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## Spremljanje procesa z zaznavali pri struženju nodularne litine z rezalno keramiko \*

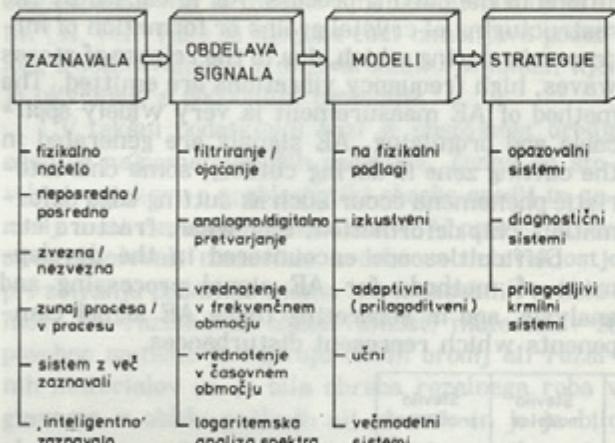
### Process Monitoring with AE Sensors In Turning Nodular Cast with Cutting Ceramics

JANEZ KOPAČ – SLAVKO DOLINŠEK

#### O. UVOD

Pri obdelavi na sodobnih večoperacijskih strojih je, zaradi vse večje stopnje avtomatizacije obdelovalnih sistemov, nadzorovanje rezalnega procesa neobhodno potrebno. Prigraditev ustreznih nadzorovalnih sistemov omogoča gospodarno uporabo orodij in zmanjšuje zastojne čase obdelovalnih procesov. Kljub temu, da se s problematiko te vrste ukvarja mnogo raziskovalcev, lahko rečemo, da so današnji sistemi nadzorovanja in preverjanja še vedno v razvoju, njihova zmožnost in zanesljivost pa sta vedno večji.

Potrebne komponente za sestavo nadzorovalnega sistema rezalnega procesa so: zaznavalo, obdelava signala, model in strategija (sl. 1) [1].

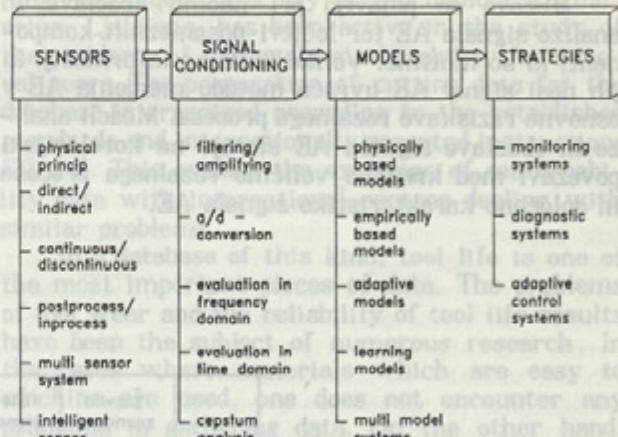


– org The development of the information and control systems in modern machining centres has become a necessity. The use of adequate monitoring and control systems improves the economy of machining and reduces down-times. Despite extensive research in this field, the present systems of monitoring and control are still considered to be in the stage of development, their capabilities and reliability however are growing all the time.

#### 1. INTRODUCTION

Due to the increasing automation of machining systems, monitoring and control of the cutting process on modern machining centres has become a necessity. The use of adequate monitoring and control systems improves the economy of machining and reduces down-times. Despite extensive research in this field, the present systems of monitoring and control are still considered to be in the stage of development, their capabilities and reliability however are growing all the time.

The components necessary to set up a monitoring and control system for the cutting process are: a sensor, a signal processing unit, a model and strategy (fig. 1) [1].



Sl. 1. Komponente opazovalnega in nadzorovalnega sistema.  
Fig. 1. Structure of a monitoring and control.

Zaznavala merijo določeno fizično veličino rezalnega procesa in posredujejo osnovno informacijo o dogajanju na rezalnem robu. Razvoj zaznaval poteka v smeri izdelave, »inteligentnih« sistemov z več zaznavali. Signal iz zaznavala moramo ustrezno obdelati (filtrirati, ojačati, digitalizirati itn.), odvisno od modela in načina opazovanja signala. Modeli so primerjalni algoritmi in primerjajo signal iz procesa z veličino, ki ustreza pravilnemu nemotenemu poteku obdelave. Iz modela dobimo informacijo o stanju obdelovalnega procesa.

Sensors measure a specific physical parameter of the process and provide the basic information about the conditions on the cutting edge. The development tendencies in this field are aimed at creating intelligent multiple sensor systems [1], [2]. The signal coming from the sensor has to be adequately processed (filtered, amplified, digitised) depending on the model and method of observation. The models are comparison algorithms comparing the signal from the process with the model algorithm representing the correct undis-

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Z ustreznimi strategijami pa se odločimo, ali proces nadaljujemo, popravimo ali pa ustavimo. S povezavo nadzornega in krmilnega sistema dobimo adaptivni nadzorovalni sistem, ki spreminja parametre obdelave glede na stanje v sistemu.

Za posredno spremeljanje stanja rezalnega orodja moramo v začetni fazi sestaviti ustrezen opazovalni sistem, če pa želimo napovedati lome orodij (kar naj bi bil končen rezultat raziskav), potem moramo diagnosticirati. Možnost je tudi, da zanesljiv in preizkušen nadzorovalni sistem povežemo z adaptivnim delom in ga naučimo, kako naj se odzove pri različnih obdelovalnih primerih [2]. Število značilnosti nadzorovalnega sistema je odvisno od števila zaznaval, signalov in modelov (sl. 2) [1], [2]. Razvoj je usmerjen v izdelavo sistemov z več zaznavali in več modeli. Ti povečujejo gostoto informacij in dajejo večjo zanesljivost nadzoru rezalnega procesa, kar je bilo tudi vodilo naših raziskav.

Novejša metoda opazovanja rezalnega procesa sta merjenje in analiza akustične emisije (v nadaljevanju AE), ki nastane pri prerazporeditvi kristalnih zrn ali nastanku mikrorazpok. Metoda merjenja AE je zelo obetavna, ker se AE vzbuja v rezalni coni pri značilnih pojavih med rezanjem kakor so: deformacija obdelovanega materiala v odrezek, obraba ter zlom orodja in podobno.

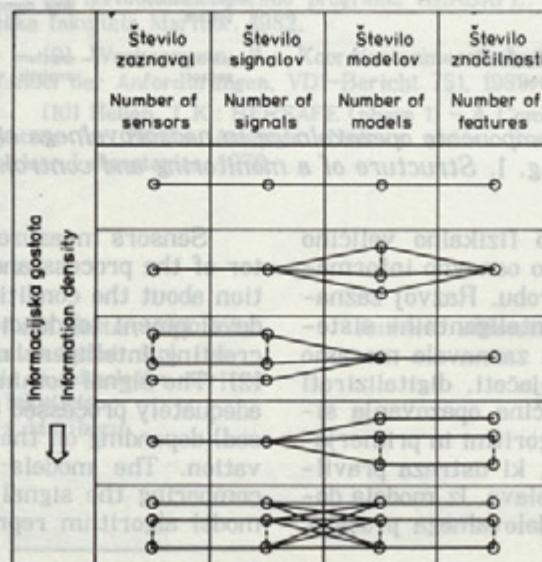
Težave se pojavijo pri načinu obdelave in analize signala AE ter ločitvi posameznih komponent, ki so motilne. Velika količina informacij, ki jih nosi signal AE uvršča metodo merjenja AE v osnovne raziskave rezalnega procesa. Modeli analize in obdelave signala AE slonijo na korelačjski povezavi med kritično veličino rezalnega procesa in določeno karakteristiko signala AE.

turbed course of the machining process. From the model one receives information about the conditions of the machining process, and, using suitable strategies, then decides whether the process will be continued, regulated or stopped. By combining the monitoring and the control system, an adaptive control system is obtained, which is capable of changing the system's parameters with respect to the conditions detected.

