ZPĚT

MONITORING OF TOOL WEAR THROUGH ACOUSTIC EMISSION

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This paper deals with an application of Acoustic Emission for monitoring of tool wear during hard turning. The results illustrate that the signals of Acoustic Emission and some derived parameters can be applied to monitoring of deformation processes in the cutting zone and process of tool wear. The Acoustic Emission system is capable to detect the specific character of chip formation during hard turning and therefore can be adapted for specific tasks associated with this cutting operation.

🗝 Key words: Acoustic Emission, hard turning, wear

1 Introduction

Hard machining is a competitive finishing process with substantial benefits in many cases [1]. In metal cutting, the principal chip morphologies classified by Komanduri and Brown [2], are continuous, serrated chip. In machining, hard and difficult – to machine materials tend to localize the heat generated due to the strain localization in a narrow band called adiabatic shear band represented in Fig. 1, 2. Adiabatic shear banding Recht [3] is used to describe a localization phenomenon that occurs in the high strain – rate plastic deformation processes such as cutting. This phenomenon can be explained in the following way: during deformation the rate of heat generation is determined by strain-rate, and the heat dissipation rate is controlled by the heat conductivity of the material. When the heat generation rate is larger than the heat dissipation rate, the temperature increases, and the softening associated with such temperature increases and exceeds the strain hardening, and the catastrophic propagation of shear occurs. 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 [4, 5, 6].

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 [2, 6, 7]. Continuous chips are formed during turning conventional soft steels (Fig. 2 - a decrease in flow stress due to thermal softening associated with increase in strain is less than offsets the associated strain hardening [2]), while hard turning can lead to a formation of segmented chips. Fig. 1, 2 illustrate the segmented chip in turning hardened steel. Fig. 1 illustrates that plastic deformation inside the segment is low and material in this area stays nearly untouched. Deformation processes are concentrated in the shear zone, tool – chip contact and tool – workpiece contact. Formation of continuous chip leads to homogenous dissipation of deformation across the whole chip (Fig. 2).

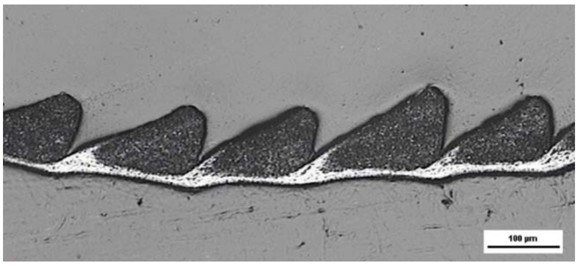


Fig. 1 Chips after turning 100Cr6 (hardened 62 HRC), REM, v_c = 100 m.min^{-1}, f = 0,21 mm
Obr. 1 Triesky po tvrdom sústružení 100Cr6 (kalené 62 HRC)

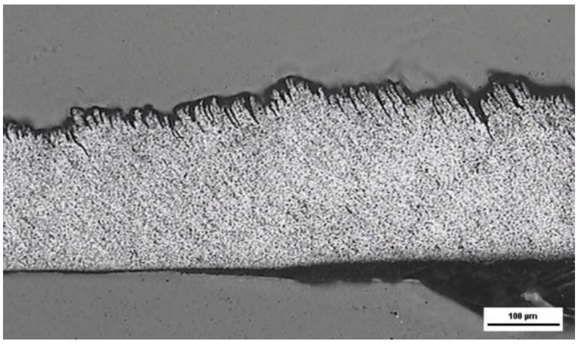


Fig. 2 Chips after turning 100Cr6 (annealed), REM, v_c = 100 m.min^{-1}, f = 0,21 mm
Obr. 2 Triesky po sústružení v stave žíhané na mäkko – 27 HRC

Investigation of a real intensity of deformation processes related to the specific cutting zones is quite difficult and could be realized through Acoustic Emission (AE). The AE non-destructive technique is based on detection and conversion of these high frequency elastic waves to electrical signals. The major AE sources [8, 9, 10] in a metal cutting process are:

- deformation and fracture of work materials in shear zone, tool-chip and tool-workpiece contact,
- deformation and fracture of cutting tool,
- collision, entangling and breakage of chips.

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 [8]. 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.

Fig. 1 and 2 illustrate that the character of deformation process during conventional soft and hard turning differs. Some studies related to the influence of the cutting speed and feed were reported in the previous papers. Some similar studies focused on tool wear were reported in the scientific journals [11]. These studies indicate some difficulties considering tool wear and surface integrity monitoring. Therefore the aim of this paper is to perform the analysis of deformation processes in scope of tool wear through the Acoustic Emission system.

2 Conditions of experiments

The experimental setup is shown in Fig. 3 and 4. Commercial piezoelectric AE sensors (D9241A - frequency range of 20 to 180 kHz, WD – frequency range of 100 kHz to 1000 kHz) by Physical Acoustics Corporation (PSC) were mounted on the top of the tool holder using. 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. The chip thickness was measured by an optical microscope.

