ANALYSIS OF CHIP FORMATION DURING HARD TURNING THROUGH ACOUSTIC EMISSION

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Resume
The paper deals with analysis of chip formation and related aspects of the chip formation during turning hardened steel 100Cr6. The paper draws a comparison of some aspects of the chip formation between turning annealed and hardened roll bearing steel. The results of the analysis show that there is the formation of a segmented chip in the case of hard turning. Frequency of segmentation is very high. A conventional piezoelectric dynamometer limits the frequency response to about 3.5 kHz. On the other hand, the frequency of process fluctuation may by obtained by using accelerometers or acoustic emission. This paper reports about the dynamic character of cutting process when hard turning and correlation among the calculated segmentation frequencies and the experimental analysis.

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1. Introduction

Development in machine tools as well as in process technology focus on cutting hardened steel and rapidly lead to a high raised industrial relevance of hard cutting. In fact, hard cutting can seriously be regarded as an alternative for grinding operations under certain circumstances. High flexibility and the ability to manufacture complex workpiece geometry in one-set represent the main advantages of hard cutting in comparison to grinding [1]. Furthermore, the substitution of grinding process with cutting processes enables to avoid coolants and therefore can actually be regarded as interesting alternative even from the ecological point of view [1, 2].

Lot of work was carried out considering this process focused on all aspects as the experimental investigation of environmentally aspect [2], surface roughness [3], analyses of chip morphology [3, 4], wear process or the progressive approach through modeling of the specific aspects [5, 6].

Applying hard cutting as a finishing process requires the generation of machined surface by pure plastic deformation. The proper understanding of the material removal mechanisms taking place during hard cutting is essential for process evaluation. The analysis of the work area is necessary to describe the chip generation in hardened materials. Depending on cutting parameters and workpiece material properties, cutting may either lead to continuous or discontinuous chip formation [7, 8].

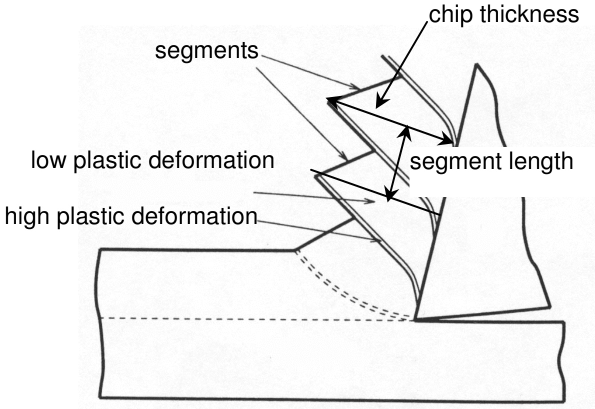


Fig. 1. Illustration of segmented chip

Continuous chip is formed during turning conventional annealed steels . On the other hand, there is the formation of the segmented chips (Fig. 1) during the hard turning [7, 8, 9]. Recht [8] introduced the adiabatic shear theory to characterize the chip segmentation process during the hard turning. The thermoplastic instability is where a decrease in flow stress due to thermal softening associated with increase in strain more that offsets the associated strain hardening [9]. Process of plastic deformation in the cutting zone affects many aspects of the cutting process. Understanding of process in the cutting zone is crucial for solution of related aspects of cutting as cutting forces, heat generation, and surface quality. And so, this paper deals with analysis of the chip formation during hard turning roll bearing steel 100Cr6.

The paper should begin with the introduction in which the present state of the issue relevant to the paper will be presented generally and concisely. It is necessary to quote references taking into consideration the remarks included in the section "References". It is necessary to present the aim of the research included in the paper and clearly point out the originality of solutions and content-related approach to the issue worked out and described by authors [1].

2. Chip segmentation

As mentioned above, cutting of hardened steel often leads to the formation of segmented chip. This phenomenon is directly related to a fluctuation of cutting force and stress distribution in the work area and influences the temperature distribution and so the process result. The term segmented chip is often used to describe all of the cyclic types, particularly the wavy and segmented types. This is unfortunate since these two types of chips are distinctly different. For example, the cycle frequency for a wavy chip is typically about 100 Hz while that for a segmented chip is 2 to 4 orders of magnitude greater [7]. Dynamic forces that fluctuate at a frequency over 10 kHz are difficult to measure. Shaw, Vyas [11] investigated that for the cutting speed 100 m.min^{-1}, feed 0.28 mm and hardness of case carburized steel (62 HRC) the segmentation frequency is about 18 kHz. Author reported that this approaches the upper limit of the audio frequency range and was verified by dynamic measurement during chip formation.