For the prediction of tool failure, which is supposed to be the final aim of this kind of research, one must first set up an adequate monitoring system to follow the conditions on the cutting tool, then we proceed to diagnostic. Another possibility is that the engineer connects a reliable, proven control system to the adaptive unit and teaches it to respond to various cases of machining [2]. The features of the monitoring and control system depend on the number of sensors, signals and models (fig. 2) [1], [2]. Trends in the development of these systems are to lead to the construction of multiple-model systems. These kinds of systems should increase the density of information and ensure their higher reliability, which has also been an objective of the research.

Measurement and analysis of the acoustic emission (AE) from metal cutting is a relatively new method used for the identification of the conditions in the cutting process. AE is caused by the restructuring of crystal grains or formation of microcracks during which, due to the release of stress waves, high frequency vibrations are emitted. The method of AE measurement is very widely applicable and promising. AE signals are generated in the cutting zone if during cutting, some characteristic phenomena occur such as cutting edge deformation, chip deformation, tool wear, fracture etc.

Difficulties are encountered in the development of methods for AE signal processing and analysis, and in separating those AE signal components which represent disturbances.



Sl. 2. Možnosti kombiniranja zaznaval in modelov

Fig. 2. Combination of sensors and models.

S hkratnim opazovanjem in primerjanjem signalov AE in dinamičnih rezalih sil ugotovimo značilnosti in primernost meritve in analize signala AE. Dinamična rezalna sila in AE sta odziv do- gajanj v rezalni coni. Z njuno primerjavo in korelacijsko z obrabo orodja lahko dobimo merila za oce- no oblike in vsebine signala v različnih razmerah dela in za različne obrabe orodja.

## 1. STRUŽENJE NODULARNE LITINE NL 60

Osnovno izhodišče za načrtovanje rezalnih pa- rametrov je še vedno tehnološka podatkovna banka. Izbrani rezalni parametri morajo zagotavljati s preizkusi ugotovljen čas obstojnosti orodja, medtem ko naj zaznava v pretežni meri opozarjajo le na nepredvidene dogodke.

V Laboratoriju za odrezovanje Katedre za obdelovalno tehniko na Fakulteti za strojništvo se s problemi obdelovalnosti materialov ukvarjam že vrsto let. Pri tem poteka priprava rezalnih podatkov za podatkovno-banko že po ustaljenih, skoraj standardiziranih in mednarodno usklajenih navodilih [3], [4]. Tako je mogoča tudi izmenjava podatkov o obdelovalnosti z mednarodnimi središči, kjer je ukvarjajo s podobnimi problemi.

V takšni podatkovni bazi je obstojnost orodja eden od najpomembnejših podatkov. Znane so številne raziskave o problematiki obrabe orodij in zanesljivosti rezultatov obstojnosti. V primerih, ko smo obdelovali materiale z dobro obdelovalnostjo pri zbiranju podatkov nismo imeli posebnih problemov. Pri raziskavah obdelovalnosti materialov za posebne namene in razvoju novih orodij ali rezalnih materialov pa je bila obraba rezalnega roba v glavnem v obliki poškodb ali zlomov in jo je bilo skoraj nemogoče napovedati v obliki enačb za čas obstojnosti.

Kot praktičen primer bomo prikazali rezultate raziskav obdelovalnosti pri struženju nodularne litine z rezalno belo keramiko. Osnovni podatki o materialu in orodju so zbrani v preglednici 1.

Glede na eksperimentalne meritve obrabe orodja in ustrezeno statistično obdelavo podatkov je mogoče z uporabo razširjene Taylorjeve enačbe za obstojnost (sl. 3) določiti ustrezeno rezalno hitrost:

$$v_c = 936,12 \times f^{-0,33} \times a^{-0,32} \times t^{-0,32} \times VB^{1,11}$$

pri čemer so  $f$ ,  $a$ ,  $t$  in  $VB$  spremenljivke in pome- nijo:  $f$  – podajanje v mm,  $a$  – globina rezanja v mm,  $t$  – čas struženja v min in  $VB$  – obrabo na prosti ploskvi v mm.

The broadness of the information contained in the AE signal makes this method part of the fundamental research methods of the cutting process. The models of AE processing and analysis rely heavily on the correlation between a critical cutting process parameter and a characteristic of the AE signal.

By simultaneous observation and comparison of AE signals and dynamic cutting forces one can find out the characteristics of the AE signal analysis and assess the suitability of measurements. By comparing dynamic cutting forces, tool wear and the AE, the criteria for the evaluation of the AE signal can be set up. On this basis, the form and content of the signal occurring in specific cutting conditions and at specific tool wear can be established.

## 1. TURNING NODULAR CAST NL 60

The main starting point in the planning of machining parameters is, for the time being, still the technological data base. The chosen technological parameters have to ensure the tool life predicted by tests, while on the other hand, the discussed AE phenomena occurring in the process act more or less only as a warning of the unpredictable events that may occur in the cutting zone.

The Laboratory for Cutting, Dept. of Machining Techniques, Faculty of Mechanical Engineering, Ljubljana, has been active in the study of the problems of materials machinability for several years. The preparation of cutting data for the database is organised according to the established standards and internationally accepted instructions [3], [4]. This enables the exchange of machinability data with international centres dealing with similar problems.

In a database of this kind, tool life is one of the most important pieces of data. The problems of tool wear and the reliability of tool life results have been the subject of numerous research. In the cases where materials which are easy to machine are used, one does not encounter any problems in gathering data. On the other hand, with materials for special purposes, in the development of new tools and tool materials, tool wear often results in cutting edge damage and failure and it has become impossible to predict it by tool life equations.

The following example illustrates the results of machinability investigations in turning nodular cast with white cutting ceramics. Table I shows the basic data on the workpiece material and the tool.

Based on experimental measurements of tool wear and statistical data processing, it is possible to determine the cutting speed, using an extended Taylor's equation for tool life (fig. 3).

where:  $f$  – feed rate [mm],  $a$  – depth of cut [mm],  $t$  – turning time [min],  $BV$  – flank wear land [mm].