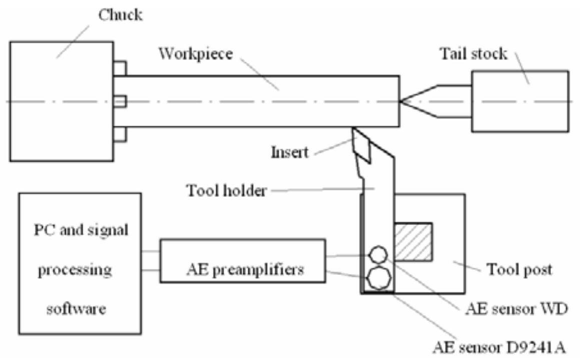


Fig. 3 Schematic of experimental setup
Obr. 3 Schéma experimentálneho merania

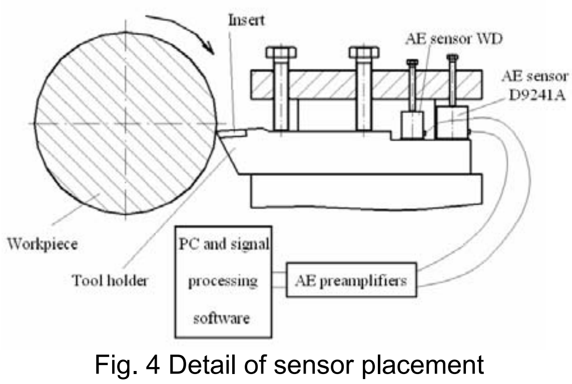


Fig. 4 Detail of sensor placement
Obr. 4 Detail umiestnenia senzorov

Tab. 1 Experimental conditions during hard turning
Tab. 1 Podmienky experimentov pri tvrdom sústružení

Cutting tool:	TiC reinforced Al_2O_3 ceramic inserts DNGA150408 (TiN coating), rake angle γ_n= -7°
Work material:	100Cr6 (hardened - 62 HRC), external diameter 56 mm, internal diameter 40 mm, 125 mm long
Cutting condition:	v_c = 100 and 170 m.min^{-1}, f = 0,09 mm, a_p = 0,075 and 0,25 mm (constant), dry cutting
Machine tool:	CNC Lathe Hurco TM8

3 Analysis of results

The process of tool wear and the related thrust force is shown in Fig. 5. The initial stage of cutting process causes a gentle decrease in the thrust force. This decrease is associated with the significant changes in tool geometry (formation of a crater on tool rake as shown in Fig. 6). The crater on the tool rake becomes stable in the following stages. Then the thrust force increases in a connection with increasing tool wear *VB* at the tool back. The normal phase of cutting process is associated with the stable interval with the low intensity of tool wear *VB*. Above the certain limiting values (in connection with increasing mechanical load) the character of tool wear changes. The normal phase represents the microscopic breakage of cutting edge. The final stages represent the massive breakage of macroscopic volumes of tool material. Shape, geometry and dimension of tool significantly change in the final stages of cutting process (Fig. 6c). This macroscopic character of tool wear leads to the removal of a certain area of *VB*. Therefore the significant decrease in the thrust force can be observed at the end of the cutting process (Fig. 5).

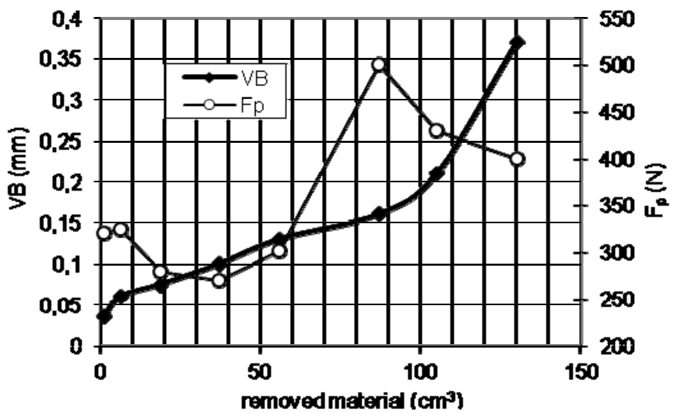
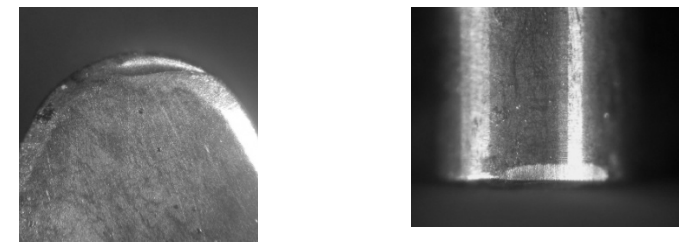
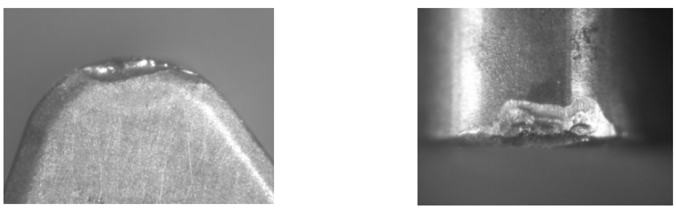


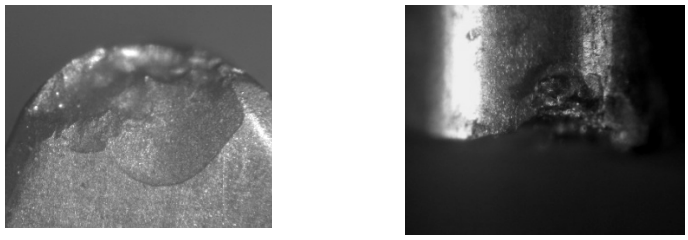
Fig. 5 Influence of removed material on *VB* and thrust force F_p for tuning [12],
Obr. 5 Vplyv objemu odobratého materiálu na *VB* a F_p pri sústružení [12],
v_c = 170 m.min^{-1}, a_p = 0,25 mm



