Contribution to the Knowledge about Cutting Tool Condition Monitoring via Force Signals

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Abstract: The paper presents results of research activities in the area of the cutting tool condition monitoring via force signals as indices of tool wear and tool failure when turning. Cutting force authentically reflects changes in the tool during cutting with good accuracy. Relationship between cutting force and wear depends on workpiece/cutting tool interface and changes of cutting conditions. Therefore modelling as well as monitoring of tool wear is quantitative different for each workpiece/cutting tool interface and highly sensitive from cutting conditions changes, which obstruct their mutual comparasion.

Keywords: cutting force, tool condition monitoring ,cutting tool wear, ceramics, cubic boron nitride

1 Introduction

In the last years, metal cutting research has received a big impulse by strong developing of new workpiece and cutting tool materials and also by application of so called CA - technologies (computer aided) not only in production control process but also in R&D activity. This impulse is predominantly focused of the computer based simulation of accompanying phenomena of cutting process, monitoring of tool condition and chip formation. Miniaturisation tendency and high requirements on surface precision and its quality and details replacement increase application of sophisticated processing methods. These methods are orientated towards utilisation of innovative machining processes such as high speed cutting, characterised by very high cutting speed and often feed rate and precision and ultra precision machining. On the other hand, economical and environmental stress lead to the utilisation of machining operation based on cutting with defined tool geometry instead of abrasive processes. Because of high-energy consumption of abrasive process and different surface integrity (hard turning with CBN as alternative method to grinding, replacement of honing by fine boring). Accordingly, complexity of cutting process requires the increased reliability to begin with computer integrated manufacturing. This is make sure the proper monitoring system which is able to replace the human experience and collect the amount of information about cutting process for it optimisation and economy. This area of development is supported by application of proper sensitive sensors and high efficient computer system into research and partially into industrial practice. Nowadays, the research is orientated to integrate the proper monitoring system together with innovative machining processes. Monitoring and methods of data processing and decision making process are predominantly oriented on prediction of cutting tool condition, chip formation and another accompanying feature of cutting process such as force, temperature, vibrations etc. Development of innovative manufacturing processes concentrates attention on utilisation of non-metallic cutting tool materials as ceramics, boron nitride and diamond. Nowadays, among the wide range of metal based cutting materials such as coated high speed steel and carbides, utilisation of non-metallic cutting tool materials is about 5 ÷ 7 % of the total amount of cutting tool materials on world market. The trend shows to the increasing of utilisation of these materials based on ceramics, boron nitride depending on higher requirements of precision and high quality of machined surfaces together with high performance of machine tool.

1.1 Background of resesarch development of cutting tool monitoring at our workplace

The long-term development in the field of research into identification of the phenomena in the cutting zone led at our workplace (Buda, et al.,1986) [2] at first, to the construction of the universal monitorisation system prototype which can provide information from the cutting zone and represent it in the form of quantified data [2, 6]. Later, (Kažimír, 1993) [5] the second activity was an in-process sensing of tool failure using cutting forces measurement and their variations. There was used direct sensing by piezoelectric force sensor. The equipment used was designed in our department (it was subjected of application for author`s certification) as an evaluation device for the piezoelectric dynamometer with the aim of evaluating the technological processes in real time by means of computer. Research effort has been continued to look for more information about the cutting force variations and tool failure under the laboratory conditions. Recent research effort and experimental investigations continue based on the former knowledge and on the higher level of equipment mainly the high power computer for data acquisition [8, 9] The build up multi-sensor system designed and developed in our department based on real time monitoring and data acquisition of cutting force signals, tool vibration signals and cutting temperature is presented in this contribution.

As known, tooling management is one of the most essential aspects of an effective FMS (flexible manufacturing systems). The effective tooling management system will reduce cost and inventory, decrease machine downtime, and improve the quality of the part being produced. One of the most important thing is a reliability and tool life of cutting tools in automation manufacturing and tool exchange, too. It is necessary monitoring and control of the tooling used in the FMS. The tool breakage detection or cutting tool failure prediction seem to be a small part but the most important part of tool management strategy. As known, to realise the fully unattached operations of the systems reliable and effective sensing technology must be developed. The sensing of cutting tool failure is crucial for the unmanned manufacturing system, since the tool failure is directly related to the damage of the work material and it is most likely to cause troubles of the machine tool and other unforeseen troubles of the facilities in the manufacturing system. Although much attention is paid to the sensing of the tool failure and efforts are devoted, the sensing technology of the tool failure is not yet matured in comparison to the sensing of the tool wear which has rather long history of research and development [3, 7]. The reason for the difficulty of sensing and prediction of the tool failure is that the tool failure takes place suddenly based on the stochastic nature, while the tool wear take place progressively. Particular care must be exercised if the cutting tool material is ceramic. Tool failure detection can be performed by post-process or in-process method. There are well-known post-process and in-process method developed to identify tool failure or breakage using different sensors and sensing methods [3, 4].