Preglednica 1. Podatki o materialu in orodju  
Table 1. Workpiece and Tool Data

Obdelovani material NL 60 (trdota 266 HB: natezna trdnost 600 N/mm<sup>2</sup>)  
Workpiece material NL 60 (hardness 266 HB: tensile strength 600 N/mm<sup>2</sup>)

Sestava/ struktura Composition	C	S	Mn	P	Cr	Cu	Mo	N	perlit	ferit
%	3,8	2,0	0,3	0,1	0,1	0,15	0,1	0,5	80	20

Rezalni material CR 05 (Bela keramika – COMET)  
Tool Material CR 05 (White ceramics)

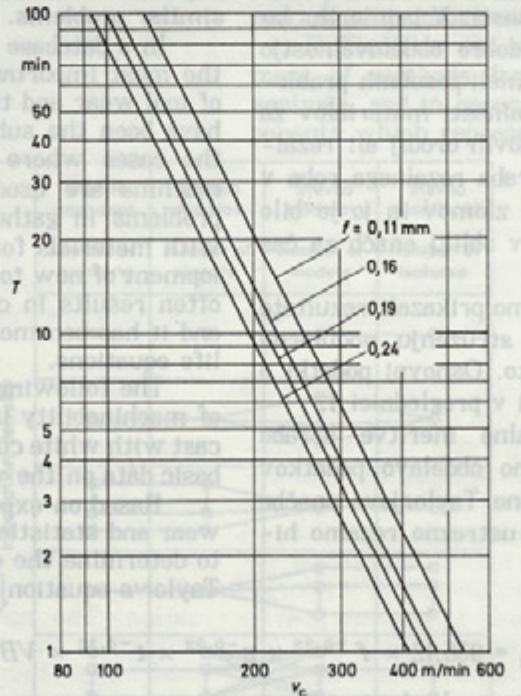
sestava composition	gostota density	trdota hardness	upogibna trdnost bending strength	natezna trdnost tensile strength
Al <sub>2</sub> O <sub>3</sub>	3,95 g/cm <sup>3</sup>	2000 HV	350 MPa	2500 MPa

Rezalna ploščica:  
Cutting plate: SNGN 120712 T02020  
Držalo:  
Tool holder: CSNL 3225 P 12

$\alpha$	$\gamma$	$\lambda$	$x$	$\epsilon$	$r$
6	-6	-4	75	90	1,2

Diagram  $T - v_c$  na sliki 3 prikazuje čas obstojnosti orodja v odvisnosti od rezalne hitrosti  $v_c$  in podajanji  $f$ . Zanesljivost takšnega diagrama je povezana s homogenostjo obdelovanega materiala in kakovostjo rezalnega materiala. Kljub temu, da

Graph  $T - v_c$  In figure 3 shows tool life time versus cutting speed  $v_c$  and feed rate. The reliability of this kind of graph depends on the homogeneity of the workpiece material and the quality of the tool material. Despite the fact that the initial difficulties in the development of cutting ceramics

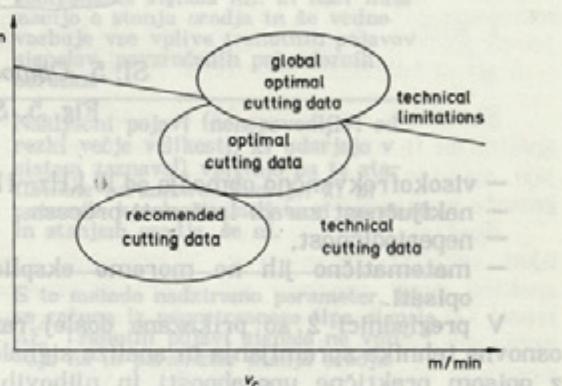
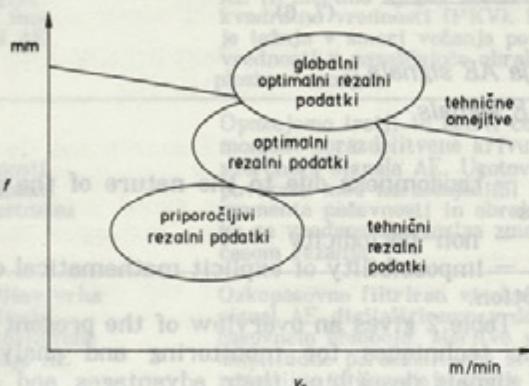


Sl. 3. Diagram  $T - v_c$  pri struženju NL60 s keramiko CR05.

Fig. 3. Tool life graph.

so bile začetne težave pri razvoju domače rezalne keramike kasneje odpravljene in je bila njena kakovost primerljiva s podobnimi izdelki drugih izdelovalcev [5], so se poškodbe orodij zaradi vključkov v materialu obdelovanca še vedno pojavljale. To je bilo še posebno opazno pri obdelavi v optimalnem področju rezalnih parametrov (sl. 4): večje rezalne hitrosti  $v_c$  in podajanja  $f$  [6], zato smo začeli pripravljati sistem z zaznavali, ki bi nas opozarjal na lome orodij.

produced by Slovene manufacturers have been removed, the quality being comparable to similar products of other manufacturers [5], tool damages, due to inclusions in the workpiece material, has nevertheless still turned up. This has been observed especially on machining within the optimal range of cutting parameters (fig. 4) with high cutting speed  $v_c$  and feed rate  $f$  [6]. Therefore we started to prepare a system with sensors which would signal tool failure.



Sl. 4. Spreminjanje rezalnih parametrov glede na vrsto podatkov [4].

Fig. 4. Definitions of data types in cutting [4].

## 2. POJAV AKUSTIČNE EMISIJE PRI ODREZOVANJU

Pod imenom akustična emisija razumemo signale v obliki mehanskega valovanja s frekvencami od 10 kHz do 10 MHz. Akustični emisijski valovi nastanejo pri prerazporeditvi in prepremikih strukture in kristalnih rešetk pod vplivom plastičnih in elastičnih napetosti v materialu. V mehansko obremenjenem materialu nastajajo mikroskopske razpoke, ki povzročajo mikronestabilnost in notranje napetosti. Prerazporeditev napetosti povzroči elastičen val AE, ki je sestavljen iz vzdolžne in prečne komponente. Signal AE razdelimo v:

- nepretrgani ali zvezni signal AE, ki nastane pri plastični deformaciji duktilnih materialov;
- izbruhi ali diskretni signal AE, ki nastane med širjenjem razpok v materialu in pri zlomu materiala.

Cone, kjer pri odrezovanju nastajajo signali AE, prikazuje slika 5 [7].

Raziskave uporabnosti merjenja signalov AE pri odrezovanju so usmerjene v razvoj metod, modelov in meril, ki naj iz enotnega nepretrganega signala AE prepozna posamezne oblike poškodb in obrab orodja. Za lom, razpoke in drobljenje orodja so značilni trenutni pojavi signalov z visokimi amplitudami. Pri drugih oblikah obrabe pa je potrebno iz celotnega spektra signalov AE razbrati in analizirati značilne signale za določeno vrsto obrabe.

Glavne značilnosti dobrijenih signalov AE so:

## 2. ACOUSTIC EMISSION DURING CUTTING

The term acoustic emission denotes signals in the form of mechanical waves in a frequency range from 10 kHz to 10 MHz. AE waves are released as a result of restructuring and changes in the crystal lattice under the influence of plastic and elastic stresses in the material. In a mechanically loaded material, micro-cracks occur, causing microinstabilities and internal stresses. A redistribution of stresses results in an elastic AE wave consisting of longitudinal and transverse components. AE signals can be classified into two main types:

- continuous AE signals occurring in plastic deformation of ductile materials, and
- outburst or discrete AE signals generated by cracks propagation and material fracture.