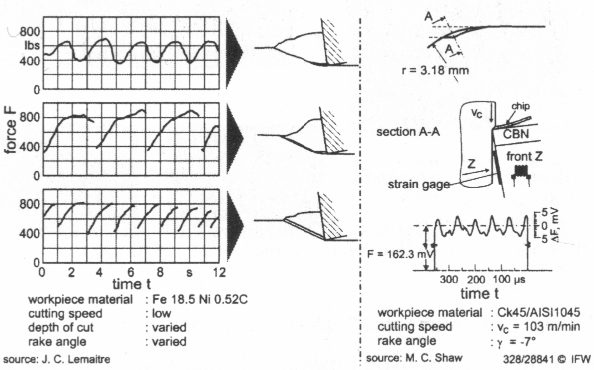


Fig. 2. Force fluctuation in hard cutting [11]

A conventional piezoelectric dynamometer limits the frequency response to about 3.5 kHz. However, an estimation of the relative changes in the force components and the frequency of force fluctuation may by obtained by using wire resistance strain gages [11] (Fig. 2) or accelerometers [12]. On the other hand, a conventional accelerometer limits the frequency response to about 20 kHz (special accelerometers limits the frequency response to about 50 kHz). Dynamic analyses of deformation processes that fluctuate at a frequency over 25 kHz with application of conventional accelerometers is difficult to carry out and usually require special techniques [11]. On the other hand, the past research and existing monitoring systems based on acoustic emission (AE) were developed. Acoustic emission techniques enable to investigate processes that fluctuate at a frequency over several MHz.

AE is usually applied for process monitoring [13]. It is one of the most effective methods for process monitoring. All the existing AE monitoring methods can be divided into the signal-based approach where signal values measured are compared to pre-defined signal values, the model-based approach where process models are determined either empirically or from physical relations, and the classification-based approach where feature vector is determined from a certain class of quality features [14]. Acoustic emission is transient elastic waves due to the rapid energy release from a localized source within a material when subjected to stress. AE sources can be dislocation movements, deformation, inclusion fracture, and crack propagation. The AE non-destructive technique is based on detection and conversion of these high frequency elastic waves to electrical signals. The major AE sources [13] in a metal cutting process are:

- deformation and fracture of work materials in primary, secondary, and tertiary shear zones,
- deformation and fracture of cutting tools between tool/chip and tool/workpiece,
- collision, entangling and breakage of chips.

AE signals can be classified into two types [15, 16] as either continuous-type AE signals or burst-type AE signals. Continuous signals are associated with shearing in the primary zone and wear on the tool flank while burst type are observed during crack growth in the material, tool fracture or chip breakage.

The major advantage of using AE to monitor a machining operation is that the frequency range of the AE signal is much higher than that of the machine vibrations and environmental noises, and does not interfere with the cutting operation [13]. The sensitivity of the AE signal to various contact areas and deformation regions during cutting has led AE signal as a basic tool for process monitoring. The friction between tool/workpiece generates a continuous AE signal, it gives rich information on a cutting process. Methods have been developed for monitoring tool wear in turning [17, 18], milling [19], drilling [20], boring [21] and grinding [22]. Except the conventional process monitoring, AE can be applied for analysis of chip form and chip flow. Uehara [23] reported the remarkable patterns of the AE related to the segmented chip formation. The AE signals accompanying with the formation of the segmented chip exhibit remarkable patterns; the tool side signal shows a periodic bursting. The amplitude of acoustic emission varies corresponding to the periodic change of the cutting force.

The chip formation during machining of hardened steel working out criteria for crack initiation and propagation. Surface which have to be machined are not perfectly smooth but rough and composed of microscopic ridges, cracks, voids, etc. Machining hardened materials, high compressive stress creates subsurface material flow but particularly leads to the formation of crack in the free surface. Strong elastic waves related to the crack formation during the segmented chip formation can be detected through the AE systems.

This paper provides a comprehensive view among the chip segmentation and signals carried out through the AE and accelerometers to verify the calculated segmentation frequencies and alternatives for analysis of the deformation process related to limits the frequency response.

3. Experimental setup

The experimental setup is shown in Fig. 5. Commercial piezoelectric AE sensors (D9241A - frequency range from 20 to 180 kHz, WD – frequency range from 100 kHz to 1000 kHz) by Physical Acoustics Corporation (PSC) were mounted on the top of the tool holder using (Fig. 3, 4). To maintain a good propagation of signals from the tool holder to the sensor, a semi-solid high vacuum grease was used. During the experiment, the AE signals were amplified, high passed at 20 kHz, low passed at 1000 kHz, and then sent through a preamplifier at a gain 40 dB to the signal processing software package. All cutting tests were performed on the CNC Lathe. The signals were real-time sampled, amplified, digitized, and then fed to the signal processing unit. The AE signals were post-processed using AEwin.

