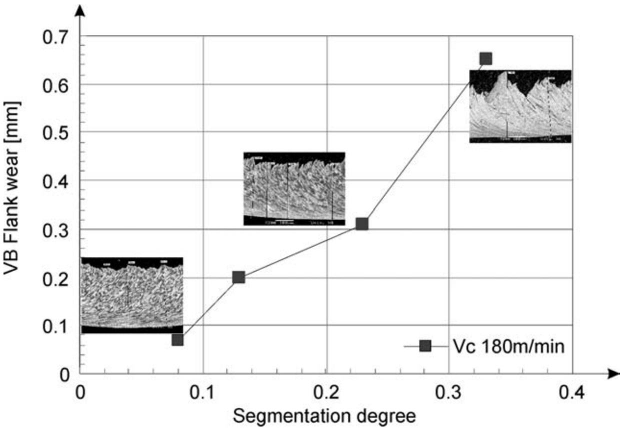

Figure 10: Correlation between chip-segmentation degree and tool wear
Slika 10: Korelacija med stopnjo segmentiranja ostružka in obrabo orodja

degree is reached, the chip changes its forming mechanism, which results in a saw-tooth chip form. This change in cross-section geometry and form is gradual and without abrupt transitions from one form to another. Certain variations in the chip-deformation degree, observed during the experiment, can be attributed to build-ups on the cutting edge, i.e., the change of cutting geometry during the cutting process.

One of the key parameters that define the character of vibrations during machining is the frequency of lamellae generation. **Figure 11** illustrates the change of frequency of chip-lamellae generation due to the variable depth of the flank wear. The frequency of chip-lamellae generation linearly decreases with the increase of flank wear depth, and increases with the progression of the depth of cut. A larger depth of cut reduces the frequency of lamellae-chip generation. Such a wide range of frequencies is the cause of large variations in the cutting force on the tool cutting edge.

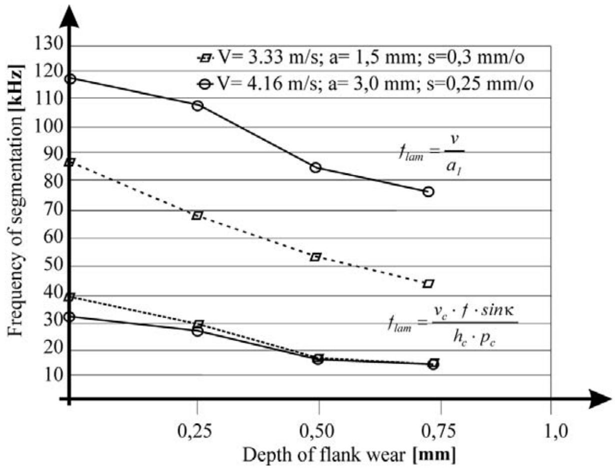

Figure 11: Dependence of the frequency of chip-lamellae generation on the tool-wear degree
Slika 11: Odvisnost frekvence nastanka lamel ostružka od stopnje obrabljenosti orodja

5 CHARACTER OF VIBRATIONS DURING THE CHIP-FORMING PROCESS

The forming of single-chip segments during the generation of a discontinuous chip results in an increased energy release and higher vibration amplitudes in comparison with a continuous chip. In addition, the consequence of discontinuous chip forming is a higher deformation energy, adiabatic shear, a varied vibration response, and the occurrence of self-excited vibrations. Tool self-excited vibrations are within the 1–50 kHz range, thus some resonance can be attributed to chip segmentation. The forming of a segmented chip can be viewed as a process of the discrete excitation of the machining system by a series of impulses whose frequency can be determined within an acceptable error margin. The vibrations occurring during machining can be detected through the response of a machining system, especially on the tool shank. An analysis of the experimental results revealed that the frequency response of the machining system varies according to the type of generated chip. The monitoring of signal, i.e., the frequency of the chip-segment forming, revealed changes in the high-frequency part of the spectrum. This was visible as an amplification of the generated signal, as shown in **Figure 12**. The frequency of lamellae generation is destabilized by the primary shear zone and the chip-forming mechanism. As already mentioned, the frequency of lamellae generation is usually higher than 10 kHz, which is beyond the measuring range of conventional accelerometers. A more pronounced peak occurrence in the analyzed vibrations spectrum was spotted at higher frequencies, closer to those characteristic of lamellae formation. The difference in signal intensities is related to a release of higher energy during the forming of a discontinued chip, as well as higher friction at the chip/tool interface. **Figure 12** illustrates the described occurrences, speaking in favour of the assumption that the vibration range above 1 kHz contains a signal that can be used for tool-wear identification. The spectrum of vibrations measured on the tool shank close to the cutting zone is a good indicator of the change in chip-forming mechanism and chip type, caused by tool-wear progression, i.e., cutting-edge degradation.