A method for detecting and monitoring the wear on a cutting tool is therefore crucial in most metal cutting processes and several research efforts have striven to develop on-line tool condition monitoring systems (TCM). This paper describes an experimental method for one such technique involving the use of three components of the cutting forces (static and dynamic).

2 Cutting force and wear relationship when finish turning

In turning operation, it is convenient to consider the total cutting force as a three-component system. These are the cutting force component F_c, the axial (feed) component F_f and the radial (passive) component F_p.

Forces, as known, are the functions of cutting conditions, properties of tool and work material, structural rigidity of the machine, status of lubrication etc. Hence the direct use of forces for tool wear identification require a threshold based on the working conditions. The effects of feed, depth of cut and speed on forces have been indicated. From such data, it will be possible to model forces as functions of cutting conditions. The effect of other variables such as tool and work materials, lubricants etc., are more subtle and complex and difficult to quantify. The possible solution to this is to develop different models for each pair of tool/work material combination.

Information value of force as an index of cutting tool wear and failure is consider as follow:

- static (mean) value of force signal is used to compare the force components for both sharp and worn cutting tool edge,

- static (mean) value of force signal is used to model force/wear and cutting variables
- dynamic value of force signal is used to indicate changes when increase progressive wear or when damage the cutting tip

The static (mean) of force signals increases as wear level increases. The cutting force component, however, is not as sensitive to progressive wear as the other feeding and radial components. Experiments have shown different response of force component to the various wear form occurring on the tool. Feed force is insensitive to crater wear, whereas the feed and passive forces may be influenced more by tool wear than the main cutting force. Both the feeding and radial components are more sensitive than the main cutting component in detection tool chipping and breakage. These components increase suddenly at the instant of breakdown of the cutting edge. The cutting force and the feed force seem to monitor the condition of the tool totally. So it is believed that these two forces should be used to predict the value of tool wear at any instant. This agrees with many investigators [6, 7] proposing that there is a strong evidence that force signals carry useful information about the different forms of tool failure and, an appropriate technique is required to recognise, and to isolate this information.
Cutting tool wear can be classified into several types as follows [1]:

- adhesive wear associated with shear plane,
- abrasive wear resulting from hard particles cutting action,
- diffusion wear occurring at high temperature
- fracture wear such as chipping due to fatigue.

Tool wear processes generally occur in combination with the predominant wear mode, dependent upon the cutting condition, work and tooling material and the tool insert geometry. For a given cutting tool and work material combination, the tool wear form may depend exclusively on the cutting conditions, principally cutting speed v_c and the non-deformed chip thickness h and a combination of aforementioned wear mechanism. The more predominantly occurring forms of cutting tool wear often identified as a principal types of tool wear in metal turning using single-point tools are nose, flank, notch and crater wear.
The tool wear monitoring methods can be classified in two categories, i.e. direct and indirect methods. In direct methods tool wear is measured directly using optical sensors or micro-isotope sensors for measurement of the progress of wear on the tool edge. Direct methods also involve measurement of volumetric lose of material from the tool. In indirect methods tool wear is estimated using various measurable cutting variables that are sensitive to the tool wear development. Typical cutting variable is the cutting force, the tool vibration signal, the acoustic emission (AE) signal, and the spindle motor current. Unlike direct methods these methods can be used for on-line tool wear monitoring. It has been widely established that variation in the cutting force can be correlated to tool wear.
Force-wear interrelationships are formulated for possible use for in-process tool state monitoring through measurement of the variation in cutting forces. Of the two major types of tool wear, i.e. flank wear and crater wear the measurement of

flank wear is of great concern since amount of flank wear is often used in determining the tool life. In addition, the mechanism of wear development can be more accurately modelled for flank wear than for crater wear. Flank wear dominates in cutting processes where high cutting speed and low feed are used (e.g. in finishing operations). Relationship between cutting force and the tool wear development has been extensively studied by many researchers and well modelled mathematically [7, 8, 9]. Cutting force/wear relationship depends on work/cutting tool interface and change of cutting conditions. Therefore modelling as well as monitoring of tool wear is quantitative different for each work/cutting tool pair.