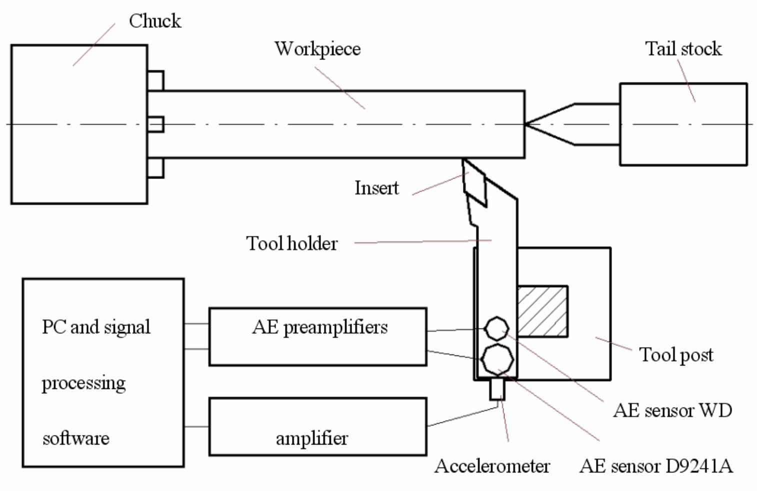


Fig. 3. Schematic of experimental setup

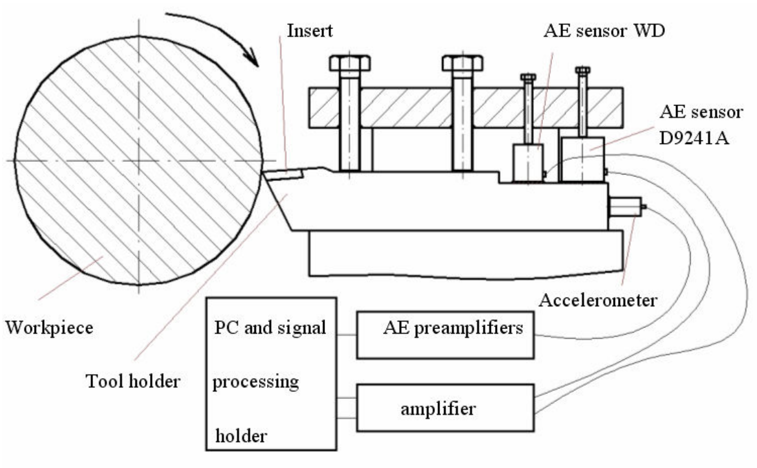


Fig. 4. Detail of sensor placement

A commercial accelerometer (Type 4517 – frequency range from 1 Hz to 20 kHz, measuring range ± 4900 $m.s^{-2}$ peak, reference sensitivity at 159.2 Hz (ω = 1000 s^{-1}) by Brüel & Kjær were mounted on the tool holder (Fig. 5 and 6. illustrate the accelerometer mounting) through the bee wax. During the experiment, the signals were filtered (5 kHz high pass filter, sampling frequency 50 kHz) to suppress the low frequency noise and then fed to the signal processing software package Dasylab 3.5 and analyzed through the Power Density Spectrums (PSD) spectrums. The AE signal recording was not carried out during the same time as the accelerometer signal, but two consecutive cuts were realized under the constant cutting conditions and the signals were recorded individually.

Tab. 1

Experimental conditions

Cutting tool:	TiC reinforced Al_2O_3 ceramic inserts DNGA150408 (TiN coating), rake angle γ_n = -7°
Work material:	100Cr6 (hardened - 62 HRC, and annealed – 27 HRC), external diameter 56 mm, internal diameter 40 mm, 125 mm long
Cutting condition:	v_c = 100 $m.min^{-1}$, f = 0.05 to 0.271 mm, a_p = 0.25 mm (constant), dry cutting
Machine tool:	CNC Lathe Hurco TM8
The chip thickness was measured by an optical microscope.	

4. Results of experiments

Measurement of the chip thickness was carried out on through the measurement of the chips on Fig. 5. The measurement of the chip thickness h_c enables to calculate the chip ratio K (equation (1) - h is equal to feed) and other related parameters as deformation angle Φ_1 and chip speed (v_{ch}) [24]. This enables to determine the segmentation frequency (equation 4).

$$K = \frac{h_c}{h} \tag{1}$$

where h is the undeformed chip thickness and h_c is the chip thickness. The deformation angle can be calculated through the equation (2).

$$tg\Phi_1 = \frac{\cos\gamma_n}{K - \sin\gamma_n} \tag{2}$$

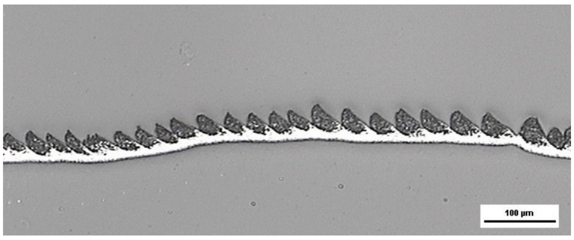
The chip speed can be calculated by the equation (3).

$$v_{ch} = v_c \frac{\sin\Phi_1}{\cos(\Phi_1 - \gamma_n)} \tag{3}$$

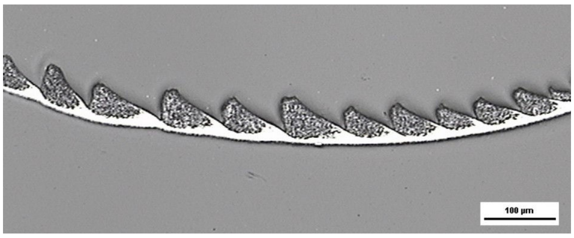
The mean cycle frequency for chip segmentation may be determined by dividing the speed of the chip v_{ch} by the mean spacing of points of maximum chip thickness p_c (segment length in Fig. 1).

$$\text{segmentation frequency} = \frac{v_{ch}}{p_c} \tag{4}$$

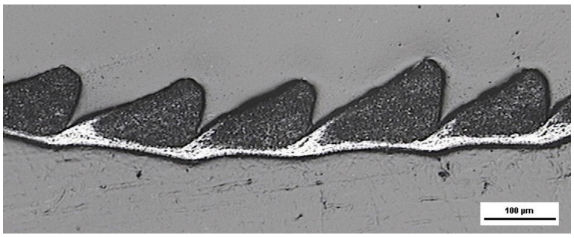
Fig. 7 illustrates that the chip thickness during turning hardened steel is much lower than for turning annealed steel. Formation of the segments during the turning hardened steel (Fig. 5) causes its elongation and decreasing of the chip thickness. As a result of formation of the thin and long chips, the chip ratio is smaller than 1 (Fig. 7) in the contrary to the turning annealed steel (the thick and short continuous chip and so the chip ratio is more than 1, Fig. 6).