a) tool face, *V* = 56 cm^3 — flank wear *VB* = 0,13 mm

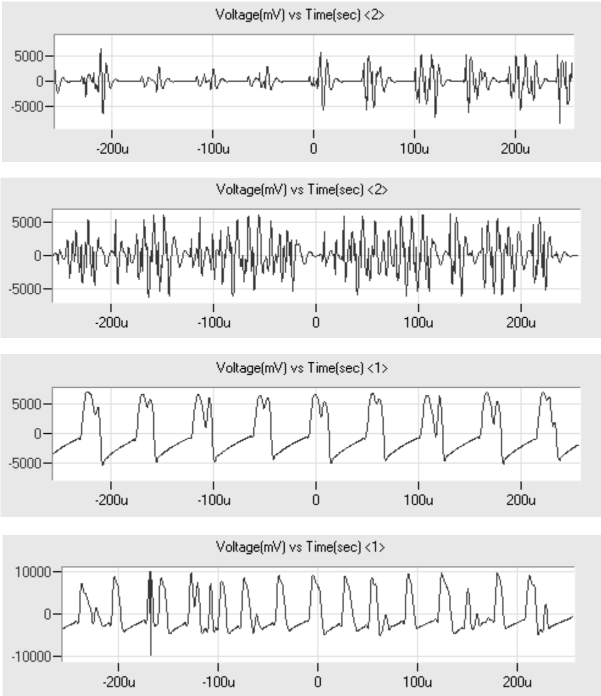


b) tool face, *V* = 105 cm^3 — flank wear *VB* = 0,21 mm



c) tool face, *V* = 130 cm^3 — flank wear *VB* = 0,37 mm

Fig. 6 Photos of tool wear, real dimension of the figures 1,5 x 2 mm
Obr. 6 Fotografie opotrebenia nástroja, skutočný rozmer 1,5 x 2 mm
v_c = 170 m.min^{-1}, a_p = 0,25 mm



a) High frequency sensor WD
VB = 0 mm

b) High frequency sensor WD
VB = 0,37 mm

c) Low frequency sensor D9241A
VB = 0 mm

d) Low frequency sensor D9241A
VB = 0,37 mm

Fig. 7 Character of AE signal in the initial and final stage of cutting process
Obr. 7 Charakter AE signálov v počiatočnom a konečnom štádiu rezného procesu
v_c = 170 m.min^{-1}, a_p = 0,25 mm

The significant changes in tool geometry can be investigated not only through the cutting force but also through other parameters such as a chip form, signals of AE, etc. Fig. 7 illustrates the character of AE signal of two sensors in the initial stages of the cutting process (Fig. 7 a, c) and in the final stage too (Fig. 7 b, d). First of all, it should be mentioned that each sensor provides a different character of a signal. This difference is attributed to a different frequency range for both sensors. While the low frequency sensor D9241 detects AE signals from 20 to 180 kHz, the high frequency sensor WD detects signals from 100 to 1000 KHz. Because of the segmented chip formation the cutting process is very unstable in relation to segments formation. The previous studies investigated that the segmentation frequencies lie in the frequency range of 14 kHz to 90 kHz. Therefore these frequencies can be detected only through the low frequency sensor. It could be viewed that the relaxing character of a signal can be obtained through the frequency sensor. The character of plastic deformation during formation of the segmented chip is connected with relaxation of stress in front of the cutting edge. This relaxation process leads to the formation of a crack in the near surface of a chip. This crack is prolongated towards the cutting edge and transforms to the plastic deformation process in this zone. The cutting zone provides two basic types of signals. The burst type is associated with the crack formation in the shear plane and the continuous one is associated with the friction and deformation processes in the shear zone, tool – chip and tool – workpiece contact, Fig. 8.

The continuous signals are associated with shearing in the primary zone, in the tool – chip and tool – workpiece contact. These processes are can be investigated and detected with the application of the WD AE sensor, because the signals related to the chip segmentation (crack propagation) are out of frequency range of this sensor. The application of D9241A sensor is limited for these analyses. The burst – type AE signal (related to the crack propagation) superposes with signals from the tool–chip and tool–workpiece interfaces and so raises the difficulties of investigation of processes in these regions. Segmentation frequencies lie in the range of D9241A sensor. These frequencies are associated with the crack formation and its propagation in the shear zone. Signal associated with a crack formation and its prolongation in the shear zone is very strong (amplitude of AE signals for all feed is on maximum 100dB) and generates the massive low frequency noise concerning friction process in the shear zone, tool – chip and tool – workpiece contact (Fig. 8). AE signals recorded by D9241A sensor are not sensitive to friction processes related to plastic deformation in the cutting zone. The initial stage of cutting process provides the relaxing character of AE of the low frequency sensor. The significant changes in the tool geometry significantly change the stress and temperature state in the cutting zone. The chip becomes less segmented (degree of segmentation decreases, see

Fig. 9), length of crack prolongation decreases and deformation processes take a more significant role. The regular character of AE signals (of D9241A sensor) and segmented chips are suppressed.