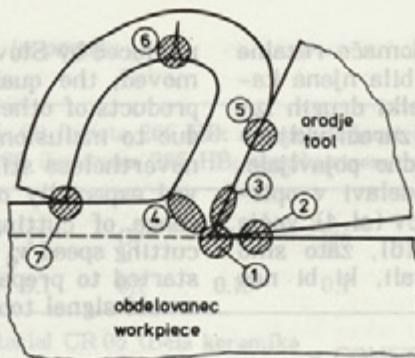
The zone of generated AE signals during cutting as seen from figure 5 [7].

Research tendencies in the field of AE signal measurements during cutting are directed into the development of methods, models and criteria for the detection of damage and tool failure from a uniform continuous AE signal. Failure, cracks and crushes are announced by accidental signals with high amplitudes. Other forms of wear have to be recognized from the entire AE spectrum from which the signal characteristic for a certain kind of damage has to be identified and analysed.

The principal characteristics of AE signals are:

- high frequency range from 10 kHz to 1 MHz

- strig in plastična deformacija obdelovanega materiala (4, 2, 3),
- razpoke v obdelovanem materialu (1),
- trenje med obdelovanim materialom, orodjem, odrezkom in lomilcem odrezka (2, 3, 5),
- trki in lomi odrezka (7, 6)



- shear and plastic deformations of work material (4, 2, 3)
- cracking of work material (1)
- friction among work material, tool, chip and chip breaker (2, 3, 5)
- collision and breakage of chips (7, 6)

Sl. 5. Območja vzbujanja AE signala.

Fig. 5. Sources of AE signals.

- visokofrekvenčno območje od 10 kHz–1 MHz,
- naključnost zaradi lastnosti procesa,
- neperiodičnost,
- matematično jih ne moremo eksplisitno opisati.

V preglednici 2 so prikazane doslej razvite osnovne tehnike spremljanja in analize signala AE z opisom praktične uporabnosti in njihovih pomankljivosti.

### 3. OPIS MERILNEGA MESTA

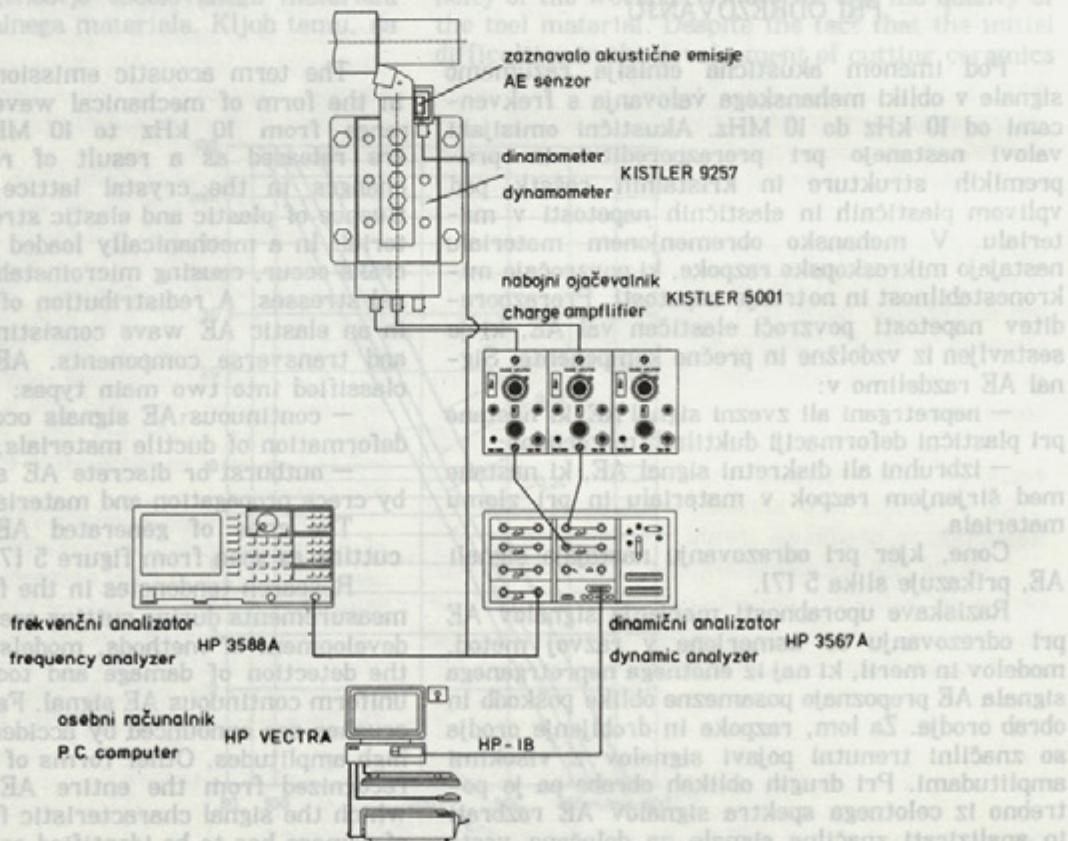
Merilna veriga je prikazana na sliki 6.

- randomness due to the nature of the process
- non-periodicity
- impossibility of explicit mathematical description.

Table 2 gives an overview of the present day basic techniques for monitoring and analyzing AE signals describing their advantages and disadvantages.

### 3. EXPERIMENTAL

The measuring chain is illustrated in figure 6.



Sl. 6. Merilna veriga.

Fig. 6. Experimental set-up.

Preglednica 2. Posredno povezane tehnike opazovanja stanja orodja na podlagi signala AE [6].

Parameter AE v povezavi s stanjem orodja	Opis	Opombe
Pojni AE čez določeno mejno vrednost	Opazujemo trenutni pojav ozkopasovnega filtriranega visoko frekvenčnega signala AE. Ugotovljena je tesna povezava med velikostjo pojavorov AE, ki v določenem času rezanja presežejo mejno vrednost in obrabo rezalnega roba.	Določitev mejne vrednosti je oteženo zaradi naključne oblike signala AE in naključnih značilnosti nastajanja odrezka, ki vzbujajo sistem zaznaval.
Energija, ki jo ima signal AE	Opazujemo ozkopasovno filtriran signal AE in merimo njegov koren povprečne kvadratne vrednosti (PKV). Dokazana je težnja v smeri večanja povprečne vrednosti z naraščajočo obrabo proste ploskve orodja.	Izračunane vrednosti so iz nepretrgane komponente signala AE, ki nosi informacijo o stanju orodja in še vedno vsebuje vse vplive trenutnih pojavorov signalov, povzročenih pri udarcih odrezka.
Vrednosti poševnosti in kurtozisa	Opazujemo tretji in četrti centralni moment porazdelitvene krivulje vzorčnega signala AE. Ugotovljena je povezava med naraščajočimi vrednostmi momenta poševnosti in obrabo, medtem ko se vrednost kurtozisa zmanjšuje s časom rezanja.	Naključni pojavi (nenapovedljivi odrezki veče velikosti, ki udarjajo v sistem zaznaval) vplivajo na te statistične parametre. Teorije, ki bi pojasnila korelacijo med temi parametri in stanjem orodja, še ni.
Določitev vrha amplitude porazdelitvene krivulje AE	Ozkopasovno filtriran visokofrekvenčni signal AE digitaliziramo v določenem časovnem območju. Meritve vrha amplitudne porazdelitvene krivulje zanesljivo prikazujejo stanje orodja.	S to metodo nadziramo parameter, ki se računa iz nepretrganega tipa signala AE. Trenutni pojavi signala ne vplivajo na ta parameter stanja orodja.
Frekvenčne komponente	Parameter stanja orodja se računa iz spektra moči frekvenčnega območja zaznavala AE. Parameter, ki je določen iz razmerja spektra moči v frekvenčnem območju 100–300 kHz in celotnega frekvenčnega področja, določa stanje orodja.	Parameter stanja orodja je neodvisen od amplitudnih vrednosti signala AE, ker izračunamo le razmerje določenih frekvenčnih območij.