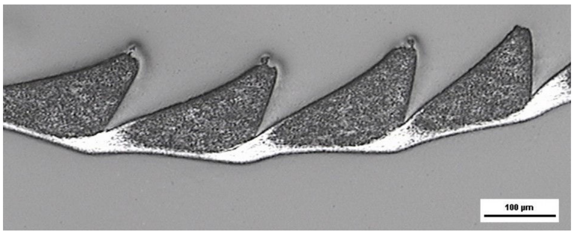
a) v_c = 100 m.min^{-1}, f = 0.051 mm



b) v_c = 100 m.min^{-1}, f = 0.09 mm



c) v_c = 100 m.min^{-1}, f = 0.21 mm



d) v_c = 100 m.min^{-1}, f = 0.271 mm

Fig. 5. Influence of feed on shear localized steel chip, 100Cr6 – hardened (62HRC)

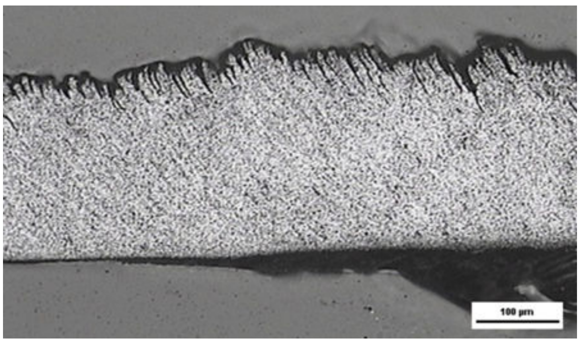


Fig. 6. Continuous steel chip, 100Cr6 – annealed (27HRC), f = 0.09 mm, v_c = 100 m.min^{-1}