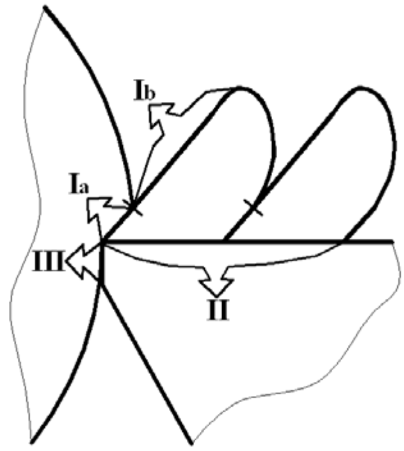
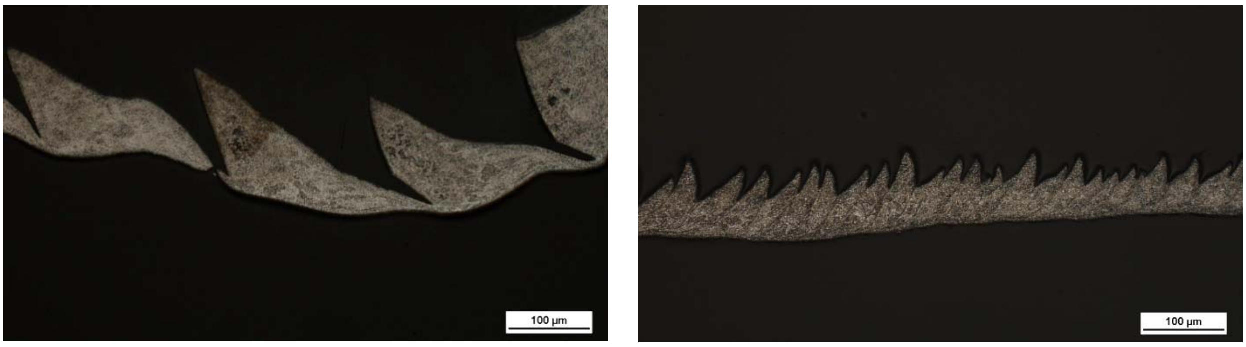


Fig. 8 Cutting zone for hard cutting
Ia) microcracked and plastically deformed shear zone
Ib) cracked region
II) tool – chip contact
III) tool – workpiece contact

Obr. 8 Zóna rezania pri tvrdom sústružení
Ia) oblasť plasticky pretvorená s výskytom mikrotrhlín
Ib) oblasť šírenia trhliny
II) kontakt čela nástroja a triesky
III) kontakt chrbta nástroja a obrobku

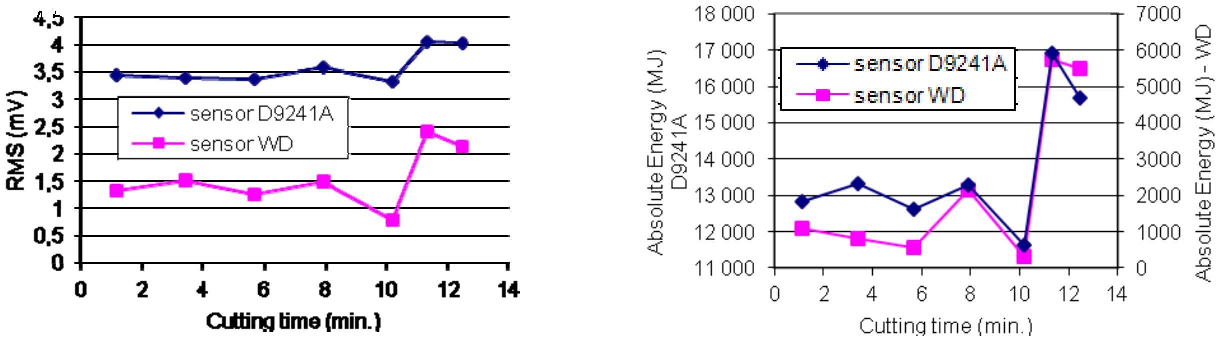


a) VB = 0 mm b) VB = 0,37 mm

Fig. 9 Photos of chips in the initial and final stage of cutting process

Obr. 9 Fotografie triesok v počiatočnom a konečnom štádiu rezného procesu

v_c = 170 m.min^{-1}, a_p = 0,25 mm



a) RMS values b) absolute energy of AE

Fig. 10 RMS and absolute energy of AE in relation to tool wear

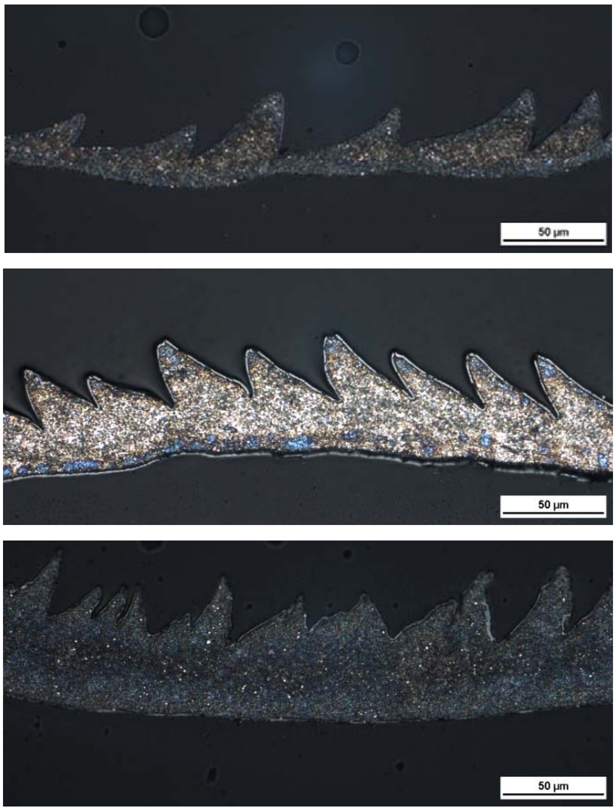
Obr. 10 Vplyv opotrebenia nástroja na RMS hodnoty a absolútnu energiu AE

v_c = 170 m.min^{-1}, a_p = 0,25 mm

The significant changes in tool geometry can be investigated through some parameters of AE such as RMS value or absolute energy (for both sensors). The massive breakage (transformation of microchipage to macrochipage) leads to increase in their values, Fig. 10.