Table 2: Indirect on-line techniques based on aeronautic emission signals [6].

AE parameter related tool condition	Description	Notes
AE phenomena exceeding a given limit value	Discrete, narrow-band, filtered high frequency AE signal is observed. A close relationship is established between AE Signal magnitude exceeding the limit value after a certain cutting time and cutting edge wear.	Determination of limit value is made difficult due to random AE signal shape and randomness of chip formation exciting the sensor system.
Energy of AE signal	A narrow-band, filtered AE signal is observed and its root of mean square value (MSV) measured. A tendency of the mean value to increase with increasing VB is proved.	The calculated values are those from the continuous AE signal component providing information about the tool condition, and still containing all the effects of discrete signals caused by chip hitting against the sensor system.
Skewness and kurtozis values	The third and fourth central moment of the sample signal distribution curve is observed. A dependence between increasing moment of obliqueness and wear is established, while kurtozis value decreases with cutting time.	Random phenomena (unpredictable hits of large chip against the sensor system) affect statistic parameters. No theory exists to explain the correlation between these parameters and tool condition.
Determination of AE signal distribution curve peak	A narrow-band, filtered high frequency AE signal is digitalized in a given time period. The measurements of the peak of the distribution curve reliably defines the tool condition.	Using this method, the parameter calculated from a continuous AE signal type is controlled. Discrete signals do not affect this tool condition parameter.
Frequency component	Tool condition parameter is calculated from the power spectrum of the AE sensor frequency range. The parameter determined by the ratio of the power spectrum within a frequency range of 100–300 kHz to the entire frequency range defines the tool condition.	Tool health parameter is independent of AE signal amplitude values as only the ratio between the given frequencies is calculated.

Zaznavalo za merjenje AE je izdelano iz polariizirane keramike PZT. Zaznavalo AE je prilepljeno s strani na držalo noža pod kotom 45 stopinj, da zajame največjo količino dolžinskih nihanj iz rezalne cone. Med zaznavalom AE in držalom noža je vstavljena še elektroizolacijska ploščica, ki preprečuje vpliv električnih tokov in ozemljuje stroj. Električno je zaznavalo zaščiteno z elektrostatičnim zaslonom v obliki bakrenega pokrova (faradejeva kletka), mehansko pa z aluminijevim pokrovom, na katerem je tudi konektor BNC.

#### 4. REZULTATI MERITEV REZALNIH SIL IN AKUSTIČNE EMISIJE

Signale iz zaznavala AE in dinamometra smo analizirali in statično obdelali. Rezultati vključujejo spekter moči, avtokorelacijsko funkcijo in gostoto porazdelitve signalov.

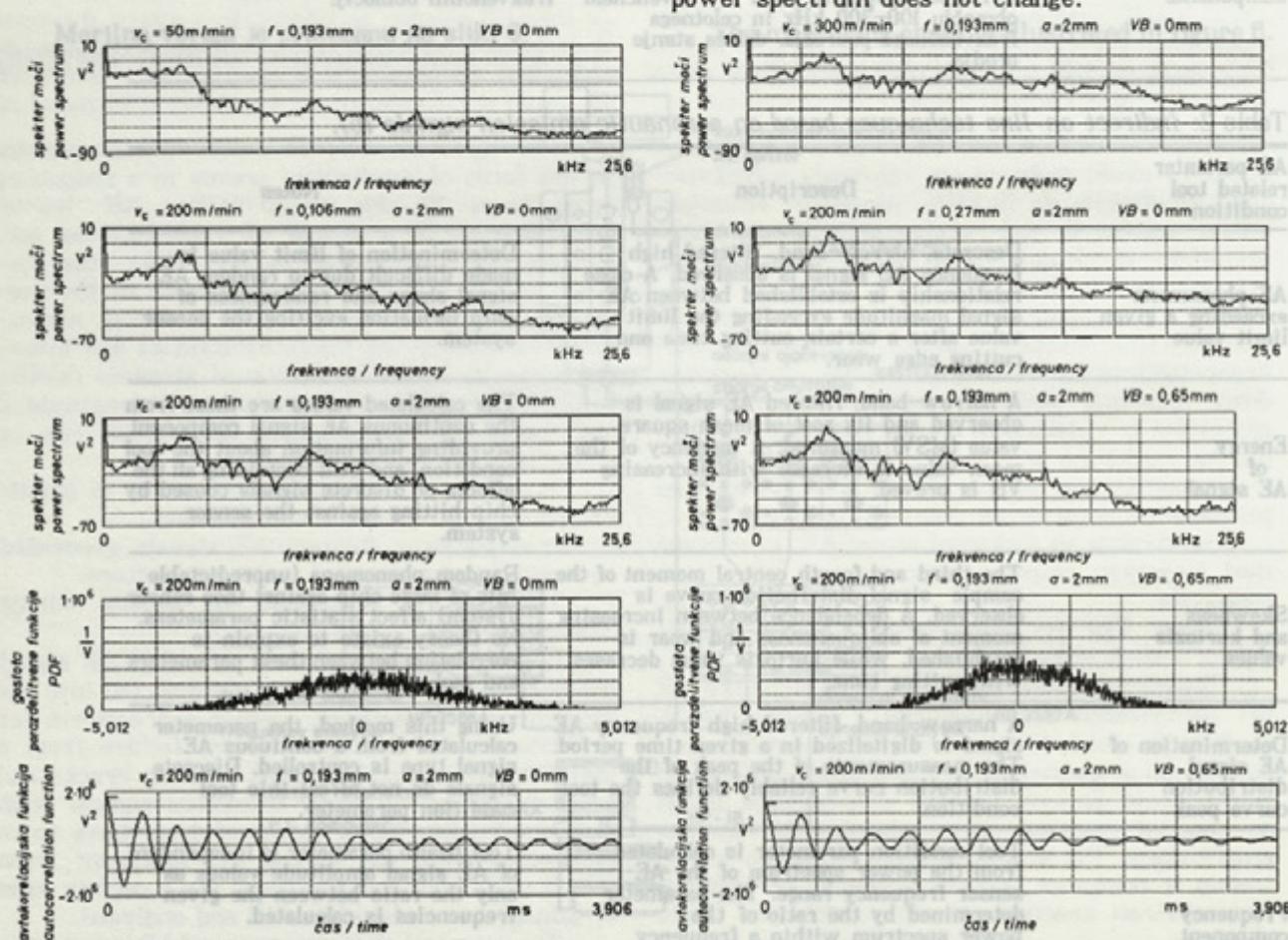
Spekter moči rezalnih sil se zvečuje z večanjem rezalnih parametrov. Najočitnejše zvečanje spektra moči opazimo pri zvečanju rezalne hitrosti (sl. 7). Podobno se zvečuje spekter moči z večanjem podajanja in globine rezanja, vendar v manjšem obsegu kakor je dovedena energija v rezalno cono. Z obrabo rezalnega roba se spekter moči sil ne spreminja.