2.1 Experimental procedure

The present work attempts to devise schemes for tool wear estimation in a turning process by measurement of steady state cutting force components, the dynamic components of the main cutting force and tool/holder vibrations in the direction of main cutting force and cutting temperature. For cutting force sensing three components piezoelectric dynamometer have been used with charge amplifier. Input signals were recorded using A/D transducer with eight analogue inputs and connected with computer where the data are permanently stored for further off-line analysis. Sampling time was 200μs. The universal lathe was employed for longitudinal turning of bearing steel (14109.3) in hardened and non-hardened state as work material. No lubricants were used. Table 1 shows the employed range of cutting condition. Types of used cutting inserts and tool holders are in Table 2.

Table. 1 Cutting condition

Cutting speed [m/min]	90; 120; 160; 250
Feed per revolution [mm]	0.09; 0,102; 0.108; 0.15; 0.18
Depth of cut [mm	0.15; 0.3; 0.8; 1.4; 2;

Table. 2 Types of used cutting tool inserts

Type of tool holder	Type of inserts
2525 CSRNR, $\chi_r=70^o$	SNGN 120408 mixed oxide ceramics D210 ($Al_2O_3 + ZrO_2$)
2525 CSRNR, $\chi_r=70^o$	SNGN 120408 mixed oxide ceramics D310 (Al_2O_3 + TiC)
2525 CSRNR $\chi_r=70$	SPUN 120308 cubic boron nitride PB2

Flank wear (VB_B), nose wear (VBc) and notch wear (VB_N) was measured using toolmakers microscope when the turning stopped. Experimental work was designed to obtain data for sharp tools and different stages of wear. The data obtained were used to establish the effect of cutting conditions on cutting forces. Static and dynamic entities of the sampled cutting force were extracted as the mean and oscillatory components respectively, and analysed in time and frequency domain from which features sensitive to tool wear were identified.

For each test cut performed a value of static force was calculated from sampled cutting force. Signals from the metal cutting process generally are non-stationary due to non-linearity of the process and workpiece non-homogenity. However, for modelling and calculation, it was assumed that the cutting static force signal was stationary and independent of time. The statistical mean of the sampled cutting force was chosen to describe the nature of the static force behaviour. Monitoring of cutting tool failure, predominantly, flank wear that is dominant wear type for finishing turning, using force signals were carried out for oxide ceramic cutting tool material and cubic boron nitride tools with lower content of boron nitride. The experimental wear tracking were orientated on data acquisition for sharp and worn tools.

3. Total cutting force components as indirect index for tool wear identification

3.1 Experimental results

3.1.1 Static (mean) force components for tool wear idnetification

Due to limitation of space and bulky nature of results only a few plots of experiments have been presented. Experimental data of mean (static) cutting force was established the model equations of force wear relationship and cutting condition changes. Force signals are basis for modelling of force – wear functionality. Table 3 summarises model equations of cutting force as a function of cutting condition and gradual flank wear for ceramic insert.

Table 3 Model equations of cutting force

Force – wear and cutting variables relationships	
$F_f=413.a_p^{0,5}.f^{0,2}.v^{0,09}.VB_B^{0,1}$ $F_p=632.a_p^{0,1}.f^{0,4}.v^{0,11}.VB_B^{0,07}$ $F_c=3150.a_p^{0,39}.f^{0,54}.v^{-0,16}.VB_B^{0,05}$	Equations valid for following conditions $v_c= 120 \div 250$ m/min; $a_p = 0,5 \div 2$ mm; $f = 0,102 \div 0,21$ mm; $VB_B = 0,01 \div 0,473$ mm Work material: non-hardened bearing steel Tool: CA D210; Insert type: SNGA 120808; Tool holder type: 2525 CSNRL; Geometry: $\kappa_r = 75^o$; $r_\varepsilon = 0,8$ mm; $\gamma_o=6^o$, $\varepsilon_r=90^o$, $\lambda_s=-6^o$

The measured mean values F_c and F_f of force signal for sharp and worn tool have been compared in Fig. 1. There are no significant differences between cutting force F_c component for sharp and worn cutting edge. Passive force component shows the similar development as cutting force F_c component. More significant differences were shown the measured feed force component. There is a higher difference between sharp and worn force signal running. This confirms the importance of feeding force component in force signal monitoring as index of cutting tool wear. Increases of force from the beginning of cutting with sharp tool to the end of cutting with acceptable flank wear width (VB_{max} = 0,485 mm) has been presented in Fig. 2. The force increase (force rate) is calculated as follows:

$$C = \frac{F_k - Fo}{F_o}.100\% \qquad (1)$$

where F_k is cutting force determined for acceptable flank wear and F_o is initial cutting force. The value for acceptable flank wear width was established according to the quality of machined surface. The required quality of the machined surface has been described by the surface roughness *Ra*.

