Wear level influence on chip segmentation and vibrations of the cutting tool

Vpliv stopnje obrabe na segmentacijo odrezka in vibracije rezalnega orodja

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Abstract: The paper presents the experimental research on wear level influence on chip formation mechanisms, chip segmentation morphology and tool vibration in turning. Based on the direct microscopic analysis of chip samples, the correlation has been established between tool wear condition and chip cross-sections. During the processing, the tool girder vibrations in the zone close to the cutting area have been registered. On the basis of the comparative analysis of experimental results (electronic microscope) and vibration signals registered in the machining operation, the correlation between tool wear level and the variation in chip segmentation form and type has been defined, as well as the frequency characteristics of the vibration. The aim of the research described in this paper is to contribute to the better understanding of chip segmentation mechanism, typology and morphology, in the sense of more qualitative definitions of input information for development of the system for tool wear condition classification.

Original scientific paper

Povzetek: V prispevku je prikazana eksperimentalna raziskava vpliva stopnje obrabe orodja na mehanizem nastanka in tip segmentacije odrezka ter vibracije orodja pri struženju. Na osnovi direktne mikroskopske analize odrezkov je formulirana korelacija med stanjem obrabe orodja in obliko prečnega prereza odrezka. Med procesom struženja so bile merjene vibracije nosilca orodja v neposredni bližini cone rezanja. Na osnovi vzporedne analize eksperimentalnih rezultatov (SEM-mikroskop) in signalov vibracij, merjenih med procesom struženja, je bila definirana korelacija med stopnjo obrabe orodja s spremembo oblike in tipom segmentacije odrezka, kot tudi frekvenčne karakteristike vibracij. Cilj raziskav, opisanih v tem delu, je prispevek k boljšemu razumevanju mehanizmov, tipov in oblik segmentacije odrezkov v smislu kvalitetne definicije vhodnih podatkov za razvoj sistema za vrednotenje obrabe orodij.

Key words: Tool wear, chip morphology, chip segmentation, vibration spectre

Ključne besede: obraba orodja, morfologija odrezka, segmentacija odrezka, vibracijski spekter

Introduction

The understanding of the correlations between chip formation mechanisms and tool wear in machining operations has a significant role in determining the influences on tool vibration, on attrition in the contact point between tool and chip in the cutting process, as well as on determining the optimal machining conditions. Based on the analysis on the cross-section type and morphology of the formed chip, it is possible to determine the following parameters: dimensions, shape and frequency of the chip lamella segmentation.[1] Thermal and chemical processes in the cutting zone at the contact point between the chip and the front tool surface cause the appearance of the diverse mechanisms and forms of tool wear. The most common forms are crater wear on the front tool surface, flank wear on the rear surface and cutting edge wear.[2] The chip formed in the condition of the increased cutting velocity and supplementary movement at the contact point between the tool and the chip induces the increased pressure on front tool surface and directly influences the velocity of the increasing wear, i.e. crater wear. Except for the better understanding of the chip formation mechanisms, chip morphology can be utilized as a tool wear condition indicator in unfavourable machining conditions. The formation mechanism, shape and direction of a chip on a front tool surface have a significant impact on wearing and the quality of the product's machining surface. In their papers, Ozcatalbas[3] and Dutta[2] analysed of the formed chip shape depending on the tool wear level. One of the important sources of tool vibrations in the machining process is the formation of chip segments. In material cutting, during the segment formation, the segmented chip induces the force impulses that generate vibrations of the tool itself. In that sense, Sun[4] researched the frequencies of chip lamella formation depending on the dynamic component variation of the cutting forces. Likewise, the research directed towards the registration of the dynamic parameters in chip lamella formation processes during turning includes the application of diverse sensors and experimental research techniques. Petrovic[5], Antic[6, 7] and Klancnik[8] used acceleration gauges for monitoring diverse dynamic parameters in the chip formation process as a basis for the development of fuzzy systems for tool wear monitoring. Furthermore, besides the stated indirect methods, Cotterell & Byrne[9] used in their research direct methods and techniques based on the high resolution cameras and high sampling rate in order to determine types and parameters of formed chips in turning, for the usage in real industrial cutting regimes.

Chip formation mechanism and its classification can be determined on the basis of the following: material microstructure, cutting speed, supplementary movement speed, cutting depth, shear angle, etc. The result of the common classification in chip morphology, type and form in turning is the classification into: continual, segmented and strip chips. Figure 1 presents the typical appearance of a continual segmentation chip with no variations in cross section structure, where the loose chip surface is flat and with no clearly distinctive lamella teeth.