The AE sensor was made of polarized PZT ceramics. It was stuck to the flank of the tool holder at an angle of 45° in order to sense the maximum amount of longitudinal waves coming from the cutting zone. Between the AE sensor and the holder an insulation plate was inserted, preventing any influence from electric currents and ensuring machine grounding. In addition, the transducer was protected electrically also by a copper lid representing the Faraday's shield, and mechanically, by an aluminium lid which was also equipped with a BNC connector.

#### 4. RESULTS OF CUTTING FORCE AND AE MEASUREMENTS

The signals from the AE sensor and the dynamometer were analysed and statistically evaluated. The results include the signal power spectrum, autocorrelation function, and signal density distribution.

The power spectrum of the cutting forces increases with increasing cutting parameters. The increase of the power spectrum is most pronounced in the case of increased cutting speed, (fig. 7). Similarly, the power spectrum also increases with an increase in feed rate and depth of cut, however to a smaller extent. With an increase in wear, the power spectrum does not change.

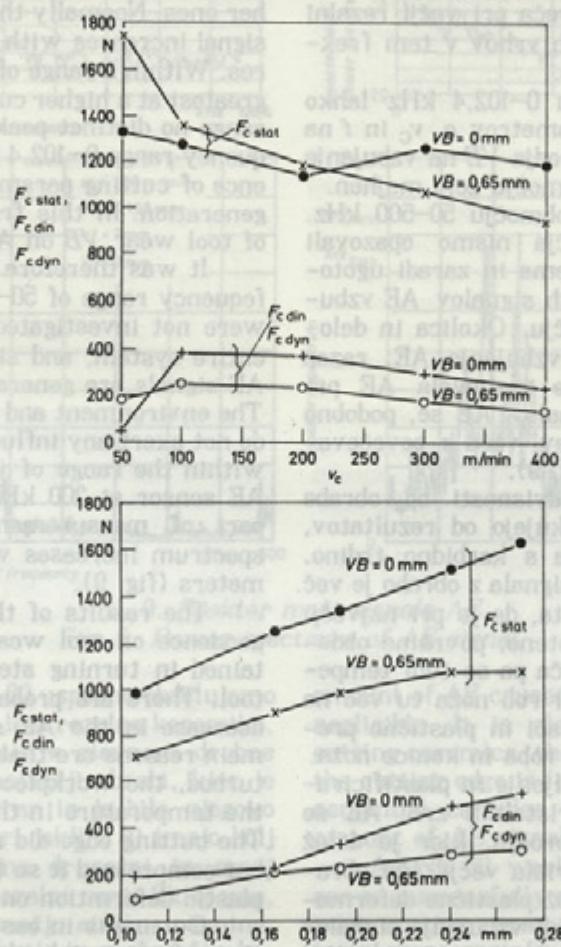


Sl. 7. Spekter moči, gostota porazdelitve in avtokorekcijska funkcija signala rezalne sile.

Fig. 7. Power spectrum, density distribution, and autocorrelation function of main cutting force signal.

Pri spektrih moči rezalne sile se zaradi resonančnih nihanj dinamometra nenehno pojavljata dva vrhova. Zaradi dušenja celotnega sistema se druga resonančna nihanja ne pojavijo. Resonančno nihanje dinamometra vpliva tudi na zaznavalo AE, saj tudi tu opazimo vrh v tem frekvenčnem območju.

Za določitev statične in dinamične komponente rezalne in podajalne sile smo v merilno verigo vezali ojačevalnik nabojev. Izmerjene vrednosti rezalne sile v odvisnosti od rezalne hitrosti, podajanja in obrabe orodja so prikazane na sliki 8.



SI. 8. Statična in dinamična komponenta rezalne sile.

Fig. 8. Static and dynamical cutting force.

Če je bilo pričakovati zmanjševanje in zvečanje tako statične kakor dinamične komponente rezalne sile v odvisnosti od rezalne hitrosti in podajanja, pa je zanimivo njuno zmanjševanje z velikostjo obrabe rezalnega roba. Podobno velja za podajalno silo. Iz rezultatov lahko ugotovimo, da se z večanjem obrabe rezalnega roba zvečuje stopnja plastifikacije v rezalni coni in s tem dušenje v dinamičnem sistemu rezalni rob – obdelovani material [11], kar se kaže na rezultatih meritev dinamičnih rezalnih sil.

In the power spectra of the main cutting force a reoccurrence of two power peaks (around 4 and 10 kHz) can be observed, being a consequence of the resonant vibrations which did not occur. The resonant vibrations of the dynamometre. Due to the damping of the whole system, other resonant vibrations of the dynamometre also have an effect on the AE sensor, the peak of the power spectrum being observed in the same frequency range. In order to determine the static and dynamic components of the cutting and feed force, a charge amplifier was added to the measuring chain. The measured values of the cutting force versus cutting speed, feed rates and tool wear are presented in fig 8.

If decreases and increases in the static as well as dynamic components of the cutting force in dependence on the cutting speed and feed rate were to be expected, it is interesting to note their decrease with increasing cutting edge wear. The same can be established for the feed force. From the results it can be found that with increasing cutting edge wear, the rate of plastification in the cutting zone also increases, and thus also the damping of the dynamic system, i.e. cutting edge/workpiece material [11]. This is reflected in the results of the measurement of the dynamic cutting forces.

Iz krivulje gostote porazdelitve rezalne in podajalne sile vidimo, da ima rezalna sila večji raztros signala okoli srednje vrednosti kakor podajalna sila. Z večanjem obrabe se raztros oziroma dinamika signala rezalne sile spreminja. Krivulja gostote porazdelitve sile se zožuje, ker se zmanjšuje raztros signala sile okoli srednje vrednosti.

Avtokorelacijska funkcija dinamičnih sil pa ima stalno množično obliko vstopnega signala in tudi vedno prenha časovno os. Vzrok je verjetno v tem, da dinamometer sledi nižjim frekvenbam, višje pa duši.

Spekter moči signala AE se v splošnem zvečuje z večanjem rezalnih parametrov. V območju med 20–100 kHz se najbolj zveča pri večji rezalni hitrosti. Izrazitih frekvenčnih vrhov v tem frekvenčnem območju ne opazimo.

V frekvenčnem območju 0–102.4 kHz lahko opazujemo vpliv rezalnih parametrov  $a$ ,  $v_c$  in  $f$  na vzbujanje AE. Vpliv obrabe orodja  $VB$  na vzbujanje AE je v tem frekvenčnem območju zelo majhen.