Figure 13 illustrates the spectra of signal (in [dB]) for various tool-wear degrees, with the following parameters: window = 2048; overlap = 512; pwelch (data_N (:,1), window, overlap,[], Fs). The frequency spectrum was limited to 50 kHz. The equipment used in this experiment allows measurements in a wider frequency spectrum (up to 100 kHz), but the limiting factor was the accelerator.

Besides cutting regimes, and the state and characteristics of the workpiece material, it is the tool-wear degree that also exerts a great influence on the type of chip generated during machining. The progression of the tool wear leads to a change of the chip type and form, regardless of constant machining parameters: speed, feed rate, depth of cut, and material characteristics. Changes in the chip type are caused by a variable cutting geometry, which is a function of the tool-wear degree. Changes in the cutting geometry and chip type directly influence the considered parameters within the analysed high-frequency part of the vibration spectrum.

6 CONCLUSIONS

A chip generated during the initial stage of machining (fresh tool insert) is flat-shaped with s smooth tool side, which is in full contact with tool rake surface, while the chip-free surface exhibits no segment teeth. Through widening of wear band and tool crater wear, the chip changes form and becomes rougher, wrinkled and

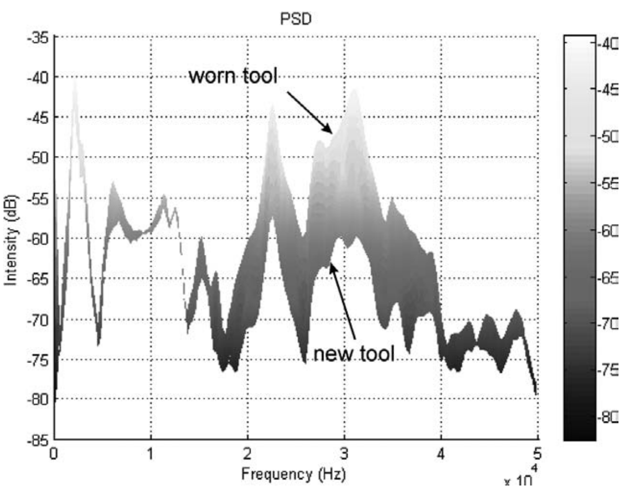

Figure 12: Energy distributions along the frequency axis for new and worn tools

Slika 12: Porazdelitev energije signala po frekvenčni osi za novo in obrabljeno orodje

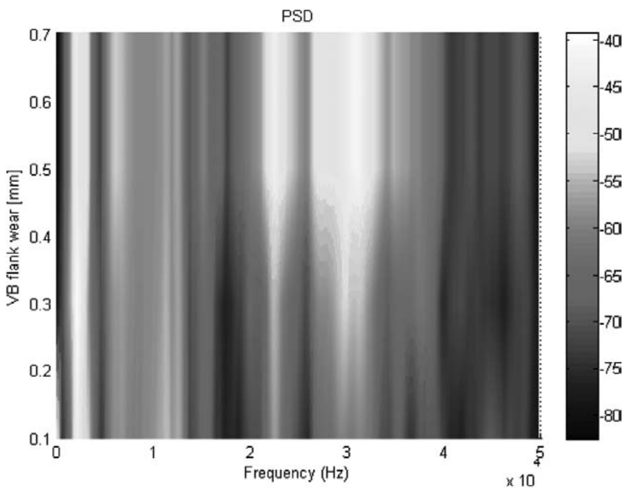

Figure 13: Variations in the vibration signal spectrum along the frequency axis, depending on tool-wear degree

Slika 13: Sprememba spektra signala vibracij po frekvenčni osi v odvisnosti od stopnje obrabljenosti orodja chipped at the ends, while the type of chip segmentation changes into discontinuous with highly pronounced teeth on the free-chip surface. A further increase of the flank wear leads to an intensification of the chip segmentation, while the frequency of lamellae generation decreases. Plastic deformation of the material in the primary cutting zone becomes more pronounced with a distinctive border between the formed segments. The cross-section of the generated chip exhibits very pronounced wrinkles on the free side in the various zones of material deformation during machining. This indicates the combined action of stress strengthening and thermal softening, i.e., the existence of a dual action in the chip formation. The zone of thermo-plastic instability has a dominant role up until the emergence of the shear zone and the forming of chip segments, when the cutting process conforms to adiabatic shear theory. The vibration response is variable, with pronounced peaks at frequencies that correspond to the frequency of lamellae generation. The change in the chip type causes the emergence of new frequency components (harmonics), which are close to the frequency of lamellae generation, with the periodic occurrence of self-excited vibrations in the interval near the tool's end-of-life.

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