Figure 2 presents a discontinual segmented chip with very distinctive lamella peaks on the loose chip end. This is the dominant form of the chip originating from the machining of the material with the increased hardness (Titanium alloy and the like). Likewise, the segmented chip is the consequence of the machining of the thermally improved materials in higher cutting speed regimes.

Discontinual type chip is the result of machining the material with dominant thermo-plastic instability. Inside the primary cutting zone, the action of shear forces and cutting forces leads to the material sliding as a consequence of thermal softening, and the discontinuity on the loose chip end is formed. The outcome of these

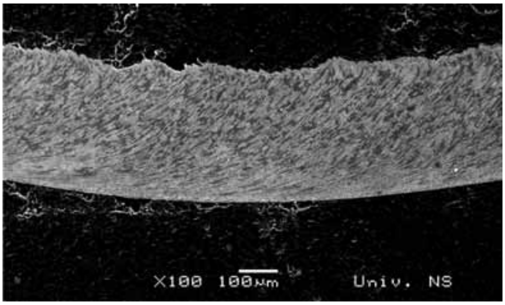

Figure 1. Continual chip

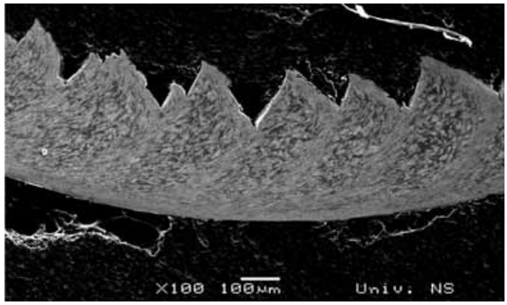

Figure 2. Segmented chip

actions is chip formation based on the adiabatic shear mechanism and discontinual type chip formation with clearly defined intensive shear zones which spreads inside the material structure. BARRY & GERALD[10] considered chip formation mechanisms in machining hardened steel and concluded that the cause of the intensive shear appearance inside the primary zone is the adiabatic type of chip formation resulting in the saw-like form of the chip. Inside the primary cutting zone, i.e. the narrow strip with highly distinctive shear, the dominant is the shear stresses aiding at the material movement of the formed segment towards the loose chip surface. The increase in material hardness, cutting velocity, cutting depth and negative front angle, in the combination with the increase in tool wear, leads to a saw-like chip type. Furthermore, it is experimentally determined that the deformed part of the chip cross section reduces with the increase in cutting speed.

The objective of the research presented in this paper is to characterize chip lamella formation in turning depending on tool wear level and based on the direct microscopic analysis of the formed chip. The comparative analysis of frequency of vibration, chip lamella formation frequency and direct microscopic analysis results can present the formulation for the correlation between tool wear level and chip formation type, with the possibility of defining the robust indicator for tool wear monitoring.

CHIP FORMATION MECHANISM

A great number of researches in the area of real industrial production have had a goal to classify chip formation in dependence to the material micro structure, cutting speed, supplementary movement speed, cutting depth, shear angle, etc. Chip formation mechanism in high cutting speed circumstances differs from those in conventional machining process.[11, 12] Namely, the chip generated in machining hard and improved materials in most cases is either a continual chip or a saw-like chip, as presented in Figures 1 and 2. According to available literature information, saw-like chip formation is in most cases the consequence of the adiabatic lamella shear. Geometric characteristics of a segment are as follows: tooth height, tooth span, undeformed tooth surface length ($L_{undeformed}$), tooth machined surface length ($L_{machined}$), and shearing angle (Φ_{seg}), as presented in Figure 3.