Zato smo AE merili v območju 50–500 kHz. Višjega frekvenčnega območja nismo opazovali zaradi dušenja celotnega sistema in zaradi ugotovitev, da se večina zanimivih signalov AE vzbuja v tem frekvenčnem območju. Okolica in delovanje stroja ne vplivata na vzbujanje AE, razen v območju lastne frekvence zaznavala AE pri 200 kHz. Spekter moči signalov AE se, podobno kakor pri prvem delu meritev, veča s povečevanjem rezalnih parametrov (sl. 9).

Rezultati, dobljeni v odvisnosti od obrabe orodja iz keramike, se razlikujejo od rezultatov, dobljenih pri struženju jekla s karbidno trdino. Vzrok zmanjševanja moči signala z obrabo je več. Poglavitni vzrok je verjetno ta, da je pri največji obrabi odtekanje odrezkov moteno, površina obdelovanca je zelo hrapava, poveča pa se tudi temperatura v rezalni coni. Rezalni rob noža tu več ne reže materiala, temveč ga tlaci in plastično preoblikuje v območju rezalnega roba in konice noža.

Rezanje je praktično lomljjenje in plastificiranje materiala po in prek kristalnih zrn. AE se močneje vzbuja pri novem orodju, kjer je delež lomljjenja obdelovanega materiala večji. Pri obablenem orodju se poveča delež plastične deformacije v rezalni coni. Zato je tudi vzbujanje signala AE v tem primeru manjše in je to poglavitni vzrok, da se spekter moči signala AE zmanjša pri zvečanju obrabe proste ploskve.

Drugi vzrok je verjetno kombinacija orodja in obdelovanega materiala. Rezalna keramika ima veliko trdoto in drugačno strukturo, zaradi česar se tudi obraba keramičnih orodij razlikuje od obrabe karbidičnih trdin. Proses rezanja pri rezalni keramiki običajno poteka pri ostrejših rezalnih parametrih kakor pri karbidični trdini. To poveča vzbujanje AE v rezalni coni zaradi loma obdelovanega materiala, zato je verjetno delež AE, ki se vzbuja zaradi obrabe orodja, manjši ali se celo porazdeli. Pri rezalni keramiki je nastajanje mikrorazpok rezalnem robu manj intenzivno kakor pri karbidičnih trdinah. Zato je tudi količina vzbujenih signala AE manjša.

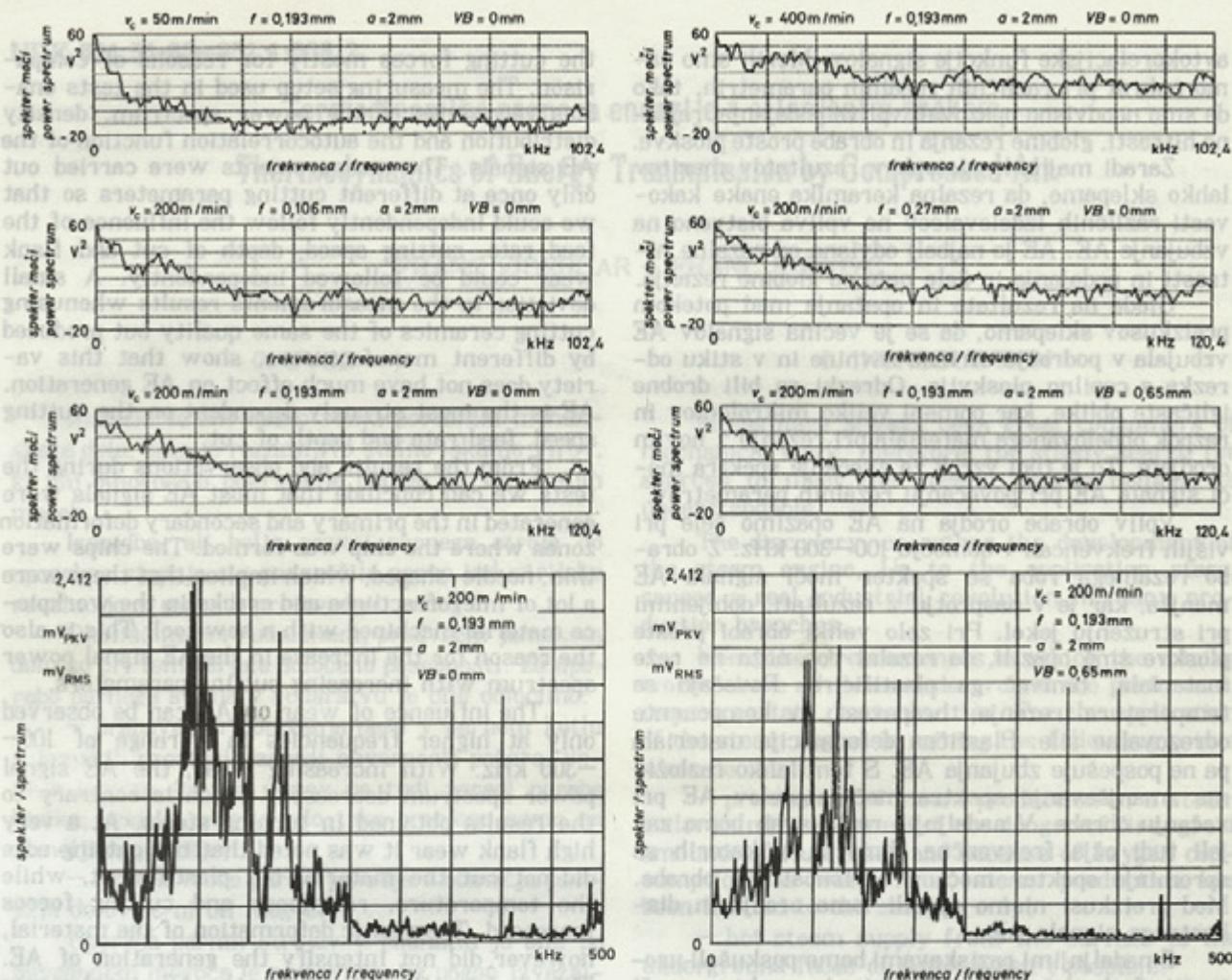
From the density distribution curve of the main cutting force and the feed force we can see that in the case of the main cutting force, the signal scattering around the mean value is greater than that of the feed force. With an increase in wear, the scattering or the dynamic component of the main cutting force does not change. The density distribution of the feed force narrows, because the force scattering around the mean value is smaller. The autocorrelation function of the dynamic forces has a constant multiplicative shape of the input signal and always oscillates over the time axis. A possible reason for this is that the dynamometer follows lower frequencies and dampens higher ones. Normally the power spectrum of the AE signal increases with increasing cutting parameters. Within a range of 20–100 kHz this increase is greatest at a higher cutting speed. In this frequency range no distinct peaks can be observed. In a frequency range 0–102.4 kHz we can follow the influence of cutting parameters  $a$ ,  $v_c$ , and  $f$  on the AE generation. In this frequency range the influence of tool wear  $VB$  on AE generation is very small.

It was therefore decided to measure AE in a frequency range of 50–500 kHz. Higher frequencies were not investigated because of damping of the entire system, and since it was found that most AE signals are generated in this frequency range. The environment and the operation of the machine do not exert any influence on AE generation except within the range of the natural frequency of the AE sensor at 200 kHz. Similarly as in the first part of measurements, the AE signal power spectrum increases with increased cutting parameters (fig. 9).