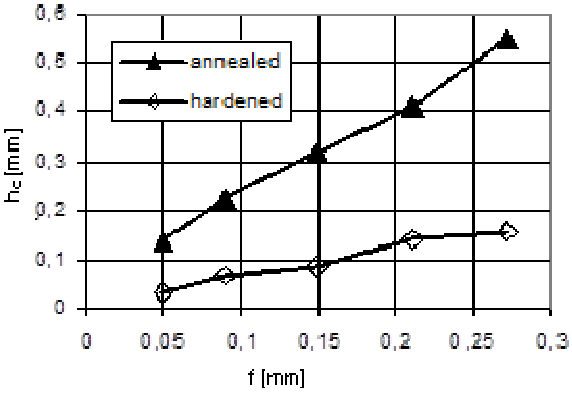


Fig. 7. Influence of feed on chip thickness

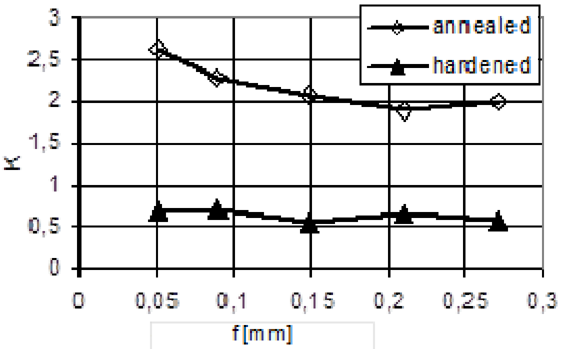


Fig. 8. Influence of feed on chip ratio

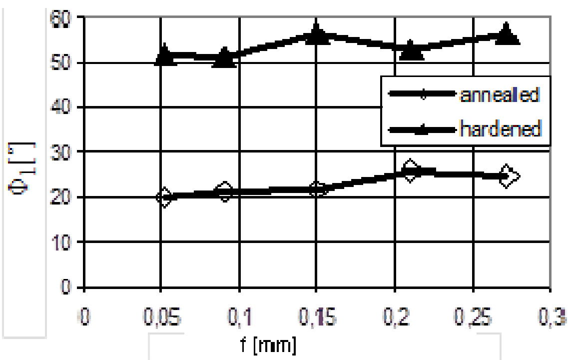


Fig. 9. Influence of feed on deformation angle

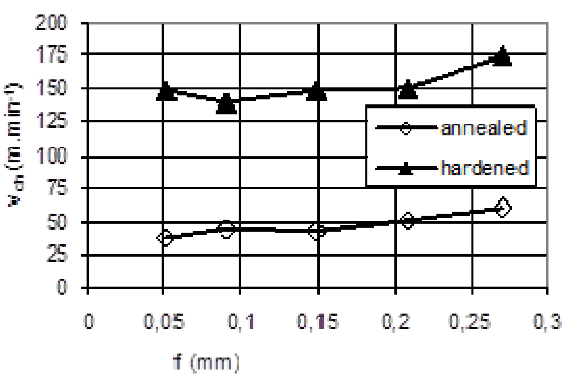


Fig. 10. Influence of feed on chip speed

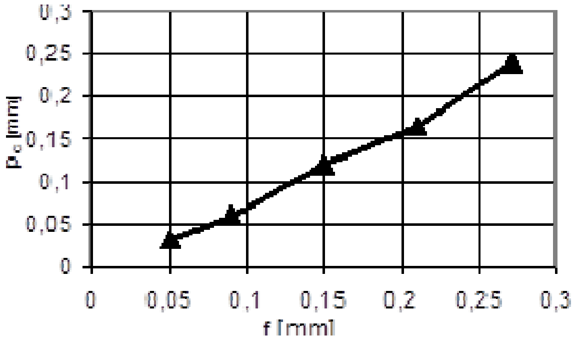


Fig. 11. Influence of feed on segment length

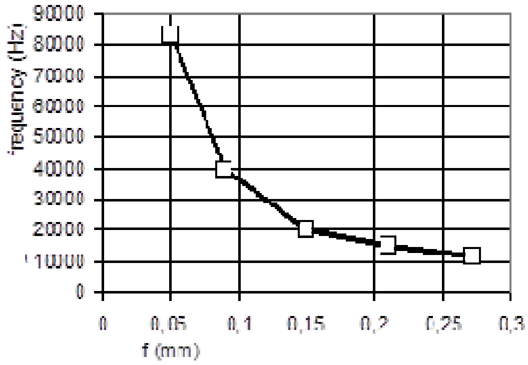


Fig. 12. Influence of feed on segmentation frequency

Intensity of plastic deformation is much lower during hard turning in comparison with turning the annealed steel. The low intensity of plastic deformation is attributed to the material inside the segment. Plastic deformation inside the segment is low and material in this area stays untouched. Although, the plastic deformation in the localized areas of the segmented chip is extremely high (white areas), the total deformation of segmented chip is much lower that that for continuous chip (during turning annealed steel). On the other hand, chip thickness and length significantly changes with feed in the case of hard turning. The segment length and thickness is increasing with increasing feed (Fig. 5, 7, 11).

As a result of the formation of the thin and long chips (when turning hardened steel) the chip speed is much higher than that when turning the annealed steel (Fig. 10).

The specific character of the chip formation is related to the very high shear angle; much higher than the shear angle for turning annealed steel (Fig. 9).

Shaw [11], Polulachon, Moisan [25] investigated the chip segmentation process during the hard turning and its stages:

- the chip formation in hard turning starts with crack initialization near the free surface. Cracks propagate and end up in a plastically deformed region close to the tip of the cutting edge (Fig. 5, white zone in the shear plane represent process of plastic deformation, shear plane without white zone represent process of cracks propagation),
- a band of concentrated shear going all the way to the tool face in a straight line, followed by bands that begin to curve toward the tool face more and more as the chip moves up the tool face,
- movement of blocks of material that gradually proceed outward due to sliding along the fully cracked surfaces, together with extension of bands of concentrated shear in the micro cracked region,
- thinning of the micro cracked region as the chip moves up the face of the tool,
- a gradual approach to the final shape of the chip as it moves up the tool face requiring several cycles before the chip leaves contact with the tool.

The significance of the thinning of the plastically deformed region as the chip moves up the tool face is that this gives rise to a chip ratio less than one. This is usually case of when hard steel is turned with a negative rake tool. Important consequence is that the chip speed will be greater than the cutting speed and the shear angle will be greater than 45º.

The general aim of taking metallographic chip samples has been to measure the segmentation frequency in the chip and comparing it with the frequency analysis from the accelerometer. Fig. 5 shows chips where periodic cracks can be observed. These series of segments are measured all over the chip, and from more than 20 values the mean values are calculated. In extensive cutting tests the registration of the segmentation distance has been statistically established. The segmentation frequency is not established as the exact value, but should be considered in the certain interval (Fig. 12).

To obtain the segmentation frequency, the segmentation distance had to be measured in a metallographic microscope, and knowing the cutting speed, the shear plane speed or the chip speed, the frequency can be calculated. As illustrates Fig. 12, the segmentation frequencies lie in the frequency range from 14 to 90 kHz. Moreover, under the high feeds the frequency interval is relatively close and spreads with decreasing feed. Application of low feed leads to formation of the small segments. Related frequencies are very high in the contrary to the high feeds. Character of segments strongly depends on distribution of stress and temperature in the cutting zone. Fig. 9 illustrates that feed does not affect the shear angle and so the dimension of the formed segment depend on the simple geometry approach outgoing from the undeformed chip thickness and the shear angle.