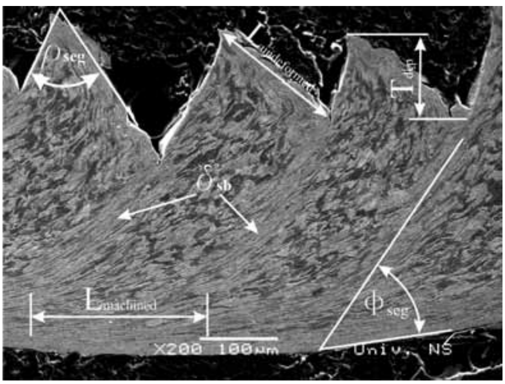

Figure 3. Chip segmentation parameters

Geometric ratio between a tooth undeformed surface length and a tooth machined surface length is presented by the expression (1).[4]

$$r = \frac{L_{udeformed}}{L_{machined}} \qquad (1)$$

In the case of ideal continual chip, this geometric ratio is $r = 1$ due to the fact that both undeformed and machined surface on the formed chip have the same length. If $r < 1$, the newly formed segment is pushed along the sliding plane ahead, due to which a crease is formed on the loose chip surface, and the machined segment surface is elongated along the front tool surface due to sliding attrition. If $r > 1$, the newly formed segment is pressed along the sliding plane forward towards the loose chip surface and it is realised from the tool peak action, forming a shorter machined surface due to less segment pressure and attrition on the front tool surface. Due to the increase in cutting speed, the continual (constant) shear gradually disappears and the chip presents the appearance of the periodical segmentation in rather distinctive zones where the material sliding is under the shearing angle from 30° to 45°. Material deformation is distinctive in the shearing zone δ_{sb}, while the material deformation in the segment is very small, as can be observed in Figure 3. It is important to mention that, due to such intensive material sliding, crack can also appear, and they can be observed together with the shear band in all cutting velocities.

Survey of experimental results

The experimental research with direct measurement on an electronic micro-

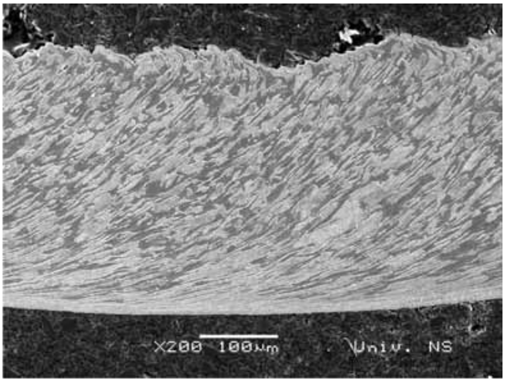

Figure 4. Continual chip segmentation

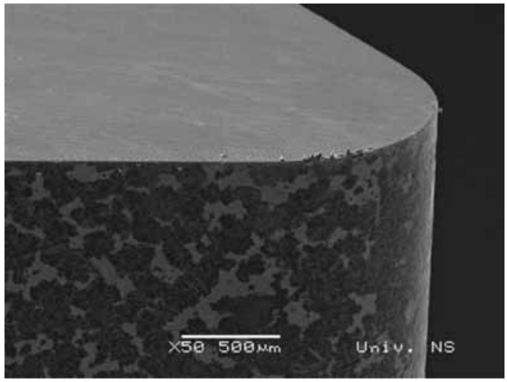

Figure 5. Tool wear condition in generating a continual chip

scope, presented in the paper, provides a good insight into the characteristics and shape of chip lamellas depending on the tool wear level. The variation in tool wear level has a direct impact on the variation of the type and form of chip formation, which is the result of the analysis on cross-sections and loose chip surface.

CONTINUAL CHIP FORMATION

Continual chip is formed by material shear in the primary cutting zone with no clearly defined segment boundaries in cross-section and no distinctive bumps on the loose chip surface. Chip formation frequency is one order larger than in the case of saw-like chip[13]. A significant influence on the lamella mechanism and shear mode in creating a certain type of a chip is related to the ratio of feed and cutting speed. The loose surface of the formed chip in machining with a new tool (continual chip) has no clearly distinctive difference in the height of the formed lamellas. The experiments do not show a direct link between chip type variation and chip thickness variation. With continual chips, the segment height on the loose chip surface is very low and corresponding to the width of an individual segment. With the formation of the discontinual type segment, the segment width is the same order as the cutting depth and it is approximately 50 % of the cutting depth.