The results of the AE power spectra in dependence on tool wear are contrary to those obtained in turning steel with a cemented carbide tool. There are probably several reasons for the decrease in the AE signal power spectrum. The main reasons are that the flow of the chip is disturbed, the workpiece surface is very rough, and the temperature in the cutting zone is increased. The cutting edge did not cut the material further but compressed it so that the material experienced plastic deformation on the edge and on the tip.

Cutting is in essence breaking and plasticification of material along and across its crystal grains. AE is more pronounced when a new tool is used, because this involves a greater amount of breaking. When the tool gets worn away, the amount of plastic deformation in the cutting zone prevails and the AE generation is smaller. This is the main reason that, with flank wear increase, the AE signal power spectra decrease.

A second reason is probably the tool/workpiece combination. Cutting ceramics has a very high hardness and strength and a different structure, which makes the wear of ceramic tools different from that of carbide tools. Using cutting ceramics the process goes on at harsher cutting conditions than this is the case with cemented carbide tools. This increases AE generation in the cutting zone caused by workpiece material fracture, making the



Sl. 9. Spekter moči signala AE.  
Fig. 9. Power spectrum of AE signal.

Obdelovani material NL 60 uspešno obdelujemo pri večjih rezalnih hitrostih le z rezalno keramiko. Odrezki pri preizkuisu so bili v glavnem drobne igličaste oblike, razen pri največji obrabi, kjer je bil odrezek močno plastificiran in je bilo njegovo odtekanje moteno. Odrezki pri jeklih, ki imajo bolj žilavo strukturo, so običajno drugačni in manj vplivajo na vzbujanje AE v rezalni coni. Sklepamo, da se večina AE vzbuja v območju strižne ravnine, stika odrezka s cepilno ploskvijo in v območju ločevanja rezalnega roba.

## 5. SKLEPNE UGOTOVITVE

Merjenje AE pri postopkih odrezovanja je obetavna metoda za nadzor rezalnega procesa, vendar obstaja mnogo neraziskanih področij in vplivov na AE, ki jih je treba z nadaljnimi raziskavami še pojasniti.

V prispevku smo analizirali pojav akustične emisije pri struženju NL 60 z rezalno keramiko. Hkrati smo spremljali dinamiko rezalnih sil, ki je namenjena predvsem za primerjavo. Merilna oprema, ki smo jo uporabili, je bila primerna za opazovanje spektra moči, gostote porazdelitve in

amount of AE caused by tool wear smaller or even negligible. It is also possible that when using cutting ceramics, the formation of microcracks on the cutting edge is less intensive than when using cemented carbides also resulting in a smaller amount of AE signals.

An NL 60 workpiece is extremely hard and can be successfully machined at higher speeds only with cutting ceramics. The chips formed in the tests were mainly very thin and needle-shaped except at a wear  $VB = 0.65$  mm where the chip was strongly plastified, and its removal was hindered. Chips from steels, having a tougher structure, are usually different and have less effect on AE generation in the cutting zone. In our opinion most of the AE was generated in the primary and secondary zone, by chip breaking.

## 5. CONCLUSIONS

AE measurement during cutting is a promising method for monitoring the cutting process although there are a number of yet unclear influences which require further investigations. The paper analyses the AE phenomenon in turning NL 60 with cutting ceramics. A parallel investigation was carried out studying the dynamics of

avtokorelacijske funkcije signalov. Merili smo samo enkrat pri različnih rezalnih parametrih, tako da smo neodvisno opazovali vplive podajanja, rezalne hitrosti, globine rezanja in obrabe proste ploskve.

Zaradi majhnih odstopkov rezultatov meritev lahko sklepamo, da rezalna keramika enake kakovosti različnih izdelovalcev ne vpliva bistveno na vzbujanje AE. AE je najbolj odvisna od rezalne hitrosti in podajanja in šele nato od globine rezanja.

Glede na rezultate in opažanja med potekom preizkusov sklepamo, da se je večina signalov AE vzbujala v področju strižne ravnine in v stiku odrezka s cepilno ploskvijo. Odrezki so bili drobne igličaste oblike, kar pomeni veliko mikrolomov in razpok obdelovanega materiala pri rezanju z novim orodjem. To je tudi vzrok za zvečanje spektra moči signala AE pri povečanju rezalnih parametrov.

Vpliv obrabe orodja na AE opazimo šele pri višjih frekvencah v območju 100–300 kHz. Z obrabo rezalnega roba se spekter moči signala AE manjša, kar je v nasprotju z rezultati, dobljenimi pri struženju jekel. Pri zelo veliki obrabi proste ploskve smo opazili, da rezalni rob noža ne reže materiala, temveč ga plastificira. Povečajo se temperatura rezanja, hrapavost in komponente odrezovalne sile. Plastična deformacija materiala pa ne pospešuje zbujanja AE. S tem lahko razložimo zmanjševanje spektra moči signala AE pri večanju obrabe. V nadaljnjih raziskavah bomo zanjeli tudi ožja frekvenčna območja, v katerih se spreminja spekter moči v odvisnosti od obrabe. Med preizkusi nismo opazili loma orodja in diskretnega signala AE.

Z nadaljnji raziskavami bomo poskušali ugotoviti frekvenčno območje, kjer je spekter moči signala AE povezan z obrabo orodja. V povezavi z drugimi raziskovalci podobne problematike želimo – povezati signale zaznavati v ustrezni adaptivni model [12].

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the cutting forces mostly for reasons of comparison. The measuring setup used in the tests enables recordings of the power spectrum, density distribution and the autocorrelation function of the AE signals. The measurements were carried out only once at different cutting parameters so that we could independently follow the influence of the feed rate, cutting speed, depth of cut and flank wear could be followed independently. A small deviation in the measurements results when using cutting ceramics of the same quality but produced by different manufacturers, show that this variety does not have much effect on AE generation. AE is the most strongly dependent on the cutting speed, feed rate and depth of cut.

From the results and observations during the tests we can conclude that most AE signals were generated in the primary and secondary deformation zones where the chip was formed. The chips were thin, needle-shaped, which implies that there were a lot of microfractures and cracks in the workpiece material machined with a new tool. This is also the reason for the increase in the AE signal power spectrum with increasing cutting parameters.

The influence of wear on AE can be observed only at higher frequencies in a range of 100–300 kHz. With increasing wear, the AE signal power spectrum decreases, which is contrary to the results obtained in turning steels. At a very high flank wear it was noted that the cutting edge did not cut the material but plasticified it, while the temperature, roughness and cutting forces increased. The plastic deformation of the material, however, did not intensify the generation of AE. This explains the decrease in the AE signal power spectrum at increased wear. Our future research will include also narrow frequency ranges in which the power spectrum changes with wear. During the tests, no fracture of the tool and no discrete AE signals were noted.

In further research we will try to find a frequency range in which the power spectrum is related to wear. In cooperation with other researchers dealing with the same problems, our future endeavours will also be to use the information from sensor signals to develop one adequate adaptive model [12].

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Naslov avtorjev: doc. dr. Janez Kopač, dipl. inž.

Authors' address: asist. mag. Slavko Dolinšek, dipl. inž. Fakulteta za strojništvo Univerze v Ljubljani

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