The similar results were obtained under the different cutting conditions. The subsequent experiment was carried out under the cutting speed 100 m.min^{-1} and cutting depth 0,075 mm. Fig. 11

shows the chip obtained in the different stages of cutting process. While the initial stage of cutting process represents the formation of a conventional segmented chip (Fig. 11a), the progressive change of tool shape and geometry lead to transformation of a formed chip because of transformation of stress and temperature state in front of the cutting edge. Fig. 11 shows that the degree of segmentation decreases, the chips becomes less segmented and more continuous. Fig. 11a represents the first stage of cutting edge (formation of chip on the radius of cutting insert). Fig. 11b illustrates chip formation in the stage when crater on the cutting edge becomes stable. Fig. 11c shows chip character in the final stages of macroscopic breakage of cutting insert.



a) VB = 0 mm

b) VB = 0,07 mm

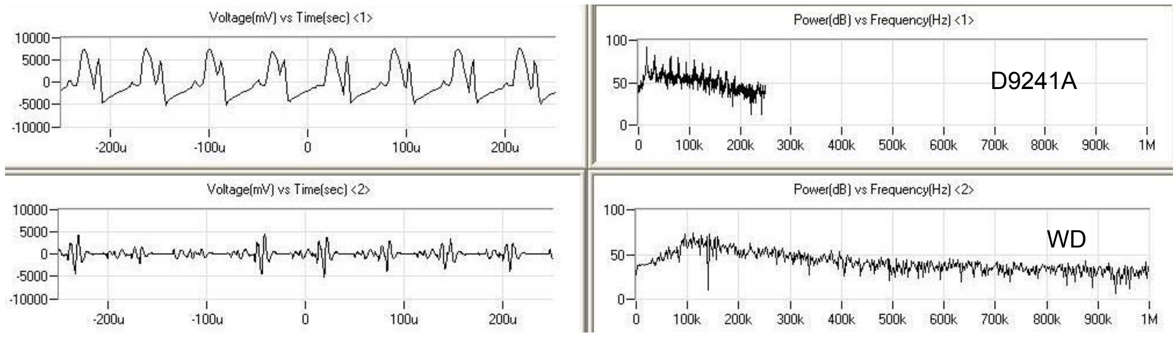
c) VB = 0,3 mm

Fig. 11 Photos of chips in the different stages of cutting process
Obr. 11 Fotografie triesok v počiatočnom a konečnom štádiu rezného procesu
v_c = 100 m.min^{-1}, a_p = 0,075 mm

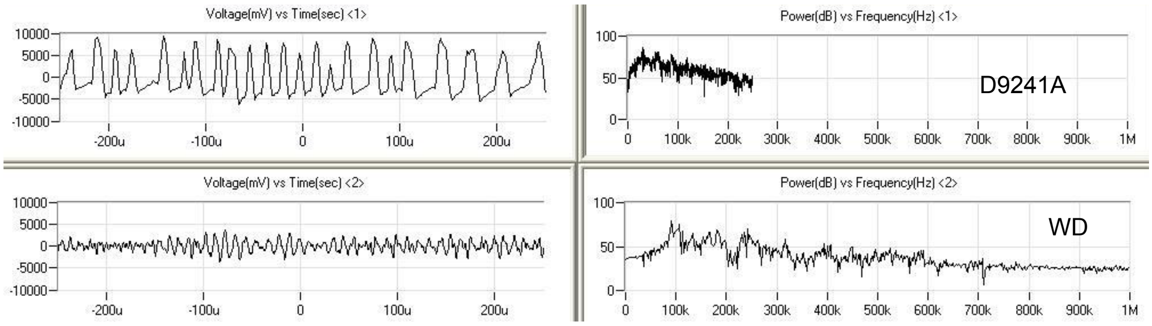
The character of AE signal (for both sensors) changes in association with the formed chip. The initial stage represents formation of a usually segmented chip and is associated with the relaxing character of AE signal of the low frequency sensor. The derived FFT spectrum exhibits an occurrence of the regular peaks in the spectrum as the evidence of a strong signal of a regular, dominant and stable frequency (segmentation frequency of a chip). The amplitude of AE signal of the high frequency sensor is low. The intensity of deformation processes is low and crack propagation in the shear zone dominates. The progressive process of tool geometry transformation leads to transformation of the formed chip and of the associated AE signals too. The regular and relaxing character of AE signal of the low frequency sensor disappears; the regular peaks in the FFT spectrum are missing and the amplitude of AE signals of the high frequency sensor increases, Fig. 12.

The identification of such parameters as RMS value or absolute energy of AE enables monitoring of cutting process through the AE signal (and derived parameters) under high cutting speeds and cutting depths. On the other hand, these parameters are less sensitive to the tool wear process under low cutting speeds and cutting depths (see Fig. 13a, Fig. 14a and Fig. 15a). The sensitivity of these parameters is low for both sensors. These parameters nearly do not change with tool wear or vary in a certain interval with no clear relationship.

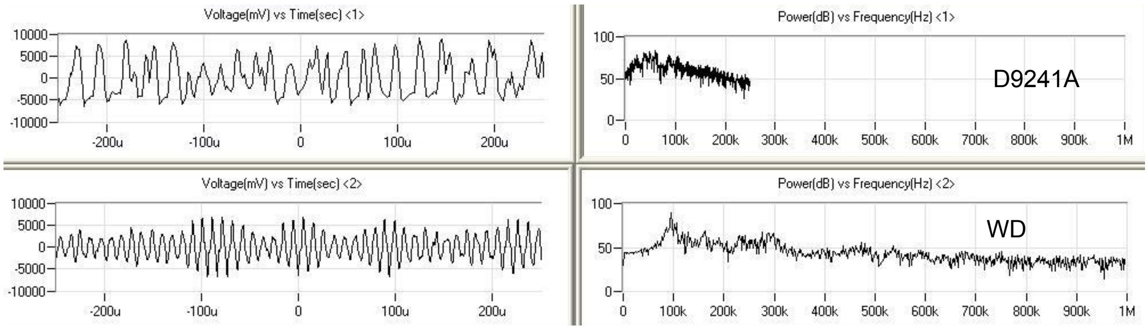
It was discussed in the previous texts that the ratio between cracks formation and deformation processes changes during tool wear. The length of cracked region decreases and deformation process are more intensive with increasing tool wear. Therefore it was considered to investigate this transformation through the ratios between parameters derived from the different sensors, because the low frequency sensor provides information about crack prolongation and the high frequency sensor information about deformation processes. The ratios between parameters derived form the low frequency and high frequency sensors were calculated as an investigation of transformation processes in the cutting zone. Fig. 13b, Fig. 14b and Fig. 15b show that these signals processing is more sensitive to the tool wear than the conventional approach illustrated and described in the previous text.



a) VB = 0 mm FFT spectrums



b) VB = 0,07 mm FFT spectrums

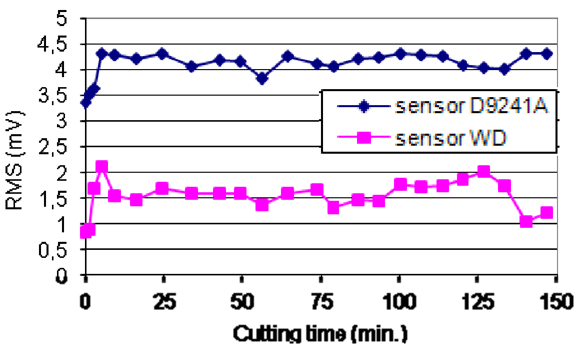


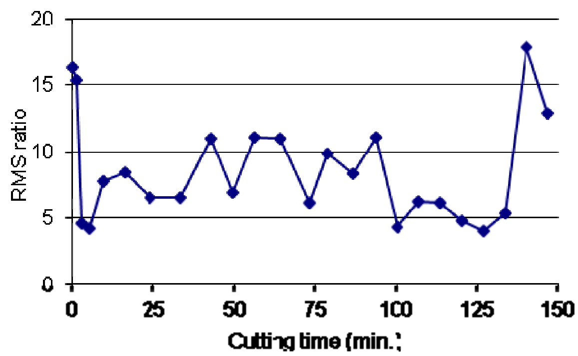
c) VB = 0,3 mm FFT spectrums

Fig. 12 Character of AE signal in the different stages of cutting process

Obr. 12 Charakter AE signálov v rôznych štádiách rezného procesu

v_c = 100 m.min^{-1}, a_p = 0,075 mm



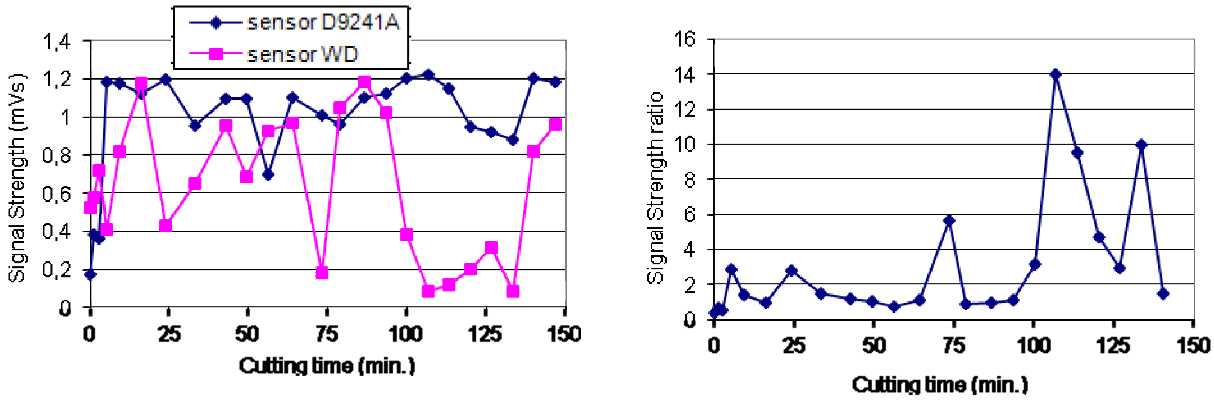


a) RMS values b) ratio of RMS values

Fig. 13 Influence of tool wear on RMS values of AE and their ratio

Obr. 13 Vplyv opotrebenia nástroja na RMS hodnoty AE a ich pomer

v_c = 100 m.min^{-1}, a_p = 0,075 mm

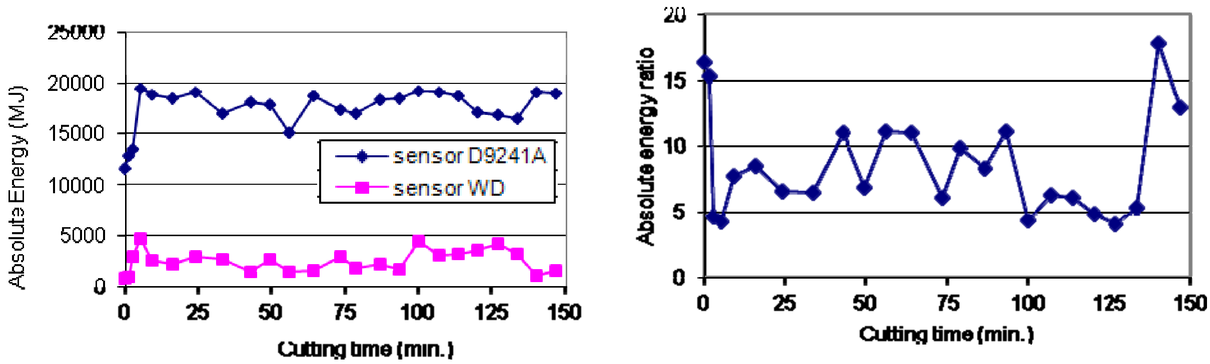


a) strength values b) ratio of signal strength values

Fig. 14 Influence of tool wear on signal strength AE and their ratio

Obr. 14 Vplyv opotrebenia nástroja na strength AE a ich pomer

v_c = 100 m.min^{-1}, a_p = 0,075 mm



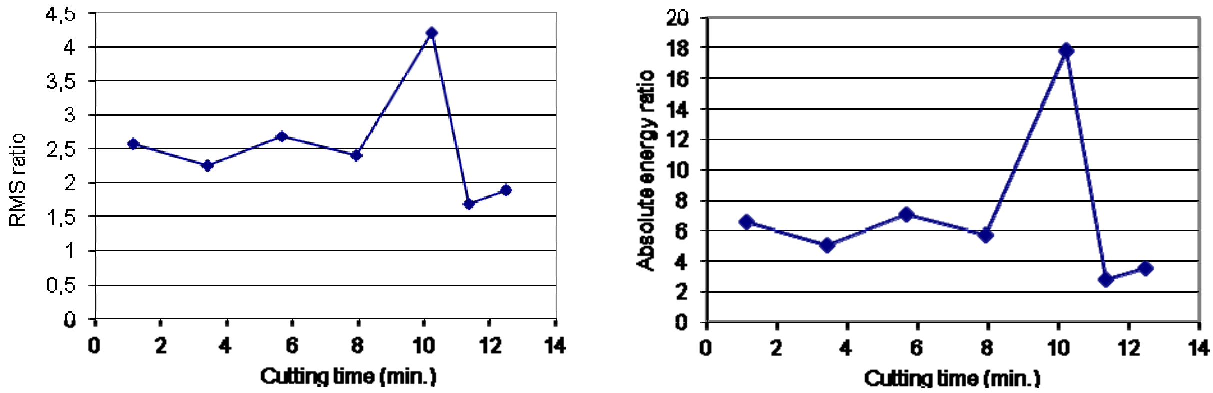
a) absolute energy values b) ratio of absolute energy values

Fig. 15 Influence of tool wear on absolute energy values of AE and their ratio

Obr. 15 Vplyv opotrebenia nástroja na absolútnu energiu AE a ich pomer

v_c = 100 m.min^{-1}, a_p = 0,075 mm

Fig. 13b and Fig. 15b show that the normal phase of cutting process can be easily separated in this way. The high ratio between signals from the high and low frequency sensors are associated with the initial phase (formation of crater on the cutting edge) and in the final stages (macrochipage of cutting edge). The central zone represents a stable process. The processing of signal strength illustrates increasing values of the calculated ratios in the final stages of cutting process.