Figure 4 presents a chip cross section formed by continual segmentation. The upper chip zone presents a loose surface of a continual chip with the mildly wavy shape and tiny indications of the beginning of lamella formation. The samples of the presented chip have been obtained by an orthogonal cutting

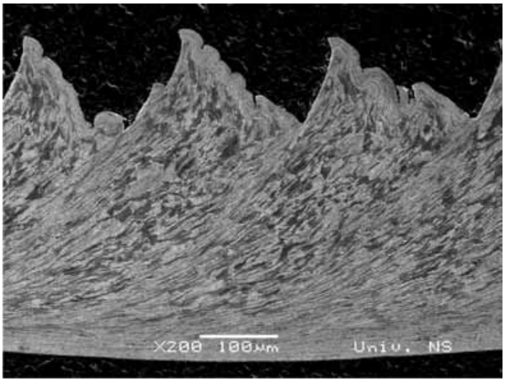

Figure 6. Saw-like type of chip segmentation

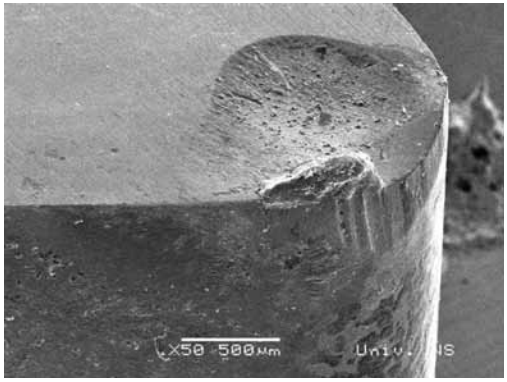

Figure 7. Tool wear condition at the time of generating a discontinual chip form

process of low alloyed tool steel with the hardness of 45 HRC. Machining parameters are the following: cutting speed is 200 m/min and feed is f = 0.2 mm/r. Figure 5 presents the cutting tool wear condition in generating a continual chip.

Discontinual chip formation

On a loose surface of a discontinual chip, presented in Figure 5, one can clearly observe the intensive shear zone on the boundaries of formed segments. Figure 6 shows a microscopic view of a chip generated on the thermally treated low alloy carbon steel, with the hardness of 45 HRC and the cutting speed 200 m/min. The increase in the wearing band and wearing crater on the front tool surface, i.e. the increase in the degradation level of the cutting geometry, Figure 7, leads to the variation in the type of the formed chip. It is evident that formed segments originated in the cycle process of segment creation beginning with the first segment all the way to the last one. After a certain period of machining, due to variations in tool wear level, the chip type also began altering. Microscopically observing, chip form becomes flatter with more distinctive material sliding on the main plane. Rear chip surface becomes wavy and uneven in comparison to the one obtained after new tool machining process.

Grain extension in material structure appears as linear in the narrow band, i.e. primary shearing zone, and it is visible in the cross section of the formed chip, as in Figure 8. Instead of creating an initial crack and break spreading downwards through the primary sliding zone, the generated deformation band is localised as a band formed due

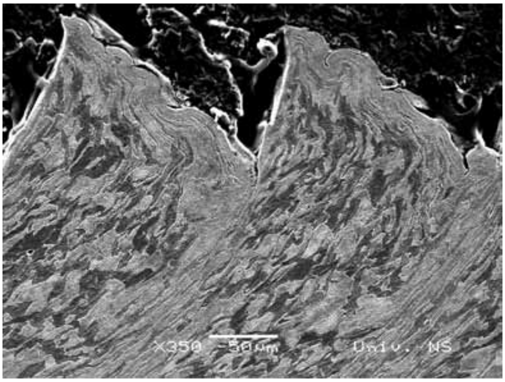

Figure 8. Discontinual form of chip segmentation

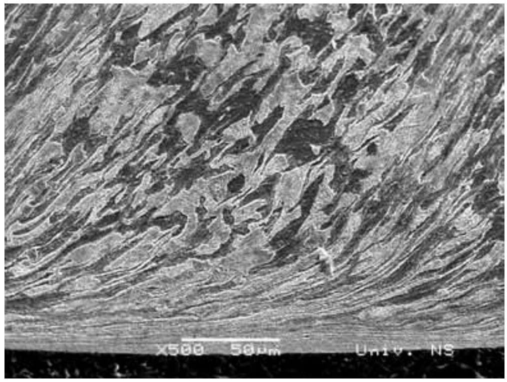

Figure 9. Merging of the intensive shearing zones on rear chip side

to adiabatic material shear. The lack in the appearance of an initial crack and distinctive material separation among segments in the upper part of the primary shearing zone demonstrates the existence of stress deformation and relaxation due to the influence of thermal softening of the main material in the narrow zone. This conclusion is based on the fact that the appearance of the very pronounced shear zone and its width is related to the sampling material, tool geometry and shape, presenting a shear initialization due to the action of cutting forces and tool's cutting edge.

The material band along the rear chip edge, which leads over the front tool surface, creates an additional shear along the edge of the chip formed due to secondary cutting zone action. The elongated zone of the rather distinctive material shear formed in the narrow zone of the rear chip side transfers to the distinctive shear band within the primary sliding zone creating individual chip segments, as it can be observed in Figure 9.

The machining conditions, in which the discontinual type chip is generated, with the very distinctive segment ends on the loose chip surface, are identical in everything to the ones in machining in which the continual chip is generated, except in the case of tool wear level. Within the observed chip segments, one can clearly identify the variations in the chip formation mechanism within the primary shear zone and the formation of the individual segment peaks on the loose chip end. It is believed that this chip shape is the consequence of s in machining conditions due to variations in cutting tool wedge geometry due to wearing. The variation in the chip morphology reflects on vibrations, processed surface quality and energy loss for material splits removal.

Vibrations and frequency of chip segmentation

One of the main parameters defining the character of vibrations in the cutting process is the frequency of lamella formation. Cotterell & Byrne[9] determined the frequency of lamella formation in their researches used f_{seg} analyses of video surveillance of lamella formation. The frequency of forming chip lamellas has a linear increase with the increase in the cutting speed, and has a decrease with the increase in the cutting depth. Frequency of creating a lamella chip has the range between 3.8 kHz and 250 kHz in processing hardened materials.[14] This range of chip segmentation frequencies also causes great force variations on the tool cutting edge.

The frequency of chip lamella formation can be calculated on the basis of the following: steps in the formation of lamellas p_c, cutting depth (width of the undeformed chip segment) h, height of the undeformed chip segment h_{ch} and cutting speed v_c, on applying the following expression:

$$f_{lam} = \frac{v_c \cdot h_{ch}}{h \cdot p_c} = \frac{v_c}{\lambda \cdot p_c} \qquad (2)$$

The vibrations in the cutting tool during machining appear due to attrition on the front and flank tool surface, wear on the tool cutting edge, bumpiness of the processed surface, etc. The basic tool vibration frequency is the resonant system frequency caused by attrition and cutting forces on the cutting edge. Since the cutting tool vibrations are high frequency vibrations (over 1 kHz), the tool vibration acceleration is selected as a parameter for tool wear monitoring.[15, 16] Vibration acceleration signal is directly in correlation to the cutting process, and also with other vibration sources due to the interaction with the tool and machining system. These researches began with the assumption that in a certain segment of the frequency spectre there is a distortion and masking of the information content which is of interest, yet it appears in such an amount that, with the application of adequate procedures, there is a possibility for extracting the information content which will aid in undoubted recognition of the current wear condition of the tool cutting edge. Monitoring the wearing process and evaluating the tool wear condition that enables a normal cutting process provides conditions for fulfilling the set quality in shapes and micro-geometry of the formed surface.

Figure 10 presents the dependency between lamella segmentation and tool wear level. It can be observed that the increase in tool wear decreases the segmentation frequency for constant cutting conditions. The research in chip segmentation explains the mechanism of chip lamella formation.

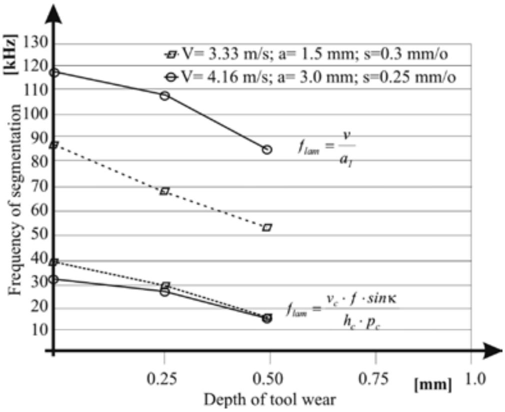

Figure 10. Dependency between lamella formation frequency and tool wear level

Vibration character in chip formation process

The formation of initial crack inside the primary shearing zone and individual chip segments during the appearance of discontinual chip results in the increased level of energy release and vibration amplitude in comparison to the continual chip. The result of discontinual chip formation is the increase in deformation energy, the appearance of adiabatic material shearing, the variations in vibrations and the appearance of self-induced vibrations. This assumption provides the connection between vibrations and cutting depth during the continual chip formation. Chip formation induces a significant level of vibrations and acoustic emission (AE) regardless the chip shape and type. If the chip width is small enough, the extension of initial crack and spreading towards the front tool surface is such that stresses and energy can be measured. The conducted researches indicate that the high-frequency segment of vibration features measured on the handle of the turning knife in the zone close to the cutting zone presents a good indicator in the variation of chip mechanism and formation type induced by cutting tool wear condition variation, i.e. degradation of its cutting edge by wearing. In the range between 1 kHz and 50 kHz the majority of tool's own vibrations is situated, so certain resonance appearances due to self-induced forces appear after chip segmentation. The formation of segmented chip can be observed as a process of discrete self-induction of the processed system with a set of impulses whose frequency can be determined with an acceptable error. Vibrations emerging during machining can be recognized in the processing system, especially on the cutting tool handle. From the analysis of experimental research results, it is concluded that the processing system outcome is different when the self-induction is induced by continual chip formation. Inside any chip segment formation cycle, the cutting identification is also destabilized by the very primary shearing zone, resulting in energy release and stress formation. As already stated, the frequency of segment formation

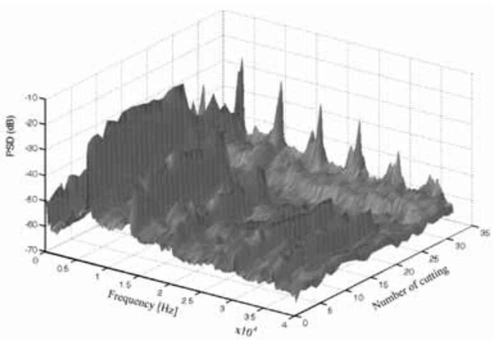

Figure 11. Signal energy distribution on frequency axis depending on the tool wear level

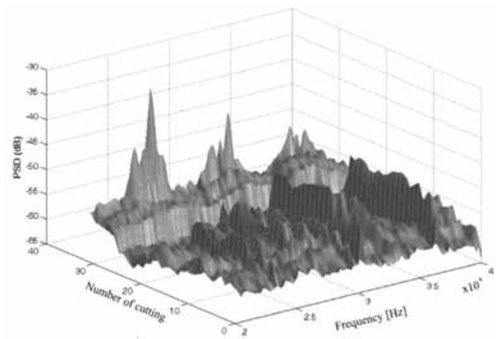

Figure 12. Signal energy distribution on frequency axis depending on tool wear level

is usually larger than 10 kHz, which is above the measuring performances level of typical acceleration gauges. The more distinctive appearance of peaks in vibration signals is observed on releasing the lamella shearing energy after generating the discontinual chip shape. Figure 11 illustrates these cases.

The analysis of the results in these experiments can provide the conclusion that the dominant influence on the type of the formed chip in the cutting process does not only have the condition and characteristics of materials and cutting conditions, but also has wear condition of the tool insert, i.e. tool geometry. Furthermore, it is determined that in maintaining constant cutting conditions (speed, feed, cutting depth, material characteristics), due to variations in tool wear level, there appears the variation in the chip type. The variation in chip type is induced by the variation in cutting geometry which alters with the tool wear level. The variation in cutting geometry, and hence chip type, directly influences the observed parameters in the analysed high-frequency segment of the vibration spectre.

Figure 12 presents signal energy spectres (in [dB]) for diverse tool wear levels processed with the following parameters: window = 2048; noverlap = 512; pwelch (data_N(:,1), window, noverlap,[], Fs).

Frequency spectre is limited to 50 kHz. The used equipment provides measuring accuracy even for a wider frequency range (up to 100 kHz), which has not been done due to limitations of the available acceleration gauge.

Conclusion

The research analysed the variation in the mechanism of chip formation process in dependence to tool wear level. The formed chip in the initial machining phase (new tool) has a flat shape with smooth rear part which is in contact with the front tool surface, while the chip loose surface has no distinctive lamella segment teeth. Cutting tool is new, sharp and without any indications of crater formation on the front surface. After the increase in wear band and crater tool wear, the chip varies the shape, and becomes more bumpy, wavy and cracked on its ends, while the segmentation type varies into the discontinual one with very distinctive teeth on the chip loose surface. The increase in flank wear increases the chip segmentation while the lamella formation frequency decreases, as it can be observed in Figure 10. The plastic material deformation in the primary cutting zone becomes more distinctive with the clear boundary between formed segments. The cross section of the created chip has very distinctive roughness on the chip loose surface in diverse zones of material deformation in the cutting process: zones with distinctive attrition next to the tool edge, primary shearing zones, zones with distinctive initial crack, and zones with decreased material deformation. It indicates the combined action of the stress toughening and heat softening, i.e. the existence of the combined action in chip formation. The formation of the discontinual type of the chip is characterized by thermal and plastic deformation due to tool and cutting force action. The zone of thermal and plastic instability dominates until the beginning of segment formation and formed shear zone. Thus, in that segment, the cutting is conducted by "adiabatic theory" of shear. Vibration response is variable, with distinctive peaks in individual frequencies overlapping with the chip segmentation frequency. The variation in chip type causes the appearance of new frequency components (harmonics) which are close to lamella formation frequency, with the occasional appearance of self-induced vibrations in the moments when the tool is at the end of its life span.

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References

[1] Barry, J., Byrne, G., Lennon, D. (2001): Observations on chip formation and acoustic emission in machining Ti–6Al–4V alloy. *International Journal of Machine Tools & Manufacture;* Vol. 41, pp. 1055–1070.

[2] Dutta, A. K., Chattopadhyaya, A. B., Rayc, K. K. (2006): Progressive flank wear and machining performance of silver toughened alumina cutting tool inserts. *Wear*; Vol. 261, pp. 885–895.

[3] Ozcatalbas Y. (2003): Chip and built-up edge formation in the machining of in situ Al4C3–Al composite, *Materials and Design;* Vol. 24, pp. 215–221.

[4] Sun, S., Brandt, M., Dargusch, M. S. (2010): The Effect of a Laser Beam on Chip Formation during Machining of Ti6Al4V Alloy. *Metallurgical and Materials Transactions A;* Vol. 41A, pp. 1573–1581.

[5] Petrovic, B. P., Jakovljevic, Z., Milacic, V. R. (2009): Context sensitive recognition of abrupt changes in cutting process. *Expert Systems with Applications;* Vol. 37, pp. 3721–3729.

[6] Antic, A., Zeljkovic, M., Petrovic, P. (2010): Development of the Tool Wear Condition Classification System Model in Turning. *Machine Design*; pp. 207–212.

[7] Antic, A., Zeljko, M., Hodolic, J., Zivkovic, A. (2010): Model of Classification System of Tool Wear Condition While Machining by Turning. *Journal of Production Engineering*; Vol. 12, No. 1, pp. 1–4.

[8] Klancnik, S., Balic, J., Cus, F. (2010): Intelligent prediction of milling strategy using neural networks. *Control Cybern.*; Vol. 39, No. 1, pp. 9–22.

[9] Cotterell, M., Byrne, G. (2008): Dynamics of chip formation during orthogonal cutting of titanium alloy Ti–6Al–4V. *CIRP Annals - Manufacturing Technolo*gy; Vol. 57, pp. 93–96.

[10] Barry, J., Gerald, B. (2002): The mechanisms of chip formation in machining hardened steels. *Transactions of the ASME, Journal of Manufacturing Science and Engineering*; Vol. 124, No. 3, pp. 528–535.

[11] Daymi, A., Boujelbene, M., Ben Salem, S., Hadj Sassi, B., Torbaty, S. (2009): Effect of the cutting speed on the chip morphology and the cutting forces. *Archives of Computational Materials Science and Surface Engineering*; 1/2, pp 77–83.

[12] Murcinkova, Z., Kompis, V., Stiavnicky, M. (2008): Trefftz functions for 3D stress concentration problems. *Computer Assisted Mechanics and Engineering Sciences;* Vol. 15, No. 3–4, pp. 305–318.

[13] Kopac, J., Sokovic, M., Dolinsek, S. (2001): Tribology of coated tools in conventional and HSC machin-

ing. *Journal of Materials Processing Technology;* Vol. 118, pp. 377–384.

[14] Ekinovic, S., Dolinsek, S., Jawahir, I. S. (2004): Some observations of the chip formation process and the white layer formation in high speed milling of hardened steel. *Journal of Machining Science and Technology;* Vol. 8, pp. 327–340.

[15] Kociusko, M., Janak, M. (2008): Creation Method of Visual Disassembly Procedure. *Journal CA Systems in Production Planning;* Vol. 9, No. 1, pp. 37–39.

[16] Marcincin, J. N. (2008): Design of Milling Toll Cutting Strategy for CNC Manufacturing Operations. *Engineering Review;* Vol. 28, No. 1, pp. 93–97.