Analysis of the periodic character of the chip segmentation can be carried out through the FFT analysis. Because of the low frequency noise related to instability of cutting process itself it was necessary to apply the high pass filter 5 kHz and processing of signal through PSD analysis. Fig. 13 illustrates the PSD spectrums for three different feeds. It is clearly observed that the measured frequencies for feed from 0.15 to 0.271 mm match the calculated frequencies illustrated in Fig. 12 and 14. Fig 13 shows that formation of massive segments under the high feed (0.271 mm) corresponds with the high amplitude of segmentation frequency. Decreasing of feed decreases this amplitude and the signal is loaded with the process noise. At low feed, the undeformed chip thickness is low. The material ahead of the tool rake is under intense compressive stress state. In such a case, large volume of material becomes fully plastic. Fig 5 illustrates that the length of cracked region in the shear plane for high feeds is much longer than that low feeds. This leads to more intensive signal related to the crack propagation under the high feeds.

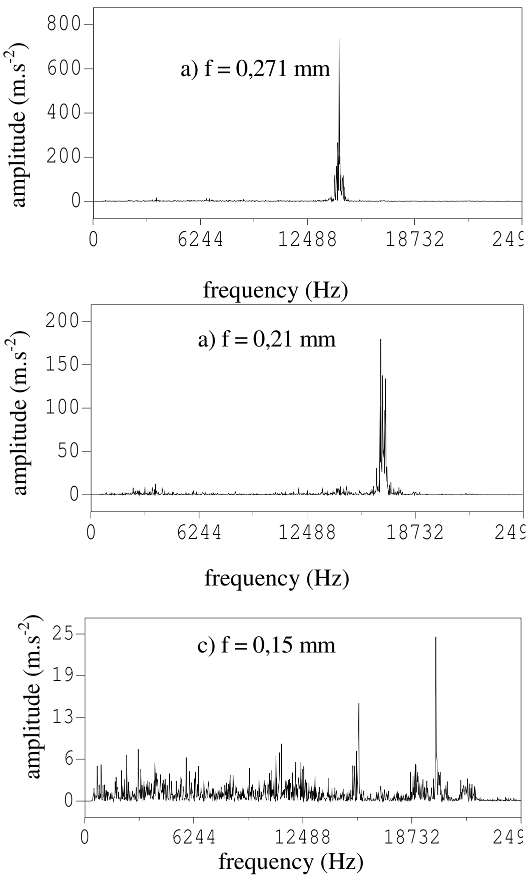


Fig. 13. PSD spectrum from accelerometer, 100Cr6 62HRC, v_c = 100 m.min^{-1}

Some aspects of chip formation verify the AE signals. Fig. 15 illustrates the AE signal for the different feeds. Amplitude of the AE signal is increasing with feeds and is related to the relaxation process of stress ahead of the cutting edge and crack propagation in the shear region and friction processes in the tool-chip and tool–workpiece contact. According to the theory of the crack propagation and segment formation, the change of the amplitude of acoustic emission indicates the change of the sliding velocity at the tool-chip interface. Many pulses like signal are observed AE signal corresponding to the periodic fluctuation (relaxation character) of the cutting process. The signal level of the AE between these pulses is quite small. In the segmented chip formation, the chip slide over the rake face with varying speed corresponding to the period of the fracture of the shear plane.

Fig. 16a show this relaxing and periodic character of the signal for feed 0.15 mm and the related character of FFT spectrum (Fig. 16b) of AE signal with the periodic peaks in this spectrum. This character of FFT spectrum confirms the dominant periodic character of recorded signal and ability of D9241A AE sensor (frequency range from 20 to 180 kHz) to detect the periodic process typical for the segmented chip formation. The segmentation frequency of this feed (0.15 mm) and the lower feeds lie in the frequency range of D9241A AE sensor.
Fig. 17 show the FFT spectrum for feeds 0.051 and 0.09 mm with evidence of the periodic peaks in this spectrum. On the other hand, the segmentation frequencies for feeds 0.21 a 0.271 mm lie outside of frequency range of both AE sensor and the periodic peaks in the FFT spectrum are missing. Moreover, Fig. 16c and 17c illustrates that character of AE signal for these feeds does not fit exactly the real periodic character of deformation processes in the cutting zone. This signal is partially deformed and the periodic character is violated because of the mismatch between the segmentation frequency of formed chip and frequency range of the applied AE sensor. Moreover, FFT spectrum of AE signal is without the periodic peaks in this spectrum.

Considering the AE sensor WD (frequency range form 100 to 1000 kHz), all segmentation frequencies lie outside of the frequency range of this sensor and the periodic character of AE signal is missing. FFT spectrum of AE signal for the WD sensor is without the periodic peaks in this spectrum (Fig. 17d).

It was reported in the previous chapters that AE signals can be classified into two types as either continuous-type AE signals or burst-type AE signals. Continuous signals are associated with shearing in the primary zone and wear on the tool flank. These processes are can be investigated and detected with application of the WD AE sensor, because the signal related to chip segmentation (crack propagation) are too strong. Fig. 15 illustrates that intensity of AE signal for WD sensor is increased with the feed and should be associated with the increasing intensity of friction processes in the cutting zone in relation to increasing feed. Application of D9241A sensor for these analyses is limited. The burst – type AE signal (related to the crack propagation) superposes with signal from the tool–chip and tool–workpiece interface and so raises the difficulties for investigation of processes in these regions.