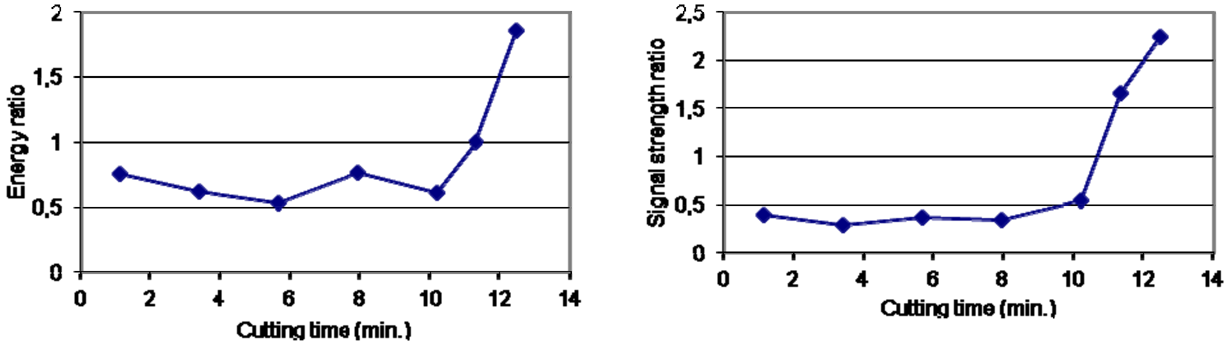


a) RMS ratios b) absolute energy ratios

Fig. 16 Ratios of RMS and absolute energy of AE in relation to the tool wear

Obr. 16 Vplyv opotrebenia nástroja na pomer RMS hodnôt a absolútnych energii AE

v_c = 170 m.min^{-1}, a_p = 0,25 mm

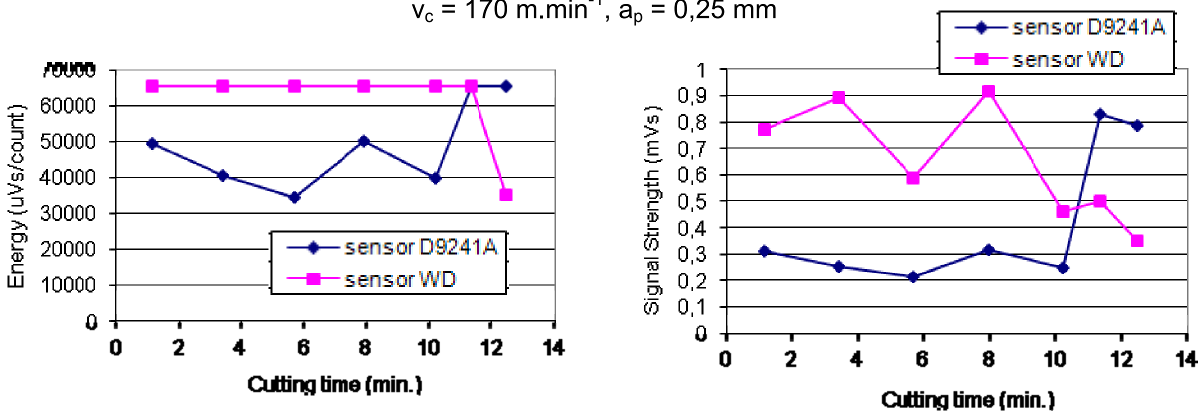


a) energy ratios b) Signal strength ratios

Fig. 17 Ratios of energy and signal strength of AE in relation to the tool wear

Obr. 17 Vplyv opotrebenia nástroja na pomer energii a strength AE

v_c = 170 m.min^{-1}, a_p = 0,25 mm



a) energy b) strength

Fig. 18 Energy and Signal strength of AE in relation to tool wear

Obr. 18 Vplyv opotrebenia nástroja na hodnoty energie a strength AE

v_c = 170 m.min^{-1}, a_p = 0,25 mm

Retrospectively the signals recorded during the previous test (at cutting speed 170 m.min^{-1} and cutting depth 0,25 mm) were processed in the same way. The analysis of RMS and absolute energy ratios show the similar character to that of the thrust force, Fig. 16. The maximums of these ratios can be obtained immediately before the macroscopic tool breakage with the following steep decrease in the phase of the catastrophic stage of tool wear. These parameters are considered to be designed for the real time monitoring of hard cutting through AE as the alerting indicators of oncoming tool massive breakage. On the other hand, steep increase in energy and signal strength ratio is associated with the macroscopic tool breakage and can be applied to indication of this state, Fig. 17.

4 Discussion and conclusion

The previous analyses showed that the investigation of ratios of different AE signals (and derived parameters) can provide more sensitive output for monitoring of hard turning. However, some parameters enable process monitoring without the following processing, Fig. 10. On the other hand, the sensitivity of the following signal processing (calculation of ratios) provide more sensitive tool for process monitoring (except for RMS and absolute energy of the low frequency sensor under the higher cutting speed and cutting depth). The values in Tab. 2 are the ratios between the highest (lowest) values of parameters in the final stage of the cutting process and the average values in the normal phase. In the case of the second experiment, the conventional parameters do not enable a successful process monitoring, while the following processing of signal through the ratios enable this monitoring. It is an interesting point of view that despite the different cutting conditions, the ratios in Tab. 2 are nearly the same for both cutting conditions.

Tab. 2 Ratio between the highest (lowest) values to the average values of different parameters
Tab. 2 Pomer medzi najvyššími (najnižšími) hodnotami a priemernými hodnotami parametrov

	Conventional evaluation			Ratio of 9241A/WD	
Cutting speed	170 m.min^{-1}		100 m.min^{-1}	170 m.min^{-1}	100 m.min^{-1}
Cutting depth	0,25 mm		0,075 mm	0,25 mm	0,075 mm
sensor	WD	D9241A	both sensors	combination	
RMS	1,2	3,25	impossible	1,96	1,9
Absolute energy	1,54	6	impossible	3,06	3
Energy	1,6	1,6	impossible	3	3,1
Signal strength	2,6	2,25	impossible	5,6	5

WD – high frequency AE sensor
D9241A – low frequency AE sensor

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MONITORIZÁCIA OPOTREBENIA NÁSTROJA PROSTREDNÍCTVOM AKUSTICKEJ EMISIE

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Článok sa zaoberá analýzou opotrebenia nástroja v reznom procese prostredníctvom akustickej emisie pri tvrdom sústružení ložiskovej ocele 100Cr6 (62HRC). V článku sú uvedené niektoré aspekty súvisiace s koreláciou medzi opotrebením rezného nástroja a niektorými parametrami signálov akustickej emisie z nízkofrekvenčného a vysokofrekvenčného snímača. Výsledky experimentov ukazujú, že v súvislosti so zmenami tvaru a geometrie reznej hrany sa výrazne mení nielen charakter deformačných procesov a tvar triesky, ale aj charakter signálov akustickej emisie. Pri vyšších hodnotách rezných rýchlostí a posuvov je možné realizovať monitorizáciu rezného procesu aj prostredníctvom niektorých parametrov, predovšetkým pri aplikácii nízkofrekvenčného senzora. Na druhej strane je identifikácia zmien rezného procesu pri menších posuvoch a hĺbkach rezu problematická, pretože súvisiaca zmena hodnôt vybraných veličín akustickej emisie kolíše vo veľkom rozsahu hodnôt, respektíve sa nemení aj napriek výrazným zmenám deformačných procesov. V súvislosti s tým bol využitý postup, kedy sa analyzuje pomer signálov z oboch senzorov. Nízkofrekvenčný senzor poskytuje informácie predovšetkým o krehkom porušení materiálu a šírení trhlín. Na druhej strane vysokofrekvenčný senzor indikuje deformačné procesy v sklzovej rovine ako aj trecie procesy v kontakte čela nástroja a triesky ako aj chrbtovej plochy nástroja a obrobku. V súvislosti s opotrebením nástroja dochádza k potlačeniu procesom súvisiacich s krehkým porušením v sklzovej rovine na úkor deformačných procesov. Pomer parametrov z oboch senzorov teda vyjadruje tieto transformačné procesy. Výsledky ukazujú, že prostredníctvom pomerov v rôznych frekvenčných pásmach je možné proces tvrdého sústruženia monitorovať aj pri nízkych posuvoch a hĺbkach rezu.

ZPĚT