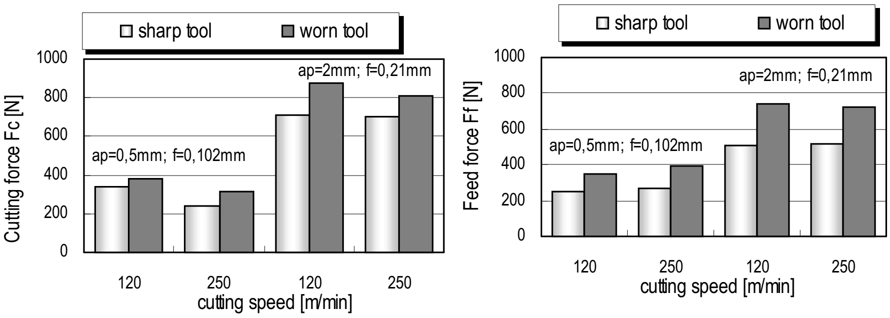

Fig. 1 Comparison of cutting and feed force components for sharp and worn tool. Testing conditions: tool material D210, measured flank wear width VB_B=0,486 mm; crater on rake face KT=0.09 mm.

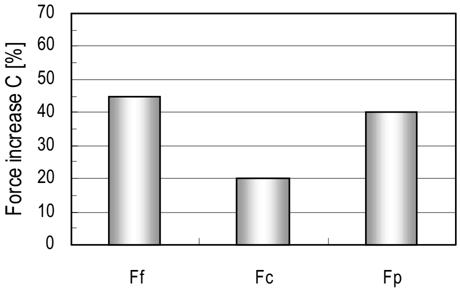

Fig. 2 Static (mean) force components average increase

In conventional turning the cutting force is the largest of the three components, though in finishing the passive force is often larger while the feed force is minimal. This arrangement is outgoing from the tool geometry and the cutting condition. Usually in finish turning the depth of cut are smaller then the nose radius of the tool (experimental values were a_p = 0,5 mm, r_ε = 0,8 mm).

Under such condition the tool nose i.e. the curved part of cutting edge, perform the whole job, thus the acting cutting edge angle varies along the tool-work contact arc of the tool nose. Alteration the cutting conditions, mainly depth of cut, cause change the relation between force components, as illustrate Fig. 3. Force-wear plots on Fig. 3 indicates also to the static force meanings of cutting tool stage. Both the passive and feed force components increase with increasing of flank wear width.

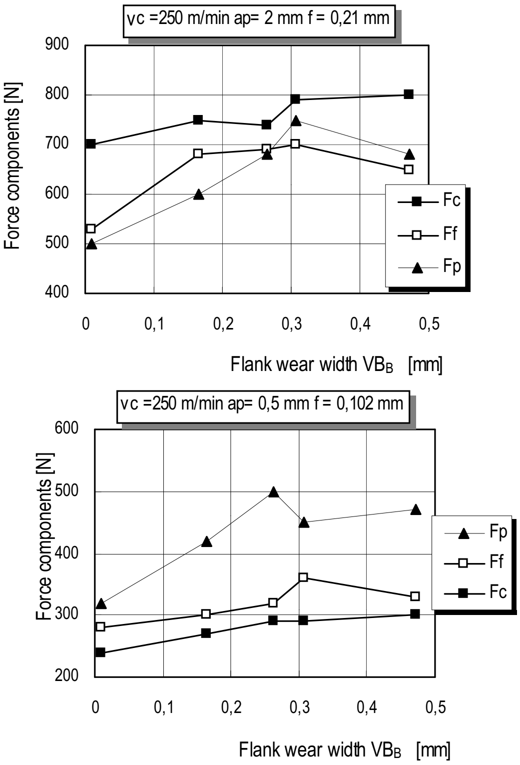

Fig. 3 Total cutting force components vs flank wear for ceramic D210

3.2.1 Dynamic force components for tool wear idnetification

Figure 4 shows force components time signals for sharp ceramic insert and beginning of chipping on cutting edge when hard turning. The radial force component changes is significant for chipping. Increasing of force due to gradual chipping is visible on Fig. 4. Fig. 5 illustrates the random character of tool failure when hard turning with CBN tool under various cutting conditions. Fig.5 shows the change of force signal for various stage of cutting edge damage, increase of radial force component when edge chipping occured and sudden failure of tool point in the beginning of operation, respectively. Experimental results show that cutting force signals are convenient for cutting edge failure identification.

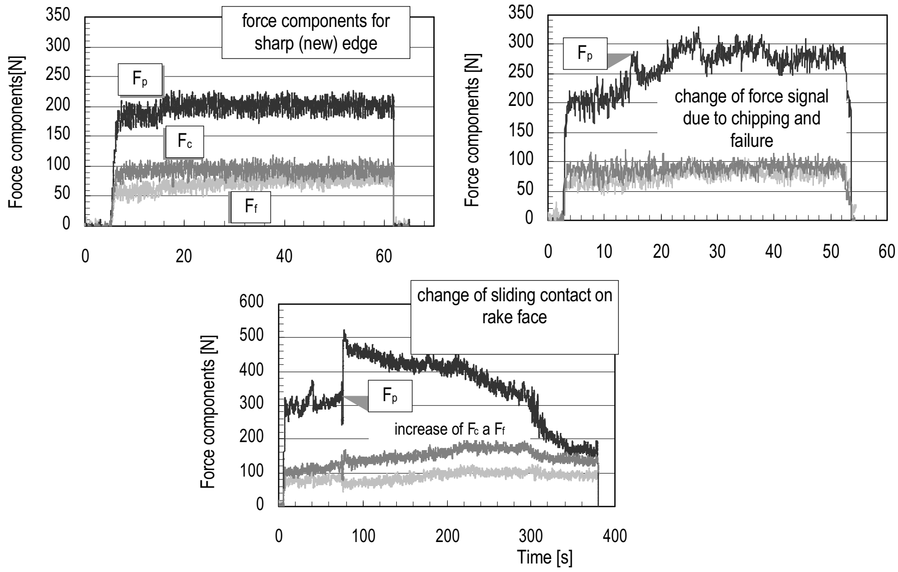

Fig. 3 Cutting force component signal
when turning with oxide ceramic inserts D310

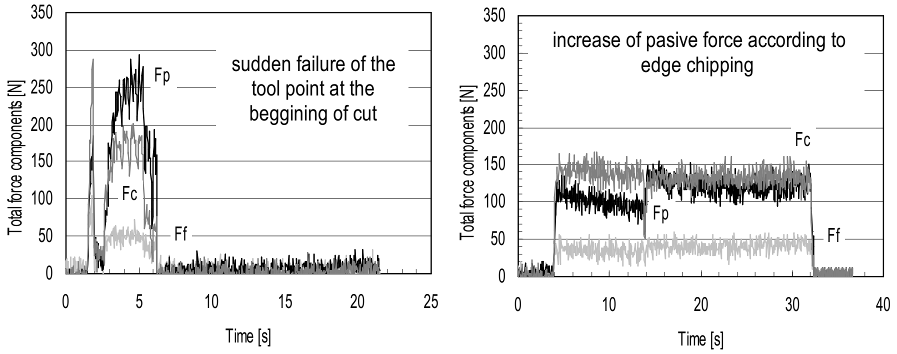

Fig. 4 Cutting force component signal for sharp tool and various stage of tool failure when hard turning with cubic boron nitride PB2 insert (a) ap = 0,3 mm; f = 0,21 mm; v = 90 m/min (b) ap = 0,15 mm; f = 0,15 mm; v = 160 m./min;

Conclusions

When finish cutting of steel, the passive (radial) force became the largest among the three force components. But the most sensitive to the changes of flank and nose wear was the mean feed force component although the passive force indicates significant increase, too.

Model equations of cutting force as a function of cutting condition and progressive wear when turning verify the leading role of feed force components in tool wear identification.

Character of dynamic value of force signal change when damage of cutting tip. Data acquisition and variou force signal collection in our research activity is oriented to create so called “library” or “models” of force signals when cutting with sharp tool to compare with signals of various type of tool edge damage. The set-up for monitoring of tool condition at our workplace enables collect another data such as tool holder vibration and cutting temperature.

These mentioned data are collected now for further processing to deeper identify of cutting process when hard turning and data collection for various tool/work material combination, mainly on ceramic inserts and CBN. The article presents only a small part of force signals the collected library represents a starting point for tool stage identification and/or failure prediction in tool monitoring system as a part of tool management in pilot project for CIM laboratory built in our workplace.

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