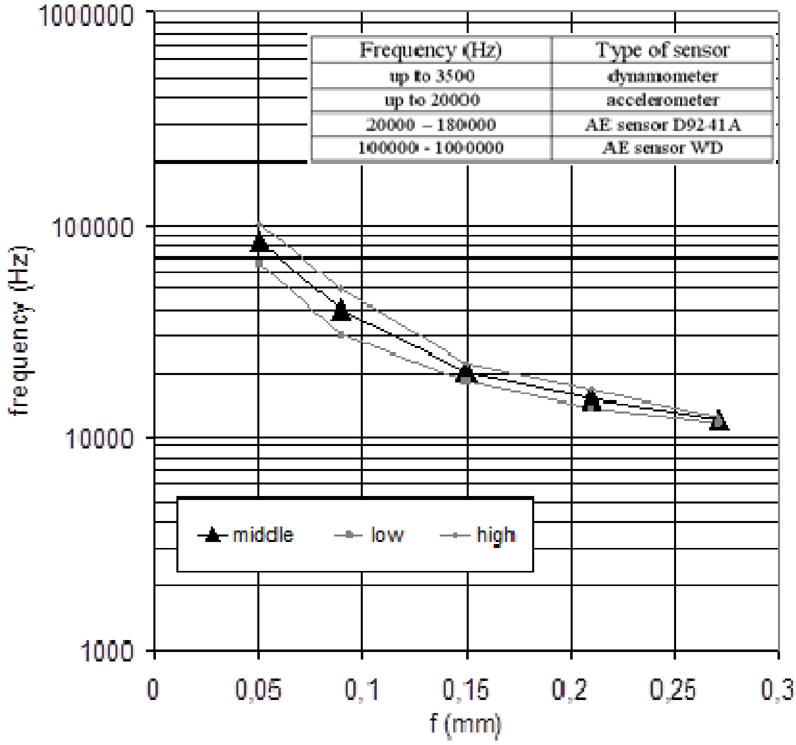


Fig. 14. Frequency ranges in the semi logarithmic scale

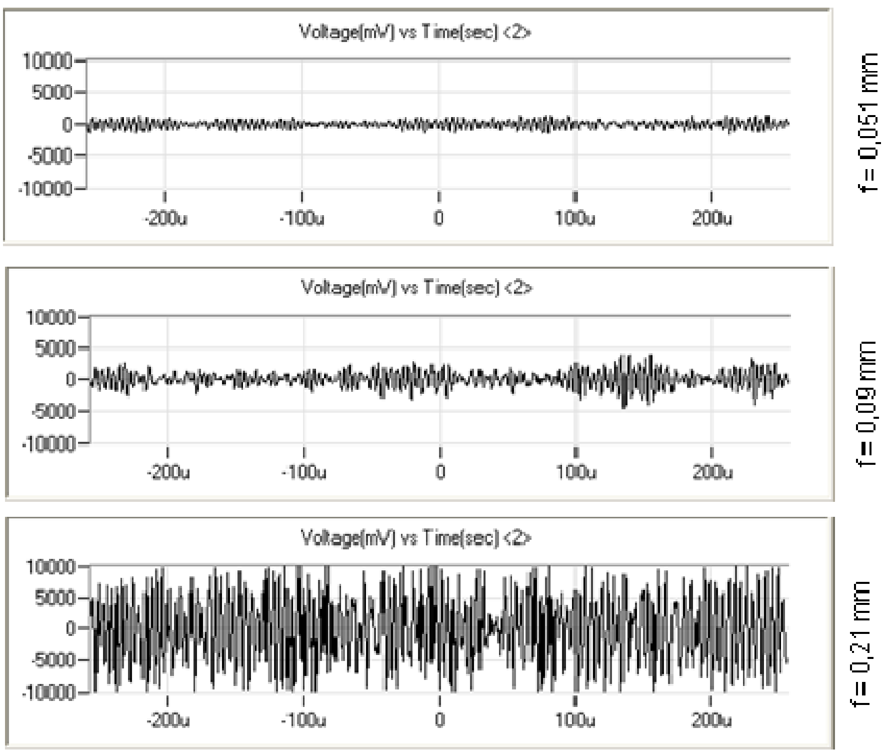


Fig. 15. Signal of AE and application of WD sensor

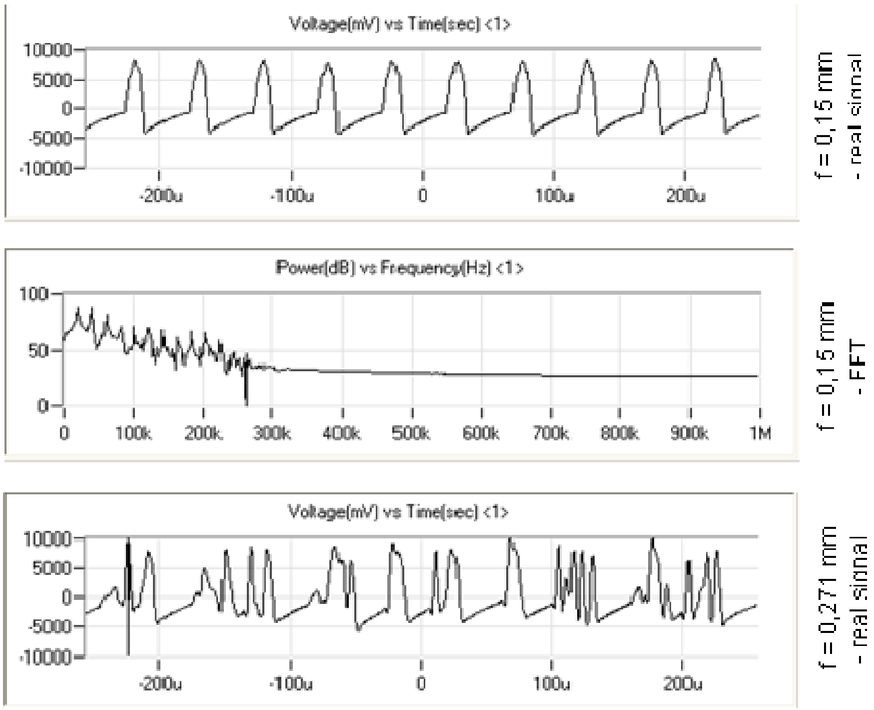
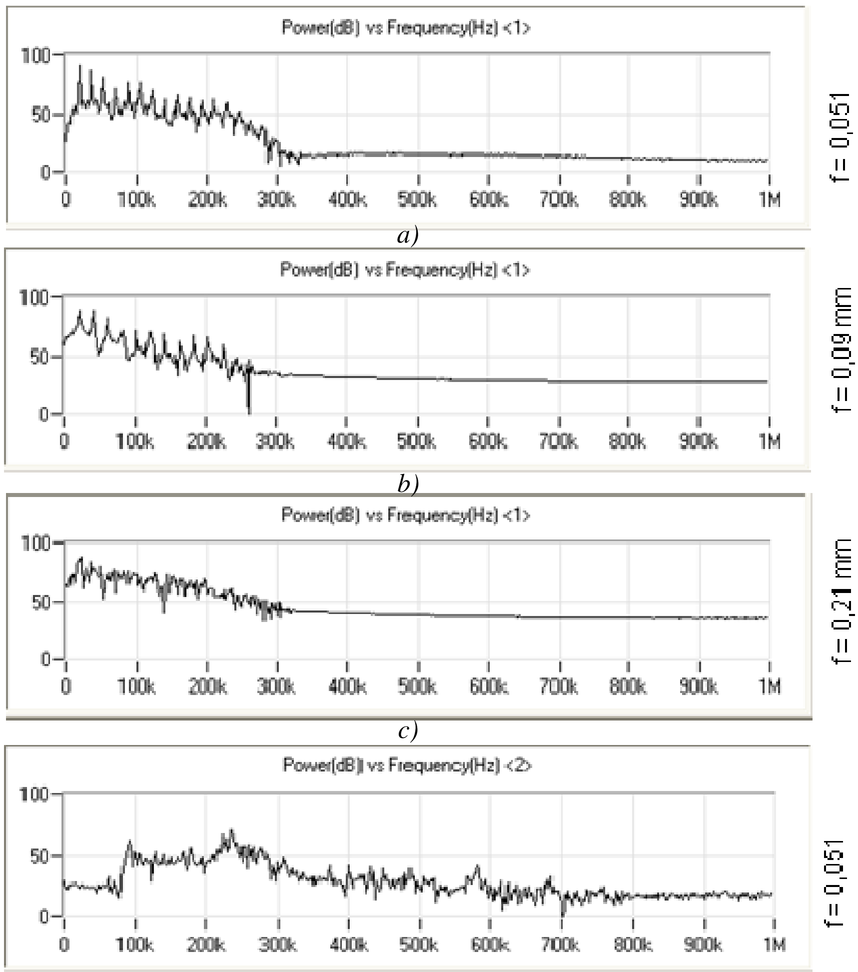


Fig. 16. Signal of AE and application of D9241A sensor and related FFT spectrum



d)

Fig. 17. FFT spectrum for D9241A sensor (a, b, c) and WD sensor (d)

5. Conclusions

The results show that AE signals and accelerometers can be used to monitor the dynamic character of plastic deformation in the cutting zone in hard turning.

- application of conventional accelerometers limits the frequency response to about 20 kHz and so application of high feeds related to formation of massive segments,
- formation of segments under the low feeds can be investigated through the suitable AE system (sensor),
- application of AE for investigation of the segmented frequencies lying under the frequency range of applied sensor leads to violation of the real AE signal,
- burst type of AE is associated with cracks propagation in the shear zone,
- continuous type of AE is associated with tool-chip and tool-workpiece sliding contact,
- FFT spectrum of AE signal with the periodic peaks in this spectrum should be associated with the periodic character of the real and true signal.

Dynamic character of cutting process in hard turning process, the specific character of chip formation significantly affect such aspects as shear and chip speed, friction processes in the cutting zone related heat generation and high temperatures in this zone with the consecutive impact on surface quality represented by residual stresses, surface hardness, structural changes and more. And so, the studies related to dynamic character of hard turning process should be investigated. Except the feed, the dynamic character of hard turning is affected by the next parameters. The most significant aspects are the cutting speed, process of tool wear and hardness of machined material [4]. Investigations focused on these aspects were already carried out and will be reported in the